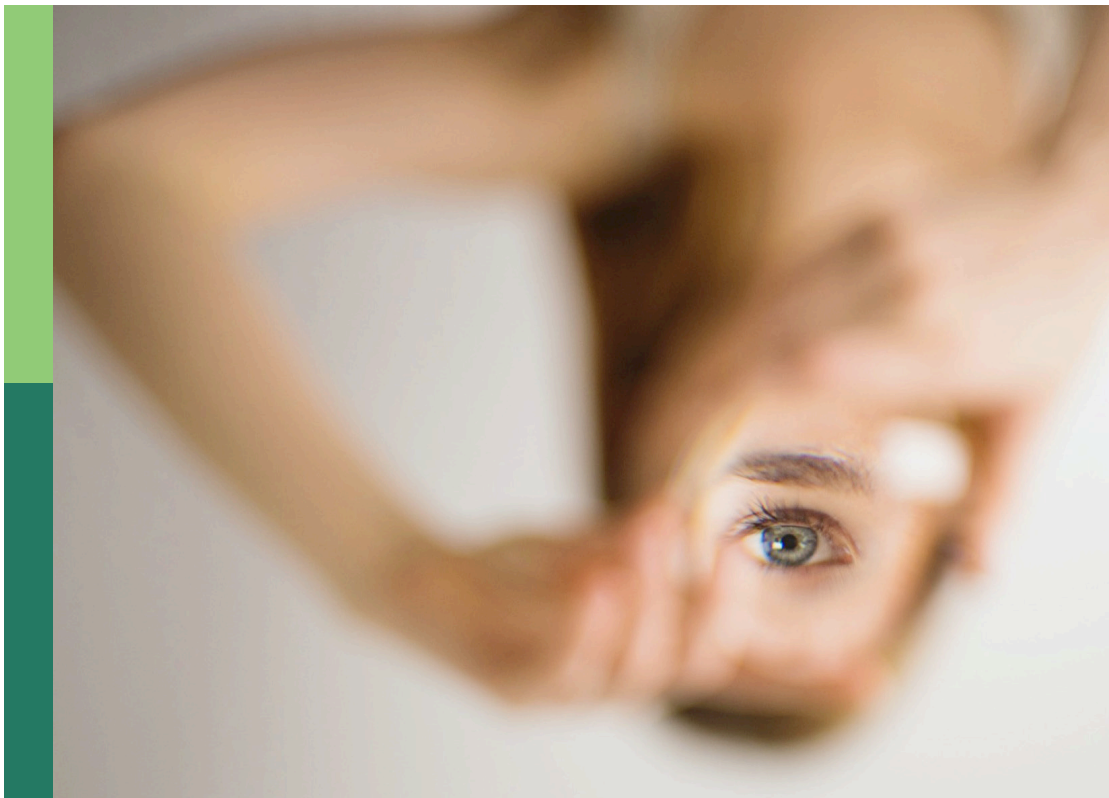
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Insights and reviews in movement science 2023

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Insights and reviews in movement science 2023

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Editorial: Insights and reviews in movement science 2023

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Editorial on the Research Topic
Insights and reviews in movement science 2023

Introduction

This Research Topic encompasses three broad domains: (1) motor control, (2) fine-tuning incremental progress, and (3) psychosocial aspects of movement, physical activity, and exercise.

Motor control: from normative data to innovative therapies

A unifying theme across this section is the quantification and enhancement of motor control through advanced assessment tools and innovative interventions that promote recovery and improve function. For example, in sports, elite marathons are one of the most impressive human endeavors. Yan et al. reviewed a large global database on the physiology, training intensity, pacing, nutritional strategies, age and sex differences, and recovery from inflammation and muscle damage during these events. By studying the relationships between the peak torque, peak power and mean power dynamometer output measures, Thompson re-analyzed the physiological implications of the isokinetic vs. isotonic operational principles largely utilized during sports training. The systematic review and meta-analysis by Julienne et al. provided the most comprehensive synthesis to date of normative data in instrumented posturography. Their findings underscore the influence of age and sex on postural control, while also exposing heterogeneity in protocols and the urgent need for standardization. Complementing this population-level view, Wang et al. examined how neuromuscular coordination is reorganized under fatigue conditions. Using EMG coupling analysis during bench press exercises, the authors revealed altered synchronization between agonist and antagonist muscle pairs, pointing to supraspinal adaptations that compensate for declining muscle force. This mechanistic insight advances our understanding of how fatigue reshapes motor output and informs both athletic training

and rehabilitation practices. Czyż et al. approached the theme of interventions from a motor learning perspective by reviewing nearly six decades of research on contextual interference. Their systematic review and meta-analysis confirmed that random practice schedules enhance transfer, with a medium effect size overall, especially among adults and older adults. The introduction of virtual reality (VR) environments into the field of physical activity opens new avenues for exploring performance enhancement, therapeutic interventions, and health promotion. Interestingly, the review of Yu et al. confirmed that a single session of transcranial direct current stimulation (tDCS) has the potential to improve motor performance in healthy subjects and athletes. In their 2024 review, Schedler et al. provided an overview of recent advances in high-resolution head-mounted displays (HMDs) and their application in training balance-related skills across the lifespan. The use of HMDs should therefore benefit the subject's overall balance, particularly during the critical phases of maturation. In the same line of inquiry, Xue et al. addressed how to leverage technology to enhance motor outcomes in children with cerebral palsy. Their systematic review and meta-analysis demonstrated that virtual reality motor games significantly improve both gross and fine motor skills. The integration of molecular genetic technologies, epidemiology, exercise physiology and biostatistics to investigate quantitative performance traits, such as muscle power output and movement recording with new motion capture was reviewed by Papadimitriou. This study focused on the implications for the biotech industry, particularly in gene therapy to combat age-related muscle power decline and personalized medicine, which will drive advancements in exercise program design. Zi and de Geus re-analyzed the genetic aspect of the Stodden model regarding the potential confounding factors of familial environment characteristics, which include household, neighborhood, and parental rearing style. Collectively, these contributions advance our understanding of motor control mechanisms, from biomechanics to genetics, and highlight promising avenues for both athletic training and rehabilitation.

Incremental progress and "fine-tuning"

Recent works have promulgated the idea of fine-tuning in exercise, physical activity and sports. This process implies incremental progress in motor development, athletic training programs, and scientific research through tweaking and slight adjustments.

Nowhere is skill development more essential than in the transition from youth to adult athlete. The study by Zheng and van der Kamp considered the strengths and limitations of the body-scaled approach often utilized in youth sports. It was highlighted that an action-scaled approach, which emphasizes task specificity, helps better guide youth sports modifications while effectively developing young athletes for the next stage of their careers.

Balance training is a particularly valuable skill for both individual athletes and teams. Chen et al. found that balance training, when combined with multi-directional movement exercises, improved the ability to change direction more quickly among young table tennis players. Similarly, the review by Gao et al. focused on the effects of instability resistance training on athletes' performance. This type of training has proven effective for improving dynamic balance abilities and core stability among many strength, power, and even endurance athletes.

The ability to monitor brain activity during athletic performance has improved significantly over the past several years. A systematic review of functional near-infrared spectroscopy (fNIRS) by Shen et al. showed that physical exercise induces positive adaptations in both the prefrontal and motor cortices through increased levels of oxygenated hemoglobin. These changes in cortical hemodynamics were found to be associated with enhanced inhibitory control and working memory. Another study by Yu et al. examined the effects of a single session of transcranial direct current stimulation (tDCS) and found significant improvements in strength, endurance, and emotional state, with smaller but still notable effects on sport-specific tasks and cognitive performance.

Implications for improved cognitive performance were also highlighted by a systematic review on eye-tracking technology (Kredel et al.). While progress in this field has been uneven since the last update, one important advancement is the use of automated gaze-cue allocations (GCAs), particularly in mobile eye-tracking studies. GCAs increase objectivity while reducing the manual workload.

Taken together, these findings reinforce the importance of fine-tuning, highlight promising avenues for future research, and suggest further applications aimed at enhancing athletic performance and excellence.

Psychosocial aspects of movement, physical activity, and exercise

Five contributions (Segar; Carrera-Bastos et al.; Jadhakhan et al.; Yang et al.; Si et al.) were specifically related to the psychosocial aspects of physical activity (PA) and exercise. One could consider motivation to be the predominant theme of these works. At first glance, tying these papers together into a single motivational model may seem unwieldy. However, conceptual and theoretical advances have made this feasible. Taken together, these studies propose that an immediate antecedent of movement is an urge or impulse to move or not move. These articles also include important fundamental aspects of motivation, such as active approach vs. active withdrawal from physical activity and sedentary behaviors, along with negative reinforcement and classic aspects of drive theory. In addition, there is a likely motivational null point where both approach and withdrawal are neutralized and wants/desires are minimized, a state similar to mindfulness, as described by Si et al.. Potentially dozens of factors have an interplay in these processes, but in terms of approach motivation, the article by Segar suggested that promoting PA/exercise over the long term could be accomplished by: 1) enhancing the affective response to PA, 2) challenging all-or-nothing decision-making, and 3) giving oneself permission for self-care, such as structured exercise.

Enhancing motivation for activity in healthy populations is quite different from minimizing pathological processes that inhibit movement. In the case of depression, withdrawal (or sometimes excessive activity) is a common hallmark of the disorder, known as psychomotor retardation or excitation. This is potentially related to dysregulated inflammatory processes (Carrera-Bastos et al.) which can be counteracted by a variety of different exercise interventions. Fear of movement (i.e., kinesiophobia), as explained by Jadhakhan et al., is an example of active withdrawal, dread, or aversion to movement, a state particularly activated by the experience or anticipation of pain. While it is understood that the majority of individuals suffer from too little movement, some subjects move too much, to the extent that their movement tendencies interfere with other objectives in their lives. With ADHD, it also seems likely that there are excessive urges to move (Yang et al.) and this should be studied more systematically in the future. Paralympic sports such as Boccia also demonstrate that, beyond their physical benefits, they emphasize social interaction, emotional regulation and empathy (Ferreira et al.). These findings illustrate the complex interplay between psychological, biological, and social factors in sustaining healthy movement behaviors.

Author contributions

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Eye-tracking technology and the dynamics of natural gaze behavior in sports: an update 2016–2022

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Updating and complementing a previous review on eye-tracking technology and the dynamics of natural gaze behavior in sports, this short review focuses on the progress concerning researched sports tasks, applied methods of gaze data collection and analysis as well as derived gaze measures for the time interval of 2016–2022. To that end, a systematic review according to the PRISMA guidelines was conducted, searching Web of Science, PubMed Central, SPORTDiscus, and ScienceDirect for the keywords: eye tracking, gaze behavio*r, eye movement, and visual search. Thirty-one studies were identified for the review. On the one hand, a generally increased research interest and a wider area of researched sports with a particular increase in official's gaze behavior were diagnosed. On the other hand, a general lack of progress concerning sample sizes, amounts of trials, employed eye-tracking technology and gaze analysis procedures must be acknowledged. Nevertheless, first attempts to automated gaze-cue-allocations (GCA) in mobile eye-tracking studies were seen, potentially enhancing objectivity, and alleviating the burden of manual workload inherently associated with conventional gaze analyses. Reinforcing the claims of the previous review, this review concludes by describing four distinct technological approaches to automating GCA, some of which are specifically suited to tackle the validity and generalizability issues associated with the current limitations of mobile eye-tracking studies on natural gaze behavior in sports.

KEYWORDS

gaze behavior, visual search, eye-tracking, eye movements, sports

1. Introduction

In 2017, Kredel et al. (2017) published a review on eye-tracking technology and the dynamics of natural gaze behavior in sports that the scientific community has quite well received. This systematic review covered 40 years of previous research, beginning with the trend-setting publication on visual search activity in sports by Bard and Fleury (1976) and ending with the comparison of elite and non-elite tennis players' gaze behaviors by Murray and Hunfalvay (2016). Based on 60 included studies, the authors reasoned that sports-related eye-tracking research seemed to strive for ecologically valid test settings (i.e., concerning viewing conditions and response modes) and experimental control along with high measurement accuracy (i.e., controlled test conditions with high-sample-rate eye-trackers linked to algorithmic analyses). To meet both demands, the authors suggested the integration of robust mobile eye-trackers in motion-capture systems whilst, at the same time, advising researchers to carefully weigh arguments concerning the fundamental trade-off between laboratory and field research. In any

case, further advancements in mobile eye-tracking methodology seemed advisable to allow for more significant amounts of gaze data to increase the explanatory power of the inferred results (*cf.* also Orquin and Holmqvist, 2018).

Given the highly dynamic developments in sports technology over recent years, the present review aims to complement the data reported by Kredel et al. (2017) by updating the analysis for the time interval of 2016–2022, thereby especially focusing on the progress concerning researched sports tasks, applied methods of gaze data collection and analysis as well as derived gaze measures.

2. Methods

In line with the PRISMA guidelines (Shamseer et al., 2015), a systematic review was conducted by searching the electronic databases Web of Science, PubMed Central, SPORTDiscus, and ScienceDirect for the keywords: eye tracking, gaze behavio*r, eye movement, and visual search (February 2022). Studies on natural dynamic visual behavior with gaze assignments on at least two different areas of interest (AOIs) written in the English language and published in peer-reviewed journals between 2016 and 2022 were included, whilst studies on perceptual training, using occlusion paradigms or without the collection of eye-tracking data were excluded. After removing duplicates from the initially identified 491 articles, 387 studies were screened by two independent raters leading to the exclusion of 260 additional studies that were not sports-related (99), not based on eye-tracking (90), actually not peer-reviewed (53) or not dealing with natural dynamic gaze behavior (18). Assessing the full text of the remaining 127 records for eligibility resulted in a further exclusion of 96 articles that were not sports-related (41), conducted without pre-defined AOIs (24), focused on non-natural or static gaze behavior (19), actually not employing eye-tracking (11) or researching perceptual learning (1). The remaining 31 articles were finally included in the review.

3. Results

In the following paragraphs, the review results will be summarized and contrasted with the review conducted by Kredel et al. (2017).

3.1. Publications

The 31 included studies are characterized in Table 1 by author names and year of publication, researched sport, sample size, visualization condition, viewing perspective, required motor response, number of analyzed trials, applied eye-tracker type and sample rate (ET), gaze-cue allocation method (GCA), number of pre-defined areas of interest (NAOI) as well as derived gaze measures, namely fixation durations (FD), number of fixations (NF), saccades (SA), viewing times (VT) and gaze dynamics, either not related (DN) or related (DE) to a specific event. In purely quantitative terms, the number of scientific publications on natural gaze behavior in sports has increased significantly in recent years (from 11 in 2007–2011 over 20 in 2012–2016 to 28 in 2017–2021).

3.2. Task

Despite the recent increase in the total number of studies, the percentage of studies in game sports decreased from 87.1% (Kredel et al., 2017) to 61.3% in the current review, which not only reflects a broader range of researched sports but a marked focus on sports referees' or judges' gaze behavior (22.6%). The sample sizes have remained essentially constant ($M = 20.7$, $SD = 10.3$; compared to $M = 20.6$, $SD = 12.4$ for 1976–2016). However, it apparently has become standard practice to base gaze analyses not only on a fraction of the sample but on all participants. Overall, the total of 1′131 researched participants in 2016 increased to a total of 1′743 participants in 2022.

Regarding the experimental setting, a strong trend can be noticed toward ensuring the results' ecological validity. Compared to Kredel et al. (2017), the percentage of studies in which gaze data was acquired under natural field conditions rose from 39.4 to 62.5%. Above, a natural viewing perspective was implemented in each of the more current studies, meaning that the scenery was presented to the participant as an evolving situation watched from a first-person perspective, contrary to 11.9% with a third-person perspective in the 2017 review. The same trend holds for the required motor response. The percentage of studies in which participants were asked to respond naturally to the presented situations (as opposed to button presses, verbal responses, etc.) increased from 60.7% for 1976–2016 to 83.9% for the recent 5-year interval.

The resulting tendency toward an emphasis on ecological validity is illustrated in summary in the left panel of Figure 1, in which the studies included in the 2017 and the 2022 review are grouped concerning the viewing conditions (field vs. lab) and response requirements (natural vs. artificial), respectively, and depicted in cumulation (thereby omitting a single publication in which no response was demanded as well as the field/artificial category that appeared only twice since 1976). Obviously, the portion of lab studies with artificial responses stagnates over recent years whilst the number of lab studies with natural responses, and more so, the number of field studies with natural responses has remarkably grown.

3.3. Gaze analysis

Compared to the review conducted by Kredel et al. (2017), the percentage of analyzed trials per participant slightly decreased from 82.3 to 79.5% and the number of total trials performed per participant considerably decreased from 41.5 ($SD = 49.1$) to 30 ($SD = 22.9$). Assuming no substantial prolongation of the single trials and given the substantial noise that gaze data is typically afflicted with, this decrease is a profound surprise.

On the other hand, the average sample rate raised in median values from 30 Hz to 60 Hz. This is partly because recent studies have used mobile eye-trackers with comparatively high-sample-rate cameras (up to 200 Hz). However, these numbers should be interpreted with caution as desirable reporting standards are still not obeyed in all cases (leading to, e.g., mixed-up eye and scene camera sample rates or sample rates not reported at all). When having a closer look at the used eye-trackers, it becomes evident that – despite the noticeable technological progress in mobile eye-tracking systems over the recent years (with, e.g., higher sample rates and video resolutions, multiple

TABLE 1 Overview of sports-related eye-tracking studies (2016–2022).

Publication	Task					Gaze analysis				Gaze measures					
Author(s)/Year	Sport	*N*	Condition	View	Response	Trials	ET	GCA	NAOI	FD	NF	SA	VT	DN	DE
Spitz et al. (2016)	Soccer (R)	39/39	Lab	1st	Artificial	20/20	s/120	Algorithmic	4	x	x	–	–	–	–
Zeuwts et al. (2016)	Cycling	12/13	Lab+Field	1st	Natural	550 m/700 m	m/50(30)	Manual	5	–	–	–	–	–	–
Chia et al. (2017)	Badminton	24/24	Field	1st	Natural	27.6/30	m/30(–)	Manual	6	x	x	–	x	–	–
Decroix et al. (2017)	Slalom Skiing	11/27	Field	1st	Natural	17/17	m/50(25)	Manual	8	x	x	–	x	–	–
Schnyder et al. (2017)	Soccer (R)	6/6	Field	1st	Natural	36/36	m/120(60)	Manual	7	x	x	–	–	–	x
Seifert et al. (2017)	Climbing	18/18	Field	1st	Natural	1 route	m/60(30)	Manual	40	x	x	–	–	x	–
Vansteenkiste et al. (2017)	Cycling	27/34	Field	1st	Natural	550 m/700 m	m/30(–)	Manual	5	x	x	–	x	–	–
Brimmell et al. (2018)	Soccer	41/42	Lab	1st	Natural	2/2	m/30(–)	Manual	4	x	x	–	x	–	–
Del Campo et al. (2018)	Soccer (R)	22/22	Lab	1st	Natural	24/24	m/–	Manual	2	x	x	–	x	–	–
Goh et al. (2018)	Bowling	21/21	Field	1st	Natural	10/10	m/25(–)	Algorithmic	8	x	x	–	x	–	–
Hunfalvay and Murray (2018)	Tennis (WC)	32/32	Lab	1st	Natural	18/18	s/60	Algorithmic	5	x	x	–	–	–	x
Pizzera et al. (2018)	Gymnastic (J)	35/35	Lab	1st	Natural	19/21	s/300	Manual	5	x	x	–	–	–	–
Robertson et al. (2018)	Judo (C)	20/22	Lab	1st	Natural	2/24	m/30(–)	Manual	9	x	x	–	x	–	–
Sáenz-Moncaleano et al. (2018)	Tennis	21/21	Field	1st	Natural	40/40	m/60(–)	Manual	4	x	–	–	–	–	x
Van Maarseveen et al. (2018)	Basketball	13/13	Field	1st	Natural	12/36	m/24(–)	Manual	9	x	x	–	x	x	–
Kim et al. (2019)	Archery	14/14	Lab	1st	No	3/3	s/–	Algorithmic	5	x	x	x	–	–	x
Vila-Maldonado et al. (2019)	Volleyball	38/38	Lab	1st	Artificial	34/36	m/– (–)	Manual	8	x	x	–	x	–	–
Aksum et al. (2020)	Soccer	5/5	Field	1st	Natural	16 min	m/– (25)	Manual	4	x	–	–	x	–	–
Bickmann et al. (2020)	Soccer (E)	21/21	Lab	1st	Natural	1 match	s/120	Manual	9	x	x	–	–	–	–
Kato (2020)	Kendo	20/20	Field	1st	Natural	4/5 sess.	m/60(–)	Manual	6	x	x	–	x	–	–
Mitchell et al. (2020)	Climbing (C)	6/6	Field	1st	Artificial	12/12	m/60(–)	Manual	3	x	x	–	x	–	–
Shearer et al. (2020)	Team Sports	34/34	Lab	1st	Artificial	11/11	s/120	Manual	3	x	x	–	–	–	–
Babadi Aghakhanpour et al. (2021)	Fencing (R)	28/28	Lab	1st	Natural	50/50	m/60(–)	Manual	4	x	x	–	–	–	–
Esteves et al. (2021)	Basketball	10/10	Field	1st	Natural	50/50	m/60(–)	Manual	6	x	x	–	–	–	–
Klatt et al. (2021a)	Basketball (R)	8/9	Field	1st	Natural	1 match	m/200(120/30)	Manual	6	x	–	x	–	–	x

(Continued)

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TABLE 1 (Continued)

Publication	Task				Gaze analysis			Gaze measures					
Author(s)/Year	Sport	*N*	Condition	View	Response	Trials	ET	GCA	NAOI	FD	NF	SA	VT	DN	DE
Klatt et al. (2021a,b)	Field Hockey	13/14	Field	1st	Natural	19.5/20	m/200(120/30)	Manual	6	x	–	–	–	–	x
Loiseau-Taupin et al. (2021)	Badminton	19/19	Field	1st	Natural	2 sets	m/200(120)	Manual	9	x	x	–	x	–	x
Rosker and Majcen Rosker (2021a)	Tennis	15/15	Field	1st	Natural	45/90	m/50(−)	Manual	25	x	–	–	–	–	x
Rosker and Majcen Rosker (2021b)	Tennis	17/17	Field	1st	Natural	60/~90	m/50(−)	Manual	25	x	–	–	–	–	x
Krabben et al. (2022)	Judo	7/8	Field	1st	Natural	12.9/20	m/120(25)	Algorithmic	7	–	–	–	x	–	x
Van Biemen et al. (2022)	Soccer (R)	14/14	Field	1st	Natural	65.4/90 min	m/60/30(−)	Manual	6	x	x	–	x	–	x

The publications are specified by researched sport (R, referee; J, judge; WC, wheelchair; C, coach; E, e-sports), sample size (N: number of participants with gaze analysis/total number of participants), visualisation condition (Lab = slides/videos, Field = *in-situ* investigation), viewing perspective (1st = agent's perspective, 3rd = agent on the field), required motor response (natural = natural action, artificial = verbal/button press/etc., no = just watching), number of trials (number of trials with gaze analysis/total number of trials), applied eye-tracker (ET, type and sample rate in Hz, m = mobile, s = stationary, – = not reported, in brackets: sample rate of scene camera), the gaze-cue allocation method (GCA, Manual = ratings, algo. = algorithmic, – = not reported), number of pre-defined areas of interest for gaze allocation (NAOI), as well as collected gaze measures (FD = fixation durations, NF = number of fixations, SA = saccades, VT = viewing times, DN = gaze dynamics not related to a specific event, DE = gaze dynamics related to a specific event, x = measured, – = not measured).

cameras per eye, and slippage correction) – most studies relied on comparably old technology with low specifications. Virtually never reported was a comprehensive set of data quality measures, as already proposed by Holmqvist et al. (2012), rendering further quality comparisons considerably more difficult, if not impossible.

The same absence of marked progress is revealed when considering the total number of analyzed frames per study – roughly estimated from the numbers of included participants, trials per participant, and eye-tracker sample rates as specified in the respective papers and assuming the analysis of a 2-s interval per trial (which, due to circumstances, can only be done for publications in which all these details are specified). The resulting numbers are depicted in the right panel of Figure 1 as a function of the year of publication, the applied eye-tracker, and the required motor response – again omitting a category that appeared only twice since 1976, namely stationary/natural. The use of stationary eye-trackers that feature high sample rates and thus remarkably raise the number of analyzed frames seems to mark a distinct episode lasting from 2010 to 2016. This turn away in more recent years can probably be best ascribed to the inevitable costs of stationary (and especially head-fixed) eye-tracking, namely, the reduction of ecological validity, as already discussed above. Likewise, no positive tendency is revealed for studies in which mobile eye-trackers came into operation, but artificial motor responses were required. In contrast, regarding mobile eye-tracking studies with natural responses, a slight increase can be noticed that not only refers to the total number of studies over consecutive 5-years intervals but also to the total number of analyzed frames. When calculating a linear trend for these investigations, this number increased from about 10′000 frames in 1990 to about 55′000 frames in 2022, corresponding to an annual increase of about 1′000 analyzed frames per study. However, compared to the depicted studies in which stationary eye-trackers allowed for more than 1 million analyzed frames per study, these numbers still fall short by orders of magnitude.

Regarding the number of AOIs reported in the papers included in the present review, the current gaze point was allocated to about eight predefined AOIs ($M = 8.2$, SD = 7.7), a number that pretty much matches the count over the previous time interval ($M = 6.8$, SD = 3.1). Details of gaze-cue allocation (GCA) were only elliptically reported and therefore remain difficult to interpret. Some studies (e.g., Sáenz-Moncaleano et al., 2018) seem to employ algorithmic event-detection algorithms (e.g., for fixations) first, and assign AOIs to events in a second step (leading to a significant reduction of manual work), whilst others (e.g., Van Maarseveen et al., 2018) perform a frame-by-frame GCA and classify fixations downstream based on these categorial allocations, obviously omitting detailed spatial characteristics of gaze locations. Some ignore these – perceptually relevant – event detections altogether or even redefine standard definitions (e.g., Loiseau-Taupin et al., 2021). Nevertheless, decent progress can be noticed concerning an algorithmic rather than a manual approach to GCA as – compared to the 8.3% reported by Kredel et al. (2017) – an algorithmic approach has been pursued in 16.1% of studies over more recent years. However, for three of the total five studies with an algorithmic GCA, the automation was at the expense of accepting a stationary collection of gaze data (Spitz et al., 2016; Hunfalvay and Murray, 2018; Kim et al., 2019). Still, the remaining two studies with a completely automated GCA (Goh et al., 2018; Krabben et al., 2022) represent significant progress in terms of algorithmic analyses of mobile eye-tracking data in sports-related settings (from 0% in 2017 to 8.0% more recently).

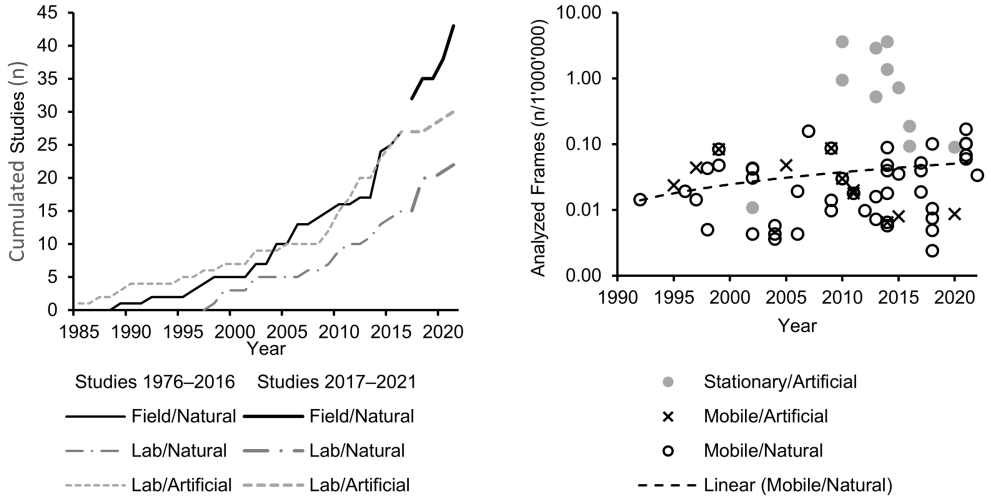


FIGURE 1
Cumulated number of studies published 1976–2021, assigned by the external validity to the categories "field/natural," "lab/natural," and "lab/artificial" (left) and estimated total numbers of analyzed frames per study as a function of year of publication (1993–2022), applied eye tracker (stationary vs. mobile), and required motor response (artificial vs. natural) (right, please note the log scale of the vertical axis).

3.4. Gaze measures

Regarding derived gaze measures, Kredel et al. (2017) report no significant trends when comparing studies conducted either in 1976–2000 or 2001–2016. This picture seems to have considerably changed over more recent years. More precisely, comparing the past with the recent study pool, a remarkable drop in the percentage of studies is revealed that report overall viewing times (VT; from 88.3 to 48.4%; for a respective critique, see Orquin and Holmqvist, 2018) or gaze dynamics without relating the gaze behavior to specific events (DN; from 33.3 to 6.5%). Whilst this decrease can probably be best ascribed to the mostly nominal informative value of these two variables in dynamic settings, the additionally observed decrease in the analysis of saccades (SA; from 25.0 to 6.5%) sparks hope that also in sports-related studies the technological limitations of low sample-rate eye-tracking devices concerning saccade analyses slowly become respected or, at least, the established nomenclature is applied more consistently.

In contrast, two further gaze measures continue to be reported in most publications, namely the number of fixations (NF; from 85.0 to 74.2%) as well as fixation durations (FD; from 88.3 to 93.5%). Depending on their definition (*cf.* Hessels et al., 2018), these measures can be automatically derived from the raw gaze data in a relatively straightforward manner by applying event-detection algorithms (e.g., IVT, but refer to Andersson et al., 2017, for a performance evaluation of different algorithms and specific caveats before their application, especially in mobile settings).

The most pronounced increase, however, pertains to the calculation of variables that specify aspects of gaze dynamics related to specific events, which essentially means that GCA is aligned to specifics of temporal movement or situational unfolding (DE; from 23.3 to 35.5%). This trend is further underlined by the fact that this statement applies to the most recently conducted seven studies included in the present review, obviously reflecting a significant growth of scientific interest in event-related spatiotemporal dynamics of natural gaze behavior in sports, or – in more psychological terms – in the dynamic coupling of visual perception and action.

4. Discussion

Compared to the Kredel et al. (2017) review for the period from 1976–2016, the present update has revealed three relevant trends. First, a generally growing scientific interest in the field of research was observed. Second, aspects of ecological validity seem to become increasingly important, which is reflected by a growing fraction of studies in which gaze data is gathered under the natural, first-person viewing conditions of the field, and natural motor responses are required, which, in turn, calls for a preferable use of mobile eye-trackers that allow for (more or less) unconstrained behavior. Third, whilst the scientific interest in more general aspects of gaze behavior (e.g., overall viewing times) seems to diminish, a trend becomes evident towards focusing on gaze measures that specify spatiotemporal aspects of gaze dynamics by event-based GCA or higher-order classification into visual strategies.

In contrast, the progress with respect to the applied eye-tracking technology seems to be limited. Foremost, common reporting guidelines as proposed already 10 years ago and recently detailed by the mainstream eye-tracking community (Holmqvist et al., 2022) are still not comprehensively employed in sports-related studies. This, however, seems of utmost importance, especially due to the significant error potential associated to mobile eye-tracking in dynamic situations (Niehorster et al., 2020; Hooge et al., 2022). Without increasing the quality of the reporting and the underlying measurement process, the formulated quest for a larger amount of gaze data per study would fall considerably short, as just employing a faster eye-tracker cannot solve potential inherent data quality issues.

Nonetheless, the total number of analyzed frames per study does also not show a remarkable increase such that the 55′000 frames currently analyzed in mobile eye-tracking studies with natural motor

responses still do not reach the standard for studies in which stationary eye-trackers were applied. One obvious solution to this problem – as already suggested by Kredel et al. (2017) – can be found in a more pronounced use of eye-tracking technology that allows for an algorithmic analysis of larger amounts of gathered gaze data. Applying appropriate event detection algorithms on high-sample-rate raw eye data, eye movements can be objectively and precisely classified (e.g., into fixations, saccades, or smooth pursuit). Beyond, concerning GCA, we currently identify four distinct approaches:

(1) manual gaze/event-to-AOI-mapping using raw scene camera images,
(2) automated gaze/event-to-AOI-mapping using pose estimation on scene camera images,
(3) automated gaze/event-to-AOI-mapping using motion-capture integration and natural visual scenes,
(4) automated gaze/event-to-AOI-mapping using motion-capture integration and artificially rendered visual scenes.

While (1) has been the *de facto* standard in mobile sports-related eye-tracking studies from the beginning, this approach has been refined by firstly employing event-detection algorithms on high-sample-rate eye-tracking data, and, in a second step, allocating these events to AOIs captured by a lower sample-rate scene camera. At the cost of losing cue-related scan paths, this leads to a significant reduction of workload while maintaining temporal precision for event-detection. Approach (2) can be seen as an extension to (1), which both seem particularly suited for unconstrained field studies. Employing algorithms for visual scene understanding (for a recent review on human pose estimation see Kumar et al., 2022), the manual AOI assignment in (1) is substituted by automated approaches in (2). While these two approaches dramatically economize the gaze analysis process and (2) also increase the objectivity of the GCA, two further advantages are specifically achieved by motion-capture integration, that is, (a) the possibility to add AOIs that do not appear in the currently analyzed video frame (e.g., the location where a tennis ball will be hit by the racket), and (b) a synchronized recording of the participant's movements, which allows relating the algorithmic gaze analysis to action events (e.g., the moment of response initiation). While approach (3) emphasizes external validity by presenting natural visual scenes, where, for instance, real opponents' limbs are motion-tracked, (4) employs artificially rendered visual scenes to maximize experimental control. By displaying either video content with previously identified trajectories of crucial AOIs or computer-generated visual scenes (e.g., leveraging game engines, where object trajectories are known *a priori*), both approaches allow a fully automated gaze-vector-based GCA as already proposed by Kredel et al. (2010, 2015). Both approaches could be scaled to constrained field research by using LPM- or IMU-based motion-capture, even if they seem particularly suited for constrained lab research. Employing head-mounted AR/VR displays with integrated eye-trackers can be seen as special cases for (3) or (4), having identical advantages, but currently still the apparent drawbacks of head-mounted high-mass and high-inertia devices for dynamic sports tasks.

To sum up, approaches as proposed in (2), (3) or (4) would allow for a substantial increase in analyzed gaze data per study without corrupting the ecological validity of test conditions and the internal validity of the measurements. This would not only enhance the generalizability of the obtained results; a respective increase would more so create conditions for a critical re-examination of findings on potential differences in gaze behavior that are overall accepted in literature but ultimately based on relatively small sample sizes. For instance, the general belief that expert athletes are distinguished by a comparatively "quiet" gaze behavior with fewer fixations of longer durations (*cf.* Mann et al., 2007; Gegenfurtner et al., 2011) – that has been questioned in recent reviews and meta-analyses (Klostermann and Moeinirad, 2020; Silva et al., 2022) – would be open to an empirical test when pursuing those algorithmic approaches. We thus would like to conclude that the application of reporting standards and reliable high-sample-rate mobile eye-trackers with algorithmic analysis of a more significant amount of gathered gaze data will be the decisive step forward in future research on the dynamics of natural gaze behavior in sports.

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effects of exercise/physical activity on fear of movement in people with spine-related pain: a systematic review

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Background: Kinesiophobia (i.e., fear of movement) can be an important contributor for ongoing pain and disability in people with spine-related pain. It remains unclear whether physical activity interventions/exercise influence kinesiophobia in this population. A systematic review was therefore conducted to synthesize the available evidence on whether physical activity interventions/exercise influence kinesiophobia in people with chronic non-specific spine-related pain.

Methods: The study protocol was registered prospectively with PROSPERO (CRD42021295755). The following databases were systematically searched from inception to 31 January 2022 and updated on 22 June 2023: PubMed, MEDLINE, Embase, CINAHL, Web of Science, PsycINFO, ZETOC, PROSPERO and Google Scholar. Inclusion criteria were randomized or non-randomized controlled studies investigating adults aged ≥18 years, reporting the effect of exercise or physical activity on kinesiophobia in individuals with chronic non-specific spine-related pain. Two reviewers independently extracted data and assessed the quality of the included studies. Bias was assessed using the Cochrane ROB2 tool and evidence certainty via Grading of Recommendations Assessment, Development and Evaluation (GRADE).

Results: Seventeen studies from seven countries involving a total of 1,354 individuals were selected for inclusion. The majority of studies ($n = 13$) involved participants with chronic low back pain (LBP), and Pilates was the most common form of exercise evaluated. Most of the studies reported a positive direction of effect in favor of exercise reducing kinesiophobia when compared to a control group. There was moderate to high risk of bias among the studies and the overall certainty of the evidence was very low.

Conclusion: This review supports the use of exercise for reducing kinesiophobia in people with chronic LBP albeit with very low certainty of evidence; Pilates (especially equipment-based) was shown to be effective as were strengthening training programmes. There was limited evidence available on the effects of exercise on kinesiophobia for people with chronic neck or thoracic pain and further research is required.

Systematic review registration: https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=295755

KEYWORDS

exercise, kinesiophobia, low back pain, neck pain, chronic pain, fear of movement

Introduction

Spine-related pain is a common global health issue and will continue to be due to the predictable nature of the world's aging population (World Health Organisation, 2021). Low back pain (LBP) has been established as one of the leading causes of disability-adjusted life years in the world for all ages (Vos, 2020). In Europe, 15% of people suffering from LBP are absent from work for over 1 month, which accounts for half of the number of days from work lost (Bevan, 2012). In the UK, 60% of adults will experience LBP in their lifetime, with up to 4% of adults aged below 45 years and up to 7% of adults aged over 45 years being disabled by chronic LBP (National Institute for Health and Care Excellence, 2022). Neck pain is also highly prevalent; globally the age standardized point prevalence of neck pain per 100,000 population is 3551.1 (95% CI; 3139.5–3977.9), with the UK showing the highest increase (Safiri et al., 2020). Neck pain is common in all age groups (Hogg-Johnson et al., 2009), and it is correlated with increased risk of disability and reduced quality of life (Hey et al., 2021).

Kinesiophobia is a concept associated with fear of physical movement that is "debilitating" and "excessive", which is expressed through fear-avoidance behaviors (Leeuw et al., 2007). For many people with spine-related pain, kinesiophobia acts as an initial protective mechanism that prevents the potential exacerbation of their condition (Trocoli and Botelho, 2016), but kinesiophobia can lead to the development of chronicity of pain and its maintenance (Vlaeyen et al., 1995; Vlaeyen and Linton, 2000). Physical activity limitations are self-imposed due to the fear of pain that may result from certain movements, causing people with chronic pain to be progressively less active, increasing the risk of physical disability (De Moraes et al., 2014). A systematic review by Luque-Suarez et al. (2019) provided strong evidence of higher levels of kinesiophobia being associated with greater levels of disability, pain intensity and a lower quality of life in people with chronic musculoskeletal pain. Early identification of kinesiophobia may be crucial in order to design treatment programmes that can target heightened kinesiophobia levels to reduce this barrier to rehabilitation (Varallo et al., 2020), and provide more effective treatment that is characterized by an improvement in physical function, reduction in pain intensity and an overall improvement in quality of life.

Previous research has investigated the association between kinesiophobia and physical activity, and the effect certain exercises have on fear of movement in people suffering from spine-related pain, and a variety of conclusions have been made. A study by Balci et al. (2020) found that both land and aquatic-based exercises have a beneficial effect on kinesiophobia in individuals with chronic LBP. Furthermore, a systematic review published in 2020 investigating the effects of Pilates found moderate evidence that Pilates effectively reduced kinesiophobia in people with chronic non-specific LBP when compared to no or minimal interventions (De Freitas et al., 2020). Additionally, a scoping review conducted by Bordeleau et al. (2022) treatments for kinesiophobia in people with chronic pain, found that The Tampa Scale of Kinesiophobia is the most widely used tool for assessing kinesiophobia. Physical exercise is the most frequently used strategy for managing irrational fear of movement. Interventions for kinesiophobia have mainly focused on musculoskeletal pain conditions, particularly low back pain and neck pain. On the other hand, a systematic review and meta-analysis by Hanel et al. (2020) found low to very low-quality evidence that fear-avoidance beliefs were reduced by exercise, but they also concluded that non-exercise interventions were equally as effective in achieving the same outcome. This review assessed exercise approaches as a whole, without differentiating between different forms of exercise. Collectively, the results of this work show that the effect of exercise/physical activity on fear of movement/kinesiophobia remains unclear and evidence on the effect of exercise/physical activity on kinesiophobia in people with spine-related pain is needed.

The aim of this systematic review was to investigate whether physical activity interventions/exercise influence the level of kinesiophobia in people with chronic non-specific spine-related pain. It was anticipated that the results of this review would provide evidence of the impact of specific forms of exercise/physical activity on kinesiophobia in people experiencing chronic non-specific spine-related pain which would facilitate clinical decision making when prescribing exercise for patients with chronic non-specific spine-related pain presenting with kinesiophobia.

Methods

Search strategy

A comprehensive search of PubMed, MEDLINE, Embase, CINAHL, Web of Science, PsycINFO, ZETOC, PROSPERO and the first 10 pages of Google Scholar was conducted from inception to 31 January 2022 and updated on 22 June 2023. A search strategy (Supplementary material 1) was developed using the following key words: physical activity, exercise, kinesiophobia, fear of movement, spinal pain, neck pain, low back pain and randomized controlled trial and adapted for each database. Additional filters/limits were added when searching for articles on the databases where they were available. The search strategy was developed by RS and FJ and iteration discussed with DF. The review protocol was registered in PROSPERO (International Prospective Register of Systematic Reviews) (registration number: CRD42021295755) and published (Jadhakhan et al., 2022). Assuming homogeneity between studies, we planned to conduct a random effect meta-analysis with and without low quality studies. This review is conducted and reported in accordance with the Preferred reporting System and Meta-Analysis (PRISMA) 2020 statement (Page et al., 2021) and conducted following the Cochrane Handbook for Systematic Review of Interventions (Higgins et al., 2021) (Supplementary material 2).

Inclusion and exclusion criteria

Studies were included if they were randomized or non-randomized controlled trials that investigated exercise or physical activity interventions for people with non-specific spine-related pain, with recorded measures of kinesiophobia taken at baseline and post-intervention. The inclusion and exclusion criteria of this review was determined using the Population, Interventions, Comparators, Outcomes and Study design (PICOS) framework (Richardson et al., 1995; Akers et al., 2009).

Population

Adults (≥ 18 years) with chronic non-specific spine-related pain (i.e., neck pain, thoracic pain and LBP).

Intervention

Any form of exercise/physical activity that may be deemed as structured with the objective of improving one or more aspects of an individual's physical fitness (Caspersen et al., 1985); interventions include: aerobic/cardiovascular exercise, Pilates, resistance/strength training, yoga, hydrotherapy, motor-control exercise, walking, core stabilization exercise.

Comparator

Any study that compared exercise/physical activity with a control group (e.g., usual care or waiting list) or passive interventions (such as education or manual therapy) or general practitioner management for kinesiophobia.

Outcome measures

Eligible studies must have reported kinesiophobia using validated measures. The Tampa Scale of Kinesiophobia (TSK) (Miller et al., 1991; Hudes, 2011), and the Fear Avoidance Beliefs Questionnaire (FABQ) (Waddell et al., 1993) are two of the most common validated measures for kinesiophobia (Sharma et al., 2020). Studies that used these were eligible. Studies that used any other validated measures for kinesiophobia were also eligible, such as the other commonly used Kinesiophobia Causes Scale (KCS), Fear-Avoidance Components Scale (FACS) and the Athletes Fear-Avoidance Questionnaire (AFAQ) (Liu et al., 2021).

Study design

Randomized controlled trials or non-randomized controlled trials.

Exclusion criteria

Studies not written in English were excluded, as were review articles, case reports, letters, editorials, single case studies, abstract, un-published work in non-peer reviewed journals and non-experimental study designs were also not considered. Studies which only included participants with a specific pathology for their pain, radiculopathy, a traumatic injury or if they were post-surgery patients.

Study selection

Screening results from the database searches were exported into a digital library using the Endnote version 20 reference management software (Clarivate Analytics, Philadelphia, PA, US). Duplicate records were automatically and manually removed. Within the digital library, the titles and abstracts of the articles were reviewed by two reviewers (RS and FJ) independently. Both reviewers discussed the included studies along with studies that required discussion for potential inclusion. Studies comparing two or more eligible exercise interventions were discussed between RS and FJ for inclusion only if the effects of the interventions were separately measured. In the event of disagreement between the two reviewers, a third reviewer (DF) adjudicated the eligibility of the article. In the event of full text availability for some of the selected studies, the lead author was contacted via email twice with a follow-up email sent 2 weeks apart. For the selected articles, full texts were acquired and screened using the same process with both reviewers (RS and FJ) to see if they met the inclusion criteria. A PRISMA (Page et al., 2021) flow diagram describes the process of the inclusion and exclusion of studies and reasons for exclusion from the latest screening stage (Figure 1).

Data extraction

The data from each study was extracted by both RS and FJ and organized into a pre-determined data extraction sheet. Data items extracted from the eligible studies were: authors, publication year, title of the study and study design, country/setting, the characteristics of the participants (age, gender, ethnicity, spinal pain diagnosis, length of diagnosis), sample size, duration/frequency of interventions, length follow-ups, outcome measure, statistical methods, results and findings. Any discrepancies were resolved by discussion and re-visiting the relevant study. A third reviewer (DF) was available to mediate any disagreement in data extraction. If any information was missing or incomplete, an initial attempt was made to contact the study authors and a follow-up email sent 2 weeks after to retrieve the missing data. Descriptive data was extracted from the included studies and were summarized in a Microsoft Excel spreadsheet (Supplementary material 3).

Risk of bias in individual studies

Risk of bias was assessed using Version 2 of the Cochrane risk-of-bias tool for randomized trials (RoB 2) (Sterne et al., 2019). The RoB-2 tool consists of five domains of bias: bias arising from the randomization process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in the measurement of the outcome, and bias in the selection of the reported result. The Risk Of Bias in Non-randomized Studies of Interventions tool was planned to be used to assess the risk of bias of non-randomized studies of interventions however all included studies were randomized trials. Two reviewers (RS and FJ) independently assessed each of the included studies. A third assessor (DF) was available if needed. The reviewers (RS and FJ) used the RoB 2 Cribsheet to follow the algorithm to determine assessment of bias for the individual domains and then present the overall judgement of the study as either low risk, some concerns, or a high risk of bias.

Evaluation of the certainty of evidence

After the evidence was collected and summarized, the assessment of certainty in the body of evidence was conducted in accordance with the Grading of Recommendations Assessment,

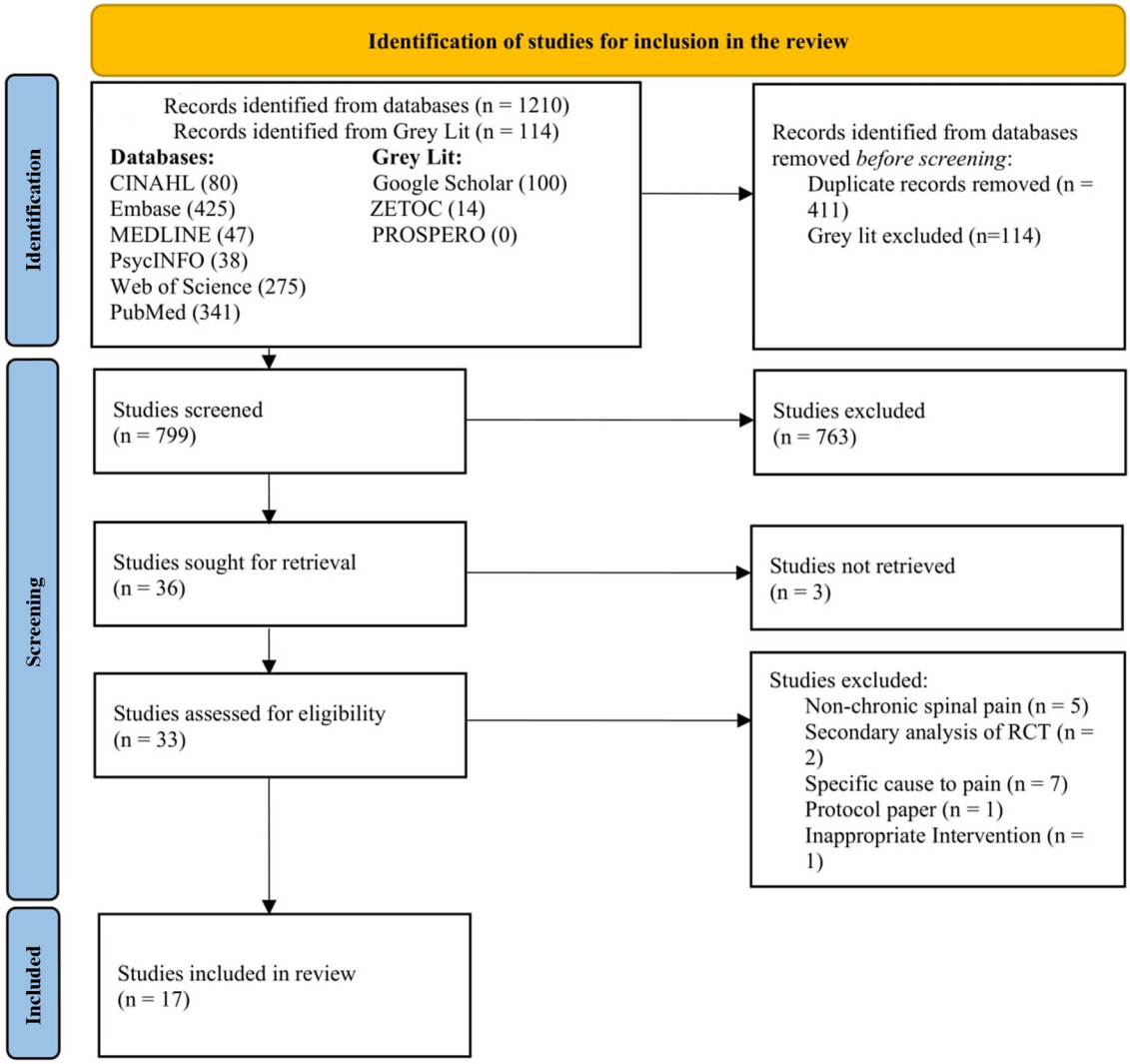


FIGURE 1
PRISMA flowchart for study screening (Page et al., 2021).

Development and Evaluation (GRADE) guidelines (Guyatt et al., 2011) and performed by one person (FJ) using the GRADE rating guidance presented in the Cochrane Handbook (Balshem et al., 2011; Schünemann et al., 2021). Consistent with GRADE, the quality of the summary evidence was assessed as high, moderate, low or very low. For each study, the following domains were assessed: imprecision, inconsistency, indirectness, risk of bias including publication bias. Applicability of results were categorized by the study interventions and rated when making judgement about the quality of evidence presented in the included studies (Guyatt et al., 2011).

Data analysis

Given the significant clinical and statistical variation between the studies included in this review, it was not possible to pool effect estimates of exercise/physical activity on kinesiophobia using meta-analysis. Variations was reported in extracted effect measures, population and measures used to ascertain kinesiophobia (e.g., TSK and FABQ). There was also difference among studies in sample size, interventions (including their duration and frequencies) length of follow-ups. Instead, we summarized effect estimates (mean difference or standardized mean difference) with 95% confidence intervals (CI) where appropriate in the included studies. Standardized Mean Difference (SMD) was extrapolated from reported (Cohen's *d*) values, exploring mean difference between groups; an effect size of 0.8 or greater was considered a relatively large effect size between two means in the sample population. In the event of missing data we attempted to contact the author(s) at least twice by email. A final reminder was sent to corresponding authors/co-authors if no response was received following our initial email. We initially planned to quantify heterogeneity using the Cochrane Q-test and the I^2 with corresponding 95% (CI) where appropriate. Higher I^2 values (>50%) (Higgins et al., 2021) indicate larger degrees of heterogeneity pertaining to variability in effect size estimates between studies (Higgins et al., 2021). Recorded measures of kinesiophobia in individuals aged (≥18 years) with chronic non-specific spine-related pain (i.e., neck pain, LBP, and thoracic pain) were extracted from each study and a narrative summary of the outcome of the included studies was presented.

Grouping studies for synthesis

Due to different types of spine-related pain reported, studies were grouped by the type of spine-related pain (neck pain, thoracic pain and LBP) for synthesis rather than pooling across all spine-related pain.

Results

In total, the search strategy yielded 1,324 articles. After excluding 411 duplicates and 114 gray literatures, the titles and abstracts of 795 articles were screened for relevance. Title and abstract screening resulted in the exclusion of 766 articles, primarily because these articles included participants with non-chronic spinal pain, conducted secondary data analysis, included participants with specific cause of pain, or used other types of intervention. Of the 33 full-text articles that were assessed, 16 were excluded after further review. Five studies were excluded because only participants with non-chronic spine-related pain were included, another two studies used secondary data from existing RCT's, seven reported specific cause of pain, one used other type of intervention and one study was a trial protocol. Seventeen articles were included in the final analysis. A flow diagram of the study selection process is presented in Figure 1.

Study characteristics

The characteristics of the included studies are presented in Table 1. The 17 studies selected were published between the years 2011 to 2023. The 17 selected studies (Nassif et al., 2011; Miyamoto et al., 2013, 2018; Da Luz Junior et al., 2014; Vincent et al., 2014; Cruz-Díaz et al., 2017, 2018; Keane, 2017; Zadro et al., 2019; Galan-Martin et al., 2020; Tagliaferri et al., 2020; Akodu et al., 2021; Vicente-Campos et al., 2021; Martins de Sousa et al., 2022; Cana-Pino et al., 2023; Hernandez-Lucas et al., 2023; Ogunniran et al., 2023) involved 1,354 participants. Variation in chronic non-specific spine-related pain, exercise/physical activity and measures used to assess kinesiophobia contributed to the significant level of heterogeneity between the studies and reported effect estimates. Most studies were performed in Spain ($n = 6$), followed by Brazil ($n = 4$), Australia ($n = 2$), Nigeria ($n = 2$), England ($n = 1$), France ($n = 1$) and the United States ($n = 1$). Most studies were conducted in a community clinic setting and University Laboratory ($n = 8$), followed by outpatient units ($n = 3$), primary care centers ($n = 2$), physical activity training unit ($n = 2$), private clinic ($n = 1$) and participant homes ($n = 1$). Studies included in this review were mostly randomized controlled trials ($n = 9$), followed by single blinded RCTs ($n = 6$), double blinded RCT ($n = 1$) and one repeated measures RCT ($n = 1$). Across all the studies, 64% ($n = 871$) of participants were female and 36% ($n = 483$) were male. The ethnicity of the participants was not reported in any of the studies. Thirteen studies recruited people with chronic LBP, three studies recruited people with chronic neck pain, and one study recruited people with (any sort of) chronic spine-related pain. The length of follow-up across the studies were between 4 weeks and 12 months. Frequency of exercise/physical activity was between 30 min and 1 h per session.

Risk of bias assessment

Key features affecting the methodological quality of each reviewed study are presented in Table 2. There was significant risk of bias detected across the studies, with the overall risk of bias considered high or with some concerns of bias. This was largely because of blinding, allocation sequence concealment and deviation from intended intervention. Five studies (Nassif et al., 2011; Miyamoto et al., 2013, 2018; Zadro et al., 2019; Galan-Martin et al., 2020) were rated as having high risk of risk, ten (Vincent et al., 2014; Keane, 2017; Cruz-Díaz et al., 2018; Tagliaferri et al., 2020; Akodu et al., 2021; Vicente-Campos et al., 2021; Martins de Sousa et al., 2022; Cana-Pino et al., 2023; Hernandez-Lucas et al., 2023; Ogunniran et al., 2023) with some concerns of bias and two (Da Luz Junior et al., 2014; Cruz-Díaz et al., 2017) deemed low risk. Most studies adequately described the follow-up period, but attrition rate was poorly defined. Only two studies had a low risk of bias in all criteria of the checklist (Da Luz Junior et al., 2014; Cruz-Díaz et al., 2017). For all studies, the analytical approach utilized was considered appropriate. In seven studies (Vincent et al., 2014; Keane, 2017; Tagliaferri et al., 2020; Akodu et al., 2021; Vicente-Campos et al., 2021; Hernandez-Lucas et al., 2023; Ogunniran et al., 2023) consisted of a small sample size which is a major limitation and demonstrate a lack of adequate sample size calculation.

Certainty of evidence

For all 17 studies, the result of the GRADE was very low suggesting the true effect is likely to be substantially different from the estimated effect (Schünemann et al., 2021) (Table 3), thus suggesting very little confidence in the effect estimates. Three studies (Da Luz Junior et al., 2014; Cruz-Díaz et al., 2017, 2018) used two types of exercise intervention (Mat and equipment based Pilates) and a GRADE ranking was undertaken. The GRADE ranking indicates low certainty that the Pilates interventions are effective at reducing fear of movement with relatively small sample size RCT's indicating larger fully-powered trials are needed to adequately test this assumption. Another study (Akodu et al., 2021) investigated the effect of neck stabilization and Pilates exercise on kinesiophobia measured by TSK. The GRADE ranking indicated low certainty that there is no effect on kinesiophobia following Pilates and neck stabilization exercise. Two studies (Miyamoto et al., 2013, 2018) investigated the effect of the frequency of Pilates and education on fear of movement measured by TSK; the GRADE ranking was very low for both interventions, meaning that we have little certainty that the observed effects are the true effects of these interventions. Two further studies (Keane, 2017; Galan-Martin et al., 2020) tested the effectiveness of land based stretching and Aqua stretch exercise and these were rated as very low. Four studies (Nassif et al., 2011; Vincent et al., 2014; Tagliaferri et al., 2020; Vicente-Campos et al., 2021) examined the effect of general strength and conditioning, muscle strengthening, motor

TABLE 1 Demographic data for included studies.

Study details				Demographic information				
Authors (year)	Country	Study design	Setting	Age	Gender	Spinal pain diagnosis criteria	Length of diagnosis	Sample size
Akodu et al. (2021)	Nigeria	Single Blinded RCT	Outpatients - Hospitals in the Lagos state	I (Pilates only) = 47.43 ± 9.22. I (Neck stabilization group) = 47.71 ± 10.02 C = 44.93 ± 6.26	Male = 19 (42%) Female = 26 (58%)	Non-specific Chronic neck pain ≥ 3 months. Participants with neck pain greater or equal to 5/10	≥ 3 months	45
Cruz-Díaz et al. (2017)	Spain	RCT	Physical therapy unit - Jaén	I (Mat Pilates) = 36.94 ± 12.46 I (Equipment based Pilates) = 35.5 ± 11.98 C = 36.32 ± 10.67	Male = 35 (36%) Female = 63 (64%)	History of LBP ≥ 12 weeks; pain between 3 and 10 on 10 cm VAS	≥ 12 weeks	98
Cruz-Díaz et al. (2018)	Spain	Single Blinded RCT	Physiotherapy laboratory of University of Jaén	I (Mat Pilates) = 36.94 ± 12.46 I (Equipment based Pilates) = 35.5 ± 11.98 C = 36.32 ± 10.67	64 total, 2 excluded. Male = 21 (34%) Female = 41 (66%)	LBP ≥ 3 months	≥ 3 months	64 (62 as 2 excluded)
Da Luz Junior et al. (2014)	Brazil	RCT	Private physiotherapy clinic	I (Mat Pilates) = 43.5 ± 8.6 I (Equipment based Pilates) = 38.8 ± 9.9	Male = 20 (23%) Female = 66 (77%)	LBP > 3 months	> 3 months	86
Galan-Martin et al. (2020)	Spain	RCT	12 Primary Care centers in Valladolid	I = 53.02 ± 10.7 C = 49.14 ± 12.14	Male = 34 (20%) Female = 136 (80%)	Non-specific CSP > 6 months	> 6 months	170
Keane (2017)	England	Repeated measures RCT	Aspire National Training Center	46 ± 17	Male = 5 (17%) Female = 24 (83%)	CLBP ≥ 3 months	≥ 3 months	29
Miyamoto et al. (2013)	Brazil	RCT	outpatient physical therapy department	I = 40.7 ± 11.8 C = 38.3 ± 11.4	Male = 16 (19%) Female = 70 (81%)	Non-specific LBP ≥ 3 months	≥ 3 months	86
Miyamoto et al. (2018)	Brazil	RCT	Physiotherapy clinic - Sao Paulo	I (P1) = 47.0 ± 11.5 I (P2) = 47.1 ± 14.9 I (P3) = 48.9 ± 16.6 C = 48.6 ± 15.8	Male = 72 (24%) Female = 224 (76%)	Non-specific CLBP > 3 months	> 3 months	296
Nassif et al. (2011)	France	RCT	Workplace of French automotive manufacturer (Peugeot Citroen, Mulhouse)	I = 45.13 ± 9.11 C = 45.34 ± 8.80	Male = 43 (57%) Female = 32 (43%)	Chronic LBP	Not stated	75
Tagliaferri et al. (2020)	Australia	RCT	Clinical exercise and healthcare centers	I (GSC) = 34.8 ± 4.9 I (MCMT) = 34.6 ± 7.2	Male = 21 (52.5%) Female = 19 (47.5%)	Non-specific CLBP > 3 months	> 3 months	40

(Continued)

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TABLE 1 (Continued)

Study details				Demographic information				
Authors (year)	Country	Study design	Setting	Age	Gender	Spinal pain diagnosis criteria	Length of diagnosis	Sample size
Vicente-Campos et al. (2021)	Spain	Single blinded RCT	Not reported (?assumed at Francisco de Vitoria University)	I = 23.25 ± 4.52 C = 23.90 ± 7.36	Male = 16 (40%) Female = 24 (60%)	Non-specific CLBP	At least 3 episodes in last 6 months	40
Vincent et al. (2014)	USA	RCT	Laboratory	I (LEXT) = 68.7 ± 7.1 I (TOTRX) = 68.6 ± 7.1 C = 67.5 ± 6.4	Men: I (LEXT) = 32%. I (TOTRX) = 29.2% C = 38.9%	LBP ≥ 6 months	≥ 6 months	49
Zadro et al. (2019)	Australia	Single blinded RCT	Participant's homes	68.3 ± 5.7	Male = 29 (48.3%) Female = 31 (51.7%)	Non-specific mechanical LBP ≥ 3 months	≥ 3 months	60
Cana-Pino et al. (2023)	Spain	Single blinded RCT	Private physiotherapy clinic	I - supervised exercise (SE) + pain neuroscience education (PNE) - 35.3+/−7.10 - I - Laser guided exercise + pain neuroscience education (PNE) - 32.0+/−6.78	Not reported	Non-specific CLBP ≥ 3 months	≥3 months	60
Ogunniran et al. (2023)	Nigeria	Single blinded RCT	from the physiotherapy outpatient clinics of both tertiary and secondary health hospitals	Kinesiology taping + core stabilization exercises = 42.1+/−12.0; Core stabilization = 42.3+/−10.8; kinesiology taping = 43.7+/−9.5	Male = 29 (67.4%); Female = 7 (16.3%)	Non-specific CLBP 2 months	2 months	43
Martins de Sousa et al. (2022)	Brazil	Double blind randomized controlled trial	Physical Education Department of Universidade Federal do Maranhão, Brazil	Control (group 1) = 30.40 (+/−7.74); intervention (group 2) = 29.35 (+/−8.80); intervention (group 3) = 31.55 (+/−6.13)	Control (group 1) = F:12; M:8; GROUP 2: F = 15; M = 5; GROUP 3: F = 14; M = 6	Non-specific chronic neck pain for more than 3 months	≥3 months	60
Hernandez-Lucas et al. (2023)	Spain	Randomized controlled clinical trial	The Pontevedra Sport Center (Spain)	Intervention: People attending the Back-School Program (BSP) = 51.0+/−7.6 - Control group = People who did not attend the BSP = 50.7+/−10	EG: F = 18; M = 10 ; CG: F = 17; M = 10	"Non-specific neck pain for at least three months, with pain intensity of 30–70 on the visual analog scale (VAS)."	3 months	55

I, Intervention group; C, Control group; P, Pilates; LBP, Low Back Pain; CLBP, Chronic Low Back Pain; CSP, Chronic Spinal Pain; RCT, Randomized controlled trial; LEXT – Lumbar Extension Resistance Training; TOTRX – Total Body Resistance Training; GSC, General strength and conditioning training; MCMT, Motor Control and Manual Therapy.

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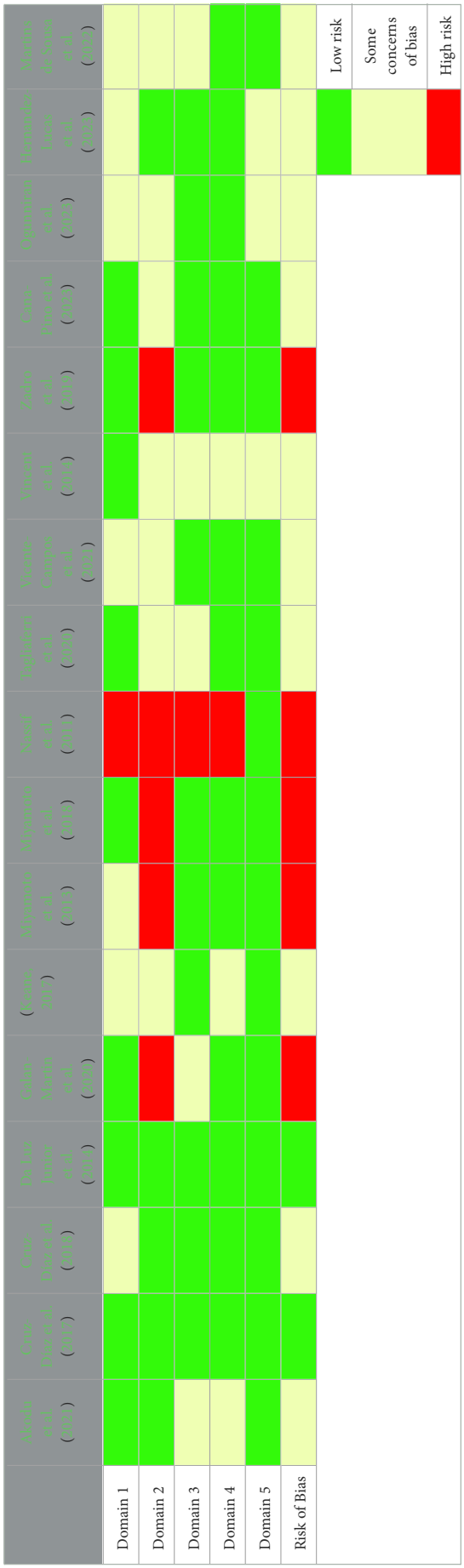
control exercise with manual therapy Hypopressive Abdominal Gymnastics and Lumbar extension resistance exercise on fear of movement measured by either the TSK, TSK-11 (Spanish version) and FABQ; the GRADE rating was either low or very low, suggesting little evidence that the observed effects are the true effects of these interventions. Another study (Zadro et al., 2019) assessed the effect of video game-based exercise (Wii Fit U) on fear of movement measured by TSK; the GRADE rating was also very low. Another study (Cana-Pino et al., 2023) examined the effect of supervised/laser guided exercise and neuroscience education (PNE) on fear of movement measured by TSK-11 (Spanish version), the GRADE ranking was very low suggesting little evidence that the observed effects are the true effects of these interventions. Ogunniran et al. (2023) examined the effects of kinesiology taping and core stability exercise on clinical variables in patients with non-specific chronic low back pain. Fear of movement/Kinesiophobia was measured by TSK, the GRADE rating was very low. Another study (Hernandez-Lucas et al., 2023) tested the effects of the Back School-based intervention on non-specific neck pain in adults. The Back schools are an educational and exercise programs with lessons given to patients or workers by a therapist with the aim of treating or preventing low back pain. Fear of movement/Kinesiophobia was measured by TSK-11 (Spanish version). The GRADE ranking indicated low certainty that there is no effect on treating/preventing low back pain following the Back School intervention. Additionally, in a study (Martins de Sousa et al., 2022) evaluating the effect of high frequency (HF) or low frequency (LF) transcutaneous electrical nerve stimulation (TENS) in a specific therapeutic exercise program for the treatment of patients with chronic neck pain; were rated as low. Fear of movement/Kinesiophobia - measured by TSK.

Characteristics of the included trials

Type of intervention

We noted considerable variation in the exercise intervention across studies. The exercise interventions among all the studies included Pilates, strengthening/stabilization education/exercise programmes (general and neck/lumbar specific), kinesiology taping and core stabilization exercise, supervised/laser guided exercises- and pain neuroscience education and forms of stretching. Some studies (Miyamoto et al., 2013; Zadro et al., 2019; Galan-Martin et al., 2020; Tagliaferri et al., 2020; Cana-Pino et al., 2023; Hernandez-Lucas et al., 2023) combined their interventions with aerobic exercise, supervised exercise and education such as pain neuroscience education. Other studies (Martins de Sousa et al., 2022; Ogunniran et al., 2023) used a combination of High- and low-frequency transcutaneous electrical nerve stimulation and exercise and kinesiology taping and core stabilization exercise. The control groups among the studies (Nassif et al., 2011; Miyamoto et al., 2013, 2018; Vincent et al., 2014; Cruz-Díaz et al., 2017, 2018; Keane, 2017; Zadro et al., 2019; Galan-Martin et al., 2020; Akodu et al., 2021; Vicente-Campos et al., 2021; Cana-Pino et al., 2023) either had no intervention, had usual physiotherapy treatment, or a form of education. From all the studies in the review, 14 (Nassif et al., 2011; Miyamoto et al., 2013, 2018; Vincent et al., 2014; Cruz-Díaz et al.,

TABLE 2 Risk of Bias-2 (RoB-2) Assessment of included studies.



Domain 1: Risk of bias arising from the randomization process. Domain 2: Risk of bias due to deviations from the intended interventions (effect of assignment/adhering to intervention). Domain 3: Missing outcome data. Domain 4: Risk of bias in measurement of the outcome. Domain 5: Risk of bias in the selection of the reported results.

TABLE 3 GRADE rating on the level of evidence of the included studies.

Intervention	Quality assessment							Number of patients		Quality
	No of studies	Design	Risk of Bias	Inconsistency	Indirectness	Imprecision	Publication bias	Intervention	Comparison	
Mat PILATES AND EQUIPMENT BASED PILATES	3	RCT	Serious limitations	No serious inconsistency	Serious indirectness	Serious imprecision	Likely	138	105	Very low
Pilates and Neck stabilization	1	RCT	Serious limitations	No serious inconsistency	Serious indirectness	Serious imprecision	Likely	31	14	Very low
Pain neuroscience education and group physical exercise	1	RCT	Serious limitations	No serious inconsistency	No serious indirectness	Serious imprecision	Likely	89	81	Very low
Land based stretching and Aqua stretch	1	RCT	Serious limitations	No serious inconsistency	Serious indirectness	Serious imprecision	Likely	20	9	Very low
Exercise based Pilates and education	1	RCT	Serious limitations	No serious inconsistency	Serious indirectness	Serious imprecision	Likely	43	43	Very low
Frequency of Pilates (1,2 and 3 times a week)	1	RCT	Serious limitations	Serious inconsistency	Serious indirectness	Serious imprecision	Likely	222	74	Very low
Muscle strengthening, flexibility and endurance training	1	RCT	Serious limitations	No serious inconsistency	Serious indirectness	Serious imprecision	Likely	37	38	Very low
General strength and conditioning v/s motor control and manual therapy	1	RCT	Agree with the criterion	No serious inconsistency	Mostly disagree with the criterion	Serious imprecision	Likely	20	20	Low
Hypopressive abdominal gymnastics	1	RCT	Serious limitations	No serious inconsistency	Serious indirectness	Serious imprecision	Likely	20	20	Very low
Total body resistance exercise and lumbar extensor exercise	1	RCT	Serious limitations	No serious inconsistency	Serious indirectness	Serious imprecision	Likely	42	18	Very low
Home-based Wii Fit U flexibility, strengthening, and aerobic exercises	1	RCT	Serious limitation	Serious inconsistency	Serious indirectness	Serious imprecision	Likely	30	30	Very low
Kinesiology taping and core stabilization exercises	1	RCT	Serious limitations	Serious inconsistency	Serious indirectness	Serious imprecision	Likely	30	13	Very low
Supervised/laser guided exercises and pain neuroscience education	1	RCT	Serious limitations	Serious inconsistency	Serious indirectness	Serious imprecision	Likely	30	30	Very low
People attending the back school program	1	RCT	Agree with the criterion	No serious inconsistency	Mostly disagree with the criterion	Serious imprecision	Likely	29	29	Low
Therapeutic exercise and high/low TENS	1	RCT	Serious limitations	Serious inconsistency	Serious indirectness	Serious imprecision	Likely	40	20	Very low
Outcome: TSK, FABQ, KCS, FACS, AFAQ scores										

TSK, Tampa Scale of Kinesiophobia; FABQ, Fear Avoidance Beliefs Questionnaire; KCS, Kinesiophobia Causes Scale; FACS, Fear Avoidance Components Scale; AFAQ, Athletes Fear Avoidance Questionnaire.

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2017, 2018; Keane, 2017; Zadro et al., 2019; Galan-Martin et al., 2020; Akodu et al., 2021; Vicente-Campos et al., 2021; Martins de Sousa et al., 2022; Hernandez-Lucas et al., 2023; Ogunniran et al., 2023) had a control group, and ten studies (Da Luz Junior et al., 2014; Vincent et al., 2014; Cruz-Díaz et al., 2017; Keane, 2017; Miyamoto et al., 2018; Tagliaferri et al., 2020; Akodu et al., 2021; Martins de Sousa et al., 2022; Cana-Pino et al., 2023; Ogunniran et al., 2023) compared two or more interventions.

Duration of the intervention

The duration of the interventions ranged from 4 weeks to 6 months. Three studies (Miyamoto et al., 2013, 2018; Da Luz Junior et al., 2014) had a 6 weeks intervention, 5 studies (Zadro et al., 2019; Akodu et al., 2021; Vicente-Campos et al., 2021; Hernandez-Lucas et al., 2023; Ogunniran et al., 2023) had an eight-week intervention duration. Another three studies (Cruz-Díaz et al., 2017, 2018; Keane, 2017) applied the intervention for 12 weeks. The remaining 6 studies (Nassif et al., 2011; Vincent et al., 2014; Galan-Martin et al., 2020; Tagliaferri et al., 2020; Martins de Sousa et al., 2022; Cana-Pino et al., 2023) had an intervention duration of 20 weeks, 11 weeks, 4 weeks, 2 months, 6 months or 4 months.

Length of follow-up

Four studies had follow-ups at 6 and 12 weeks following the end of the intervention period (Cruz-Díaz et al., 2017, 2018; Keane, 2017; Cana-Pino et al., 2023). Three studies (Miyamoto et al., 2013, 2018; Da Luz Junior et al., 2014) had follow-up at 6 weeks, 6 and 12 months. Another five studies (Zadro et al., 2019; Akodu et al., 2021; Vicente-Campos et al., 2021; Martins de Sousa et al., 2022; Ogunniran et al., 2023) had follow-ups at 4 and 8 weeks. A further three studies (Nassif et al., 2011; Tagliaferri et al., 2020; Cana-Pino et al., 2023) had follow-ups at 2, 3 and 6 months. One study had a follow-up at the end of a 4-week intervention (Vincent et al., 2014). Another study (Hernandez-Lucas et al., 2023) did not report follow-up period.

Outcome measures characteristics

We noted significant diversity in the criteria utilized to ascertain the presence of kinesiophobia. The most important differences were: (1) where studies used different versions of the self-assessment questionnaire (TSK) or FABQ to assess kinesiophobia. Eleven studies (Nassif et al., 2011; Miyamoto et al., 2013, 2018; Da Luz Junior et al., 2014; Cruz-Díaz et al., 2017; Keane, 2017; Zadro et al., 2019; Tagliaferri et al., 2020; Akodu et al., 2021; Martins de Sousa et al., 2022; Ogunniran et al., 2023) used the 17 items TSK questionnaire. One study (Vincent et al., 2014) used a combination of FABQ and the shorthand TSK-11 version to assess fear of movement/kinesiophobia. Five studies (Cruz-Díaz et al., 2018; Galan-Martin et al., 2020; Vicente-Campos et al., 2021; Cana-Pino et al., 2023; Hernandez-Lucas et al., 2023) used the Spanish version of the shorthand TSK-11 to measure fear of movement/kinesiophobia.

Effect of exercise on kinesiophobia

Findings from the included studies have been pooled to describe the effect exercise has on kinesiophobia for people with different types of spine-related pain.

Chronic neck pain

One study (Akodu et al., 2021) investigated the effect of neck stabilization exercise and Pilates on kinesiophobia and found that both neck stabilization exercise ($Z = -3.077$; $p = 0.002$) and Pilates ($Z = -2.994$; $p = 0.003$) significantly reduced kinesiophobia levels at 8 weeks following the intervention compared to dynamic isometric neck exercises over the same period. This study indicates Pilates and neck stabilization exercises are effective in reducing kinesiophobia over 8 weeks in people with chronic neck pain. Another study (Martins de Sousa et al., 2022) evaluating the effects of high and low frequency transcutaneous electrical nerve stimulation (TENS) and a series of therapeutic exercises which include performing flexion, extension, inclination, and rotation movements of the cervical spine for the treatment of patients with chronic neck pain. The study found no significant clinical difference between participants allocated to the therapeutic exercise and placebo-TENS (group 1) and participants in the low TENS group (group 2) and kinesiophobia [mean difference between the groups−0.40 (−4.64, 3.84), $p > 0.05$], mean difference placebo TENS and high TENS was also not significant [mean difference between the groups −0.31 (−5.68, 5.06), $p > 0.05$]. The Back schools-based intervention, an educational and training programs with lessons given to patients or workers by a therapist with the aim of treating or preventing back pain was used by Hernandez-Lucas et al. (2023). This study investigated the effects of a Back schools-based intervention on non-specific cervical pain in an adult population. The study found a significant treatment effect between the experimental group (people attending the Back school program) compared to control (People who did not attend the Back school program) on TSK-11; [mean difference 7.0 (95% CI: −8.3 to −5.4), $p < 0.001$, $g = 2.04$].

Chronic low back pain

Pilates was an intervention for people with chronic LBP in five studies, with four of them showing beneficial effects in reducing kinesiophobia. One study found that both mat Pilates and equipment-based Pilates significantly reduced kinesiophobia over 6 weeks and 12-week intervention period, and both differences were significant ($p < 0.05$) when compared to the control group (Cruz-Díaz et al., 2017). A significant reduction in TSK scores were observed at 12 weeks following Mat Pilates, with mean scores of 31.7 (+/−3.2) at 12 weeks compared to 34.5 (+/−4.1) at baseline. Equipment based Pilates also showed a significant improvement in TSK scores, with mean scores of 32.0 (+/−3.6) at 12 weeks compared to 36.5 (+/−3.9) at baseline. In contrast Da Luz Junior et al. (2014) compared a six-week equipment-based and mat Pilates interventions and found that after 6 month

there was a statistically significant improvement in kinesiophobia [mean difference = 4.9 points (95% CI 1.6 to 8.2)] following equipment-based Pilates. These results suggests that equipment-based Pilates may have a longer-term effect on kinesiophobia levels than mat Pilates.

A study (Miyamoto et al., 2018) investigating the frequency of Pilates administered (once, twice and three times per week) in three groups of patients compared to advice/education, found that Pilates significantly reduced kinesiophobia at a 6 weeks follow-up. Participants having Pilates twice a week showed the greatest reduction in kinesiophobia, baseline mean 40.8 (+/−7.5) compared to 37.4 (+/−8.7) at 6 weeks. However, no significant difference was found for any of the three groups at 6- and 12-months follow-up. Additionally, Cruz-Díaz et al. (2018) found that after a 12-weeks Pilates exercise programme, the exercise group showed a significant improvement in kinesiophobia when compared to the control group at six [mean change 5.5 (+/−0.7), $p < 0.001$] and 12 weeks follow-up [mean change 5.0 (+/−0.8), $p < 0.001$]. Conversely, another study (Miyamoto et al., 2013) found that Pilates combined with an educational booklet resulted in no significant between group differences (booklet group v/s Pilates) at a 6 months follow-up [adjusted mean difference 0.6 (95% CI: −1.8 to 3.1), $p = 0.61$].

Keane (2017) assessed the effect of land and water-based stretching compared to a control group in people with chronic LBP and found that after 12 weeks, only water-based stretching significantly (baseline mean = 37.1 v/s 12 weeks mean = 28.8, $p = 0.03$) reduced kinesiophobia. Nassif et al. (2011) investigated the effect of major muscle group training in people with LBP compared to a control group that had no direct intervention. Strengthening exercises significantly improved kinesiophobia post intervention [baseline mean 46.7 (+/−6.8)] at 2 months follow up [mean 41.6 (+/−6.93), $p < 0.001$]. Additionally, a general strength conditioning exercise programme reduced kinesiophobia [mean difference −6.6 (−9.9, −3.2, $p < 0.001$)] compared to a motor control (combined with manual therapy) exercise programme at the 6 months follow-up (Tagliaferri et al., 2020). On the other hand, Vicente-Campos et al. (2021) found no significant improvement in kinesiophobia following Hypopressive Abdominal Gymnastics programme compared to a control group [mean difference −2.00 (95% CI: −4.75 to −0.75, $p = 0.15$] after 8 weeks. Furthermore, in a study of obese older adults with chronic LBP, the effect of two exercise protocols [total body resistance training (TOTRX) and a lumbar extension resistance exercise training (LEXT)] were compared to a control group (standard care) for 4 months on fear of movement or re-injury and avoidance behavior. At the four-month follow-up, there was no statistical difference between the two exercise groups: TSK: TOTRX: mean baseline 24.5 (+/6.6) at 4 months mean 21.0 (+/−6.9); LEXT mean baseline 25.2 (+/−6.7) at 4 months mean 20.9 (+/−5.9). FABQ: TOTRX: mean baseline 13.2 (+/−14.2) at 4 months mean 8.3 (+/−10.5); LEXT mean baseline 11 (+/−5.9) at 4 months 9.1 (+/−7.2). Both exercise modalities shows improvement in fear of movement and avoidance behavior Vincent et al. (2014). Zadro et al. (2019) investigated the effect of a video game-based exercise programme against a control group for 8 weeks on fear of movement/re-injury. The results showed that there were no significant between group difference in fear of movement/re-injury ($\beta = -2.97$, 95% CI = −6.14 to 0.21, $p = 0$ 0.07) post-intervention at 8 weeks. Cana-Pino et al. (2023) examined the effect of two exercise modalities: Supervised Exercise (SE)/Laser Guided Exercise (LGE) and Pain Neuroscience Education (PNE) on fear of movement/kinesiophobia in participants with Non-Specific Chronic Low Back Pain (NSCLBP). The result showed a significant between-group difference post-intervention scores at 20 weeks in terms of kinesiophobia (TSK-11) ($p < 0.05$) and a high effect size (d = 0.81). Another study (Ogunniran et al., 2023) examined the effects of Kinesiology taping (KT) and Core-stabilization exercises (CSE) separately and in combination on Kinesiophobia in patients with NSCLBP. The results showed that there was statistically significant difference in kinesiophobia ($p < 0.001$) across the three groups at the end of 8 week post-intervention. KT and CSE showed the greatest improvement in kinesiophobia at 8 weeks (21.08 ± 3.75 95% CI: 18.70 to 23.47), CSE (34.79 ± 7.89 95% CI: 29.81 to 39.73) and KT (36.40 ± 8.40 95% CI: 30.39 to 42.41) compared to baseline KT and CSE (42.54 ± 7.37 95% CI: 37.47 to47.20), CSE (42.24 ± 7.64 95% CI: 37.98 to 48.33) and KT (41.31 ± 9.10 95% CI: 34.32 to 46.28).

Chronic thoracic pain

There were no studies that specifically investigated people with chronic thoracic pain. However, a study by Galan-Martin et al. (2020) investigated the effect of an 11-week physical exercise programme (combined with education) on people with chronic spinal (cervical, thoracic, LBP, and combined) pain and found a significant improvement in kinesiophobia levels in the exercise group at 6 months when compared to baseline scores and the control group.

Discussion

This systematic review is the first to investigate and compare the effect of different exercise/physical activity interventions in reducing kinesiophobia in people with chronic non-specific spine-related pain. The review indicated that there are a variety of exercises that are effective in reducing kinesiophobia in people with chronic spine-related pain, but that the majority of studies had been conducted on people with chronic non-specific LBP. In contrast only three studies investigated neck pain, and none focused specifically on thoracic pain, highlighting the need for further research to investigate the effects of exercise on kinesiophobia in people with chronic non-specific neck and thoracic pain. The exercises with significant effect in reducing kinesiophobia in people with chronic LBP were Pilates (multiple types), water-based stretching and strengthening. Miyamoto et al. (2018) and Cruz-Díaz et al. (2018) support the use of Pilates to reduce kinesiophobia in people with LBP, but the studies have methodological issues that raise concerns of bias which affects the reliability of the findings. Miyamoto et al. (2018) reported that they were unable to blind participants to the intervention groups, which may have affected the performance of participants (Karanicolas et al., 2010).

Additionally, Cruz-Díaz et al. (2018) reported that there were significant differences in body mass index between the two groups prior to intervention.

The studies by Cruz-Díaz et al. (2017) and Da Luz Junior et al. (2014) were deemed as having low risk of bias. Both studies show a beneficial direction of effect in reducing kinesiophobia following mat and equipment-based Pilates. Additionally, Da Luz Junior et al. (2014) concluded that equipment-based Pilates has a longer lasting effect in reducing kinesiophobia. The proportion of males to females in both studies were not proportionate, with females outweighing males, which may compromise generalisability of these findings. The imbalance of genders is a limitation in both studies and future studies should aim to recruit an equal number of men and women. There has been some indication that women with chronic non-specific LBP have greater levels of kinesiophobia than men on movements or actions that require dynamic balance (Kahraman et al., 2018), and this difference indicates that both genders should be equally investigated, to compare any potential differences in kinesiophobia and the effects exercise may have.

The notion that exercise has a beneficial effect on kinesiophobia in people with chronic spine-related pain is evidenced by the findings of Galan-Martin et al. (2020), who found kinesiophobia was reduced more in those who underwent physical exercise than those having physiotherapy treatment excluding exercise. This study was the only one to have participants who had chronic non-specific pain from any area in the spine or more than one area. This study was deemed high risk because of incomplete blinding; both the participant and Physiotherapist (who led the session) were not blinded. Findings from Miyamoto et al. (2013), shows that exercise/Pilates combined with education was not significantly different to education alone in reducing kinesiophobia. On the other hand, supervised exercise with or without laser guided exercise, when combined with PNE, reduces kinesiophobia in patients with NSCLBP (Cana-Pino et al., 2023). However, the effect of exercise on kinesiophobia cannot be ascertained since it has been performed in combination with PNE and the effect was only assessed for 3 months, longer term effect cannot be showed. Findings from Ogunniran et al. (2023) shows improvement in Kinesiophobia in the three groups (KT and CSE group, CSE only group and KT only group). Although, improvement was greater in the combined KT and CSE group, showing that modalities such as KT and CSE are effective in the treatment of NSCLBP. Additionally, a study by Hernandez-Lucas et al. (2023) evaluating the effects of the Back School on non-specific neck pain in adults aged $\geq$18, showed a beneficial effect on kinesiophobia, however, this study did not have a post-intervention follow-up, making it difficult to ascertain its long-term effect. Furthermore, due to the small sample size, generalisability of the results may be compromised. Conversely, (Martins de Sousa et al., 2022) reported that high/low frequency TENS, compared to placebo TENS, in combination with exercise did not provide clinical benefits to patients with chronic neck pain.

Overall, the risk of bias was moderate/high in ~80% of the included studies. Based on the GRADE assessment, there is only very low certainty of evidence that exercise/physical activity are effective at reducing fear of movement, primarily due to the wide variations between the included studies in terms of exercise/physical activity modalities and outcome assessment tools. A systematic review and meta-analysis by Hanel et al. (2020) had similar findings to this review; they found that exercise improved kinesiophobia in patients with chronic LBP, but the overall quality of evidence was "very low to low".

Strengths and limitations

The current review has several strengths. The review protocol was registered in PROSPERO, published (Jadhakhan et al., 2022) and was conducted and reported in accordance with the PRISMA 2020 statement (Page et al., 2021). Two independent reviewers were involved in study selection, data extraction and quality assessment, and a third reviewer was available to ensure overall methodological consistency and to resolve any disagreements. To ensure an exhaustive review of the available literature, a comprehensive search strategy was implemented with broad inclusion criteria. However, there are some limitations which should be noted. Significant heterogeneity was found between the included studies, particularly pertaining to methods of ascertaining exercise/physical activity, variation in chronic non-specific spine-related pain and measures used to assess kinesiophobia which precluded meta-analysis. Furthermore, due to limited data on ethnicity and gender, sub-group analyses to explore the effect of these variable was not possible. The generalisability and applicability of these findings may be reduced, because of the setting, population and criteria to ascertain kinesiophobia. Additionally, there were limitations in the study selection process such as the search was restricted to English language publications.

Conclusion

Exercise/physical activity can significantly reduce kinesiophobia in people with chronic non-specific spine-related pain, although the majority of the studies included in this review investigated chronic non-specific LBP. Favorable short-term effects on kinesiophobia were evidenced from Pilates (equipment-based) exercises for people with LBP. General exercise and strengthening training appeared to also be effective at reducing kinesiophobia in people with LBP. However, the overall the certainty of the evidence was very low. Further research should consider exploring the effect exercise has on kinesiophobia in people with chronic non-specific spine-related pain, with robust methodology required to produce the highest quality of evidence. Additionally, further research is needed to investigate the effect exercise has on kinesiophobia for people with chronic non-specific neck and thoracic pain, as there was very limited evidence to draw any meaningful conclusions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DF and FJ conceived the study design. RS drafted the first version of this review and this was reviewed and revised by DF and FJ. The search strategy was developed by RS and FJ and iteration discussed with DF. The search was performed by RS. FJ and RS performed screening for study selection, collected data from the included studies, conducted quality assessment, and performed data analysis/synthesis. DF is guarantor. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2023.1213199/full#supplementary-material

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Exercise promotes brain health: a systematic review of fNIRS studies

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Exercise can induce brain plasticity. Functional near-infrared spectroscopy (fNIRS) is a functional neuroimaging technique that exploits cerebral hemodynamics and has been widely used in the field of sports psychology to reveal the neural mechanisms underlying the effects of exercise. However, most existing fNIRS studies are cross-sectional and do not include exercise interventions. In addition, attributed to differences in experimental designs, the causal relationship between exercise and brain functions remains elusive. Hence, this systematic review aimed to determine the effects of exercise interventions on alterations in brain functional activity in healthy individuals using fNIRS and to determine the applicability of fNIRS in the research design of the effects of various exercise interventions on brain function. Scopus, Web of Science, PubMed, CNKI, Wanfang, and Weipu databases were searched for studies published up to June 15, 2021. This study was performed in accordance with the PRISMA guidelines. Two investigators independently selected articles and extracted relevant information. Disagreements were resolved by discussion with another author. Quality was assessed using the Cochrane risk-of-bias method. Data were pooled using random-effects models. A total of 29 studies were included in the analysis. Our results indicated that exercise interventions alter oxygenated hemoglobin levels in the prefrontal cortex and motor cortex, which are associated with improvements in higher cognitive functions (e.g., inhibitory control and working memory). The frontal cortex and motor cortex may be key regions for exercise-induced promotion of brain health. Future research is warranted on fluctuations in cerebral blood flow during exercise to elucidate the neural mechanism underlying the effects of exercise. Moreover, given that fNIRS is insensitive to motion, this technique is ideally suited for research during exercise interventions. Important factors include the study design, fNIRS device parameters, and exercise protocol. The examination of cerebral blood flow during exercise intervention is a future research direction that has the potential to identify cortical hemodynamic changes and elucidate the relationship between exercise and cognition. Future studies can combine multiple study designs to measure blood flow prior to and after exercise and during exercise in a more in-depth and comprehensive manner.

KEYWORDS

exercise, physical activity, brain plasticity, functional near-infrared spectroscopy (fNIRS), review

1 Introduction

Exercise intervention is a convenient and adaptive approach to effectively enhance the cognitive function and emotion of individuals (Verburgh et al., 2014; Kawagoe et al., 2017). Indeed, an increasing number of studies have demonstrated its beneficial effects on the healthy development of brain function (Mandolesi et al., 2018; Chen, 2020). Recent studies have predominantly focused on the variations in cognitive function and brain functional activity, such as cerebral blood flow, before and after exercise intervention (Fujihara et al., 2021; Kim et al., 2021; Zhang et al., 2021). Exploring real-time alterations in cerebral blood flow during exercise interventions can reveal hemodynamic changes (Endo et al., 2013; Eggenberger et al., 2016; Carius et al., 2020) and execution (Chen et al., 2017; Coetsee and Terblanche, 2017; Yang et al., 2020) and enhance our understanding of the mechanism underlying the effects of exercise on the brain.

The development of functional near-infrared spectroscopy (fNIRS) has enabled the exploration of hemodynamic changes in cerebral blood flow during exercise interventions. Specifically, it allows non-invasive monitoring of brain tissue oxygenation and hemodynamics (Hoshi, 2005) and possesses distinct advantages over other neuroimaging modalities, such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI). In addition, it balances both temporal resolution and spatial resolution and is comparatively less sensitive to motion (Leff et al., 2011; Scarapicchia et al., 2017). Previous exercise intervention studies using fNIRS devices largely focused on exercise interventions such as walking (Hamacher et al., 2015), posture, and walking (Herold et al., 2017), which are practical within the laboratory setting. Given the diversity in experimental designs, the effects of exercise on the brain exhibit substantial variability.

The application of fNIRS in the field of sport and exercise psychology is heterogeneous due to variations in the utilization of fNIRS and experimental design. Therefore, to improve uniformity across different studies investigating the influence of exercise on brain functional activity, this review aimed to examine studies that employed near-infrared spectroscopy to detect changes in brain hemodynamics before, during, and after exercise. The purpose of this review was as follows: (1) offer recommendations regarding study designs and research related to fNIRS technology in exercise intervention studies; (2) analyze the designs of various exercise protocols and compare the results obtained after or during exercise; and (3) evaluate the characteristics of changes in cerebral blood flow after and during exercise. Overall, the objective of this review was to investigate the effects of various exercise interventions on alterations in brain functional activity from different perspectives (before and after exercise vs. during exercise).

2 Methods

This systematic review was performed and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines (Page et al., 2021) and the Cochrane Collaboration Handbook (Higgins et al., 2019).

2.1 Search strategy

Two reviewers (J.M.H. and T.X.) conducted an independent literature search to screen related studies. The third reviewer, Q.Q.S., resolved disagreements by arbitration.

Scopus, Web of Science, PubMed, CNKI, Wanfang, and Weipu databases were searched from inception to June 15, 2021. The keywords were (Verburgh et al., 2014) exercise (physical activity, exercise, fitness, and sport) and (2) fNIRS (functional near-infrared spectroscopy). These terms were consistently applied across each database, serving as the main topic and free-text words in the title.

2.2 Eligibility criteria

Studies were considered eligible if they fulfilled the following criteria: (1) the subjects were healthy; (2) the articles were published in the English language or Chinese language in peer-reviewed journals; (3) exercise-related intervention studies utilizing large muscle groups of the whole body; and (4) at least one cerebral cortical blood flow change was assessed using fNIRS.

Our review focused on the effect of exercise interventions on common healthy participants. The exclusion criteria were as follows: unclear exercise protocols, exercise protocols not designed to improve brain or cognitive health (e.g., exercise test to exhaustion), and studies involving combined interventions (e.g., nutrition and cognition). To ensure generalizability, research utilizing clinical samples (e.g., overweight/obese) and those examining special groups (athletes or people with long-term exercise habits) were excluded.

2.3 Data extraction

Duplicated studies screened from the database search and reference lists were initially excluded. Next, the titles and abstracts were individually evaluated by two authors (J.M.H. and T.X.) to further exclude articles based on the eligibility criteria. Afterward, the two authors independently evaluated the articles. Disagreements were resolved by discussion and consensus among the three authors (Q.Q.S., J.M.H., and T.X.).

The two authors independently extracted the following data from eligible studies: (1) basic information, including the year of publication, participant characteristics, and study design; (2) study design, including study group or condition design, fNIRS state (resting-state or task-design), physiological outcome index, and behavioral outcome index; (3) fNIRS device parameters, including types of fNIRS devices, fNIRS sampling frequency, number of light emitting diodes, laser diodes, channels, fNIRS instrument location and area of interest, and position/arrangement and placement of the light source and detector; (4) the exercise intervention design, covering exercise type, exercise intervention period, frequency of exercise, exercise intensity, and single intervention duration; and (5) the primary endpoints of the studies.

TABLE 1 Quality of included studies.

References	Random sequence generation (selection bias)	Allocation concealment (selection bias)	Blinding of participants and personnel (performance bias)	Blinding of outcome assessment (detection bias)	Incomplete outcome data (attrition bias)	Selective reporting (reporting bias)	Other bias
Auger et al. (2016)	U	U	U	U	L	L	L
Byun et al. (2014)	U	U	U	U	L	L	L
Carius et al. (2020)	L	U	U	U	L	L	L
Chen et al. (2017)	L	U	H	U	L	L	L
Coetsee and Terblanche (2017)	L	U	U	U	L	L	L
Endo et al. (2013)	L	U	L	L	L	L	U
Fujihara et al. (2021)	H	U	U	U	L	L	L
Hashimoto et al. (2018)	L	U	U	U	L	L	L
Eggenberger et al. (2016)	L	U	H	H	L	L	H
Herold et al. (2019)	U	U	U	U	L	U	L
Hyodo (2012)	U	U	U	U	L	L	L
Jiang and Wang (2016)	U	U	U	U	U	L	L
Ji et al. (2019)	U	U	U	U	U	L	L
Kenville et al. (2017)	L	U	U	U	L	L	L
Kim et al. (2021)	U	U	L	L	U	L	L
Kriel et al. (2016)	L	U	U	U	L	L	L
Kujach (2018)	L	U	U	U	L	L	L
Kurz et al. (2012)	U	U	U	U	L	L	L
Lai et al. (2020)	L	U	L	U	L	L	L
Lambrick et al. (2016)	L	U	U	U	L	L	L
Miyashiro et al. (2021)	L	U	U	U	L	L	L
Monroe et al. (2016)	U	U	U	U	U	L	L
Stute et al. (2020)	U	U	U	U	L	L	L
Wen et al. (2015a)	U	U	U	U	U	L	L
Wen et al. (2015b)	L	U	U	U	U	L	L
Xu et al. (2019)	U	U	U	U	U	L	L
Yanagisawa (2010)	U	U	U	U	L	L	L
Yang et al. (2020)	L	L	U	L	L	L	L
Zhang et al. (2021)	L	U	U	U	L	L	L

L, Low risk; H, High risk; U, Unclear risk.

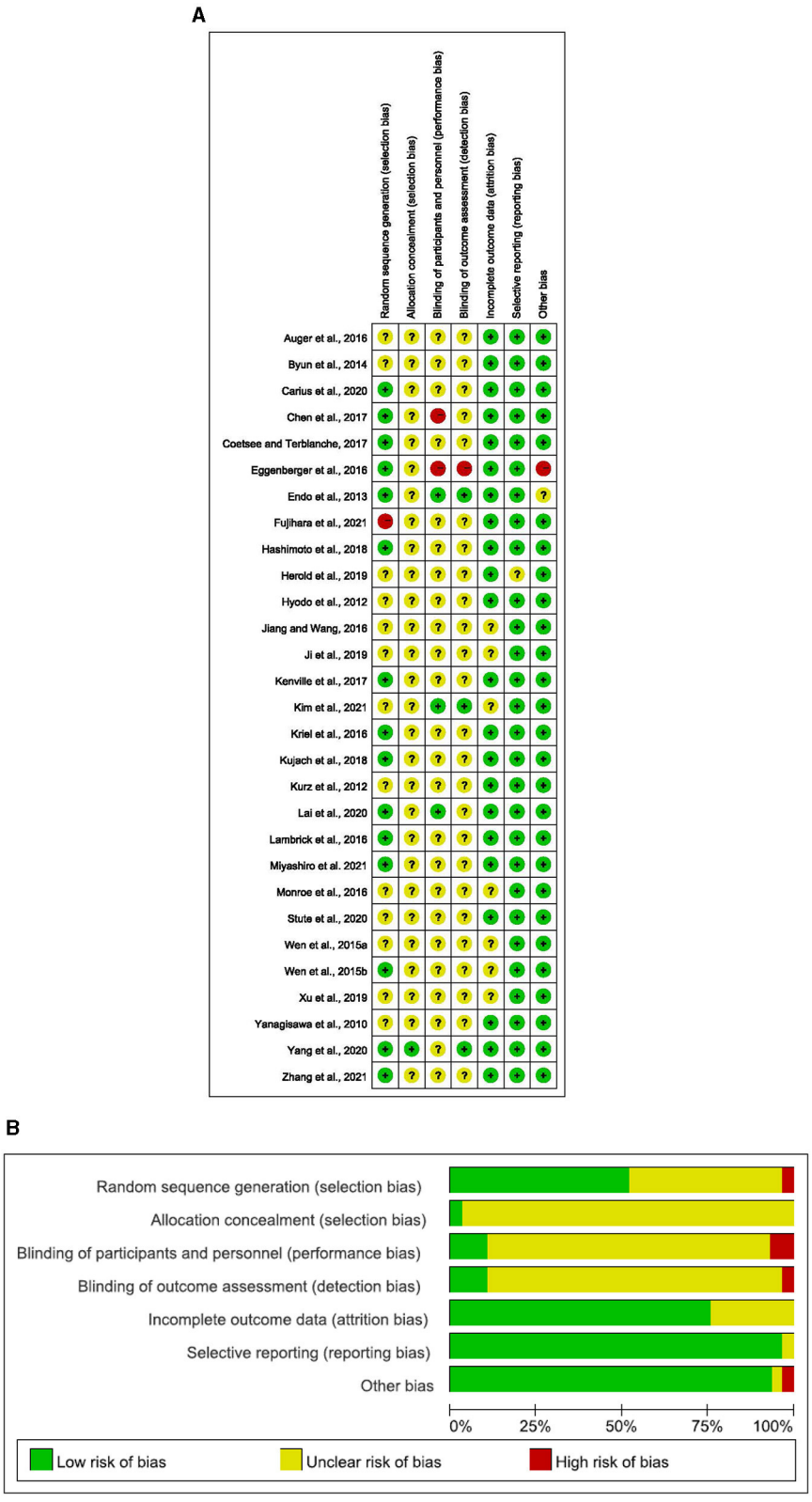


FIGURE 1
(A) Risk of bias ratings. **(B)** Risk of bias graph: percentage of trials with low, unclear, or high risk of bias ratings for each domain (Yanagisawa, 2010; Hyodo, 2012; Kurz et al., 2012; Endo et al., 2013; Byun et al., 2014; Wen et al., 2015a,b; Auger et al., 2016; Eggenberger et al., 2016; Jiang and Wang, 2016; Kriel et al., 2016; Lambrick et al., 2016; Monroe et al., 2016; Chen et al., 2017; Coetsee and Terblanche, 2017; Kenville et al., 2017; Hashimoto et al., 2018; Kujach, 2018; Herold et al., 2019; Ji et al., 2019; Xu et al., 2019; Carius et al., 2020; Lai et al., 2020; Stute et al., 2020; Yang et al., 2020; Kim et al., 2021; Miyashiro et al., 2021; Zhang et al., 2021).

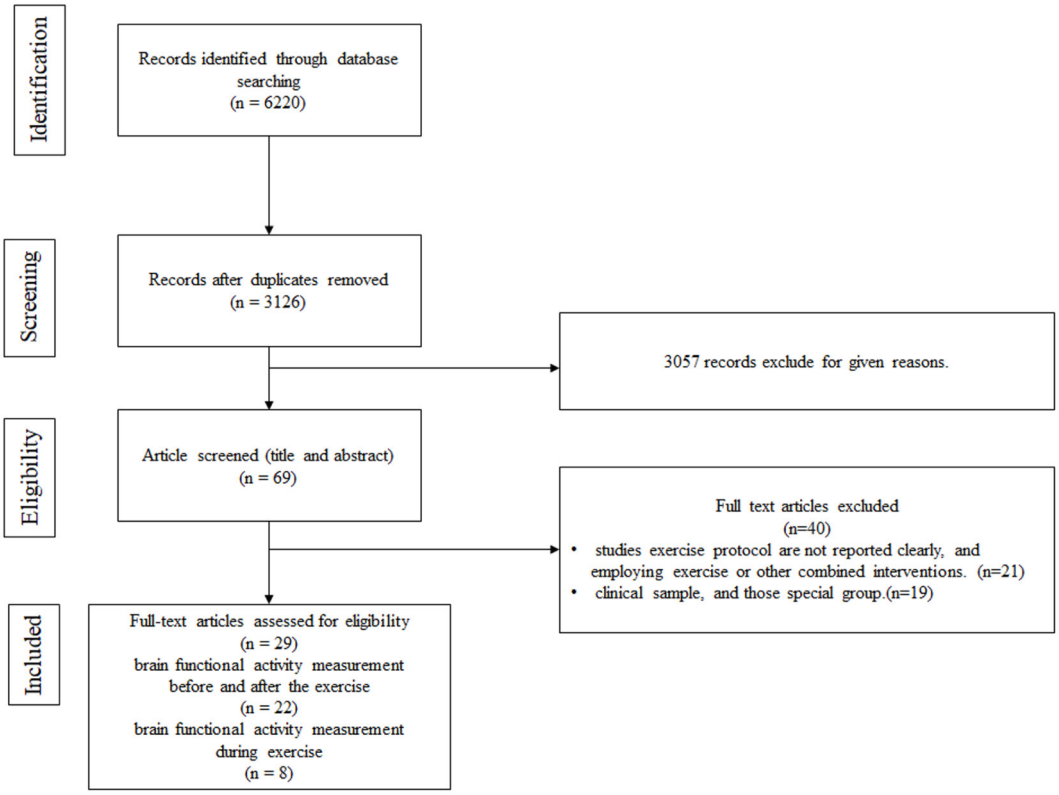


FIGURE 2
Flow chart.

2.4 Risk of bias assessment

The risk of bias in selected studies was independently assessed by two authors (J.M.H. and T.X.) using the Cochrane Collaboration Risk-of-Bias tool (Higgins et al., 2011, 2019). Disagreements were resolved by discussion with another author (Q.Q.S.) to achieve consensus (see Table 1 and Figure 1).

3 Results

3.1 Study selection and characteristics

The search process is detailed in a flow chart illustrated in Figure 2. The search strategy yielded 6,220 studies from the pre-defined databases. After excluding duplicates and reviewing the full text, 69 studies met the criteria based on the consensus reached by the reviewers. From these, 22 eligible articles were included in the first category (cerebral hemodynamics were measured before and after exercise) and 8 in the second category (cerebral hemodynamics were measured during exercise). Among them, one study was simultaneously in both categories.

Overall, 29 studies were included in the systematic review. Regarding the study region, 18 studies were conducted in Asia (Yanagisawa, 2010; Hyodo, 2012; Endo et al., 2013; Byun et al., 2014; Wen et al., 2015a,b; Jiang and Wang, 2016; Chen et al., 2017; Coetsee and Terblanche, 2017; Hashimoto et al., 2018; Kujach, 2018; Ji et al., 2019; Xu et al., 2019; Lai et al., 2020; Yang et al., 2020; Kim et al., 2021; Miyashiro et al., 2021; Zhang et al., 2021), 5 in Europe (Eggenberger et al., 2016; Kenville et al., 2017; Herold et al., 2019; Carius et al., 2020; Stute et al., 2020), 2 in Oceania (Kriel et al., 2016; Lambrick et al., 2016), 3 in North America (Kurz et al., 2012; Auger et al., 2016; Monroe et al., 2016), and 1 in Africa (Coetsee and Terblanche, 2017). A total of 664 participants were examined, with sample sizes ranging from 10 to 67. The age of patients across studies spanned from 72.3 months to 75 years.

3.2 Quality of included studies

The details on the quality of the included studies in bias risk assessment are summarized in the supporting material. Of note, 28 studies did not provide details on selective reporting, 27 studies reported no other biases, 23 studies reported complete outcome data, 15 studies reported random sequence generation, 1 study reported allocation concealment, 1 study reported blinding of participants and personnel, and 1 study reported blinding of outcome assessment.

3.3 Study design

Twenty-two studies measured cerebral hemodynamics before and after exercise interventions, eight studies (including only adults) documented cerebral hemodynamics during the exercise

intervention, and one study recorded cerebral hemodynamics before, during, and after the exercise intervention.

3.3.1 Study design encompassing measurements before and after exercise intervention

In this category (see Table 2), 22 studies provided information on cerebral hemodynamics and activity before and after exercise in the exercise group compared to levels measured before exercise in this group (14 studies) (Yanagisawa, 2010; Hyodo, 2012; Endo et al., 2013; Kujach, 2018; Miyashiro et al., 2021; Byun et al., 2014; Wen et al., 2015a,b; Jiang and Wang, 2016; Lambrick et al., 2016; Hashimoto et al., 2018; Ji et al., 2019; Xu et al., 2019; Kim et al., 2021) or cerebral hemodynamics levels measured before and after exercise in another group (8 studies) (Eggenberger et al., 2016; Chen et al., 2017; Coetsee and Terblanche, 2017; Lai et al., 2020; Stute et al., 2020; Yang et al., 2020; Fujihara et al., 2021; Zhang et al., 2021).

Only one study measured hemodynamic changes and activity in the resting state. In this particular study, baseline brain activity was assessed in the seated position for 5 min (Endo et al., 2013).

All studies evaluated cortical hemodynamic activation using different task designs: 14 studies assessed inhibitory control (Flanker or Stroop task) (Yanagisawa, 2010; Hyodo, 2012; Endo et al., 2013; Byun et al., 2014; Wen et al., 2015a,b; Jiang and Wang, 2016; Lambrick et al., 2016; Chen et al., 2017; Coetsee and Terblanche, 2017; Kujach, 2018; Ji et al., 2019; Yang et al., 2020; Fujihara et al., 2021), 3 studies examined working memory (N-back task) (Lai et al., 2020; Stute et al., 2020; Kim et al., 2021), 1 study investigated attention (paced auditory serial addition test) (Hashimoto et al., 2018), 1 study assessed cognitive reappraisal (implicit cognitive reappraisal task) (Zhang et al., 2021), 1 study investigated the mirror neuron system (table-setting task) (Xu et al., 2019), one study applied a concentration task (2-back task) (Miyashiro et al., 2021), and one study assessed an exercise task (walking) (Eggenberger et al., 2016). Interestingly, the majority of designs were block designs used in 12 studies (Wen et al., 2015a,b; Eggenberger et al., 2016; Jiang and Wang, 2016; Chen et al., 2017; Hashimoto et al., 2018; Ji et al., 2019; Xu et al., 2019; Lai et al., 2020; Yang et al., 2020; Zhang et al., 2021), whereas an event-related design was applied in four studies (Yanagisawa, 2010; Hyodo, 2012; Byun et al., 2014; Kujach, 2018). The remaining studies did not report the study design.

Nine studies carried out physiological measurements after exercise, among which seven studies measured heart rate (HR) (Hyodo, 2012; Endo et al., 2013; Wen et al., 2015a,b; Lambrick et al., 2016; Kujach, 2018; Stute et al., 2020). Other physiological indicators, namely, heart rate reverse (HRR) (Fujihara et al., 2021), mean arterial blood pressure (MAP) (Endo et al., 2013), walking endurance (Coetsee and Terblanche, 2017), oxygen intake (VO_2), minute ventilation (V_E), respiratory exchange ratio (RER), and energy expenditure, were exclusively analyzed in one particular study (Lambrick et al., 2016).

Twelve studies investigated other behavioral indexes without examining cortical hemodynamic activation, among which eight studies measured Rating of Perceived Exertion (RPE) (Hyodo, 2012; Endo et al., 2013; Byun et al., 2014; Wen et al., 2015a,b; Kujach, 2018; Stute et al., 2020; Fujihara et al., 2021), and two studies measured Two-Dimensional Mood Scale (TDMS) (Byun et al., 2014; Kujach, 2018). Other behavioral indices, namely the Profile of Mood States (POMS) (short version) (Chen et al., 2017), physical fitness (Lai et al., 2020), Eston-Parfitt Scale (Lambrick et al., 2016), Trail Making Test Part A (TMT-A), Trail Making Test Part B (TMT-B), Stroop Word-Color Interference task, Executive Control task, Montreal Cognitive Assessment (MoCA), Short Physical Performance Battery (SPPB), Falls Efficacy Scale International (FES-I), and geriatric depression scale (GDS), were solely analyzed in one study (Eggenberger et al., 2016).

3.3.2 Study design involving measurements during exercise interventions

In this category (see Table 3), eight studies presented data on cerebral hemodynamic activation during the exercise intervention. Of note, all studies used exercise tasks to investigate the task design. Most studies either used block designs or did not specify the design, whilst few studies provided a detailed description of the design of exercise tasks. As anticipated, studies adopting a block design employed relatively short durations for each block, similar to the cognitive task, ranging from 20 to 40 seconds.

These exercise tasks, such as walking (Kurz et al., 2012; Herold et al., 2019), cycling (Endo et al., 2013; Auger et al., 2016; Kriel et al., 2016; Monroe et al., 2016), basketball slalom dribbling (Carius et al., 2020), and barbell squats (Kenville et al., 2017) were easy to perform in laboratory settings.

Furthermore, six studies conducted physiological measurements, of which five studies measured HR (Endo et al., 2013; Kriel et al., 2016; Monroe et al., 2016; Herold et al., 2019; Carius et al., 2020). Some physiological indicators, namely MAP (Endo et al., 2013), VO_2 (Kriel et al., 2016), peak power output (PPO) (Auger et al., 2016), power output (Kriel et al., 2016), peak power (Monroe et al., 2016), oxygen uptake (Monroe et al., 2016), and LF/HF ratio (Herold et al., 2019), were only analyzed in one specific study.

Five studies investigated the effects of exercise on behavioral indices that only appeared in one particular study, namely stride time interval (Kurz et al., 2012), PRE (Endo et al., 2013; Monroe et al., 2016), Profile of Mood States-Brie (POMS-B) (Monroe et al., 2016), walking speed (Herold et al., 2019), and visual analog scale (VAS) (Carius et al., 2020).

3.4 fNIRS devices

3.4.1 Measurements before and after exercise interventions

Most included studies conducted fNIRS tests before and after a single, long-term exercise intervention using eleven different fNIRS devices. The device sampling frequency ranged from 1 to 50 Hz, with the majority of devices utilizing 16 emitting diodes and 16 laser diodes. The number of channels ranged from 2 to 48.

Four studies focused on multiple cortical areas (Hashimoto et al., 2018; Xu et al., 2019; Stute et al., 2020). Among them, one study focused on motor areas, such as the premotor cortex (PMC) (Xu et al., 2019; Stute et al., 2020), whilst two studies reported findings on the parietal cortex (Xu et al., 2019; Stute et al., 2020),

TABLE 2 Study design of measurement before and after exercise intervention.

References	Age	Group or condition comparison	fNIRS state and task	Task design	Physiological outcome index	Behavioral outcome index
Yanagisawa (2010)	21.5 ± 4.8	Ex condition; con condition	T ask state: Stroop task	Event-related	NA	NA
Hyodo (2012)	69.3 ± 3.5	Ex condition; con condition	Task state: Stroop task	Event-related	HR	RPE
Endo et al. (2013)	23 ± 1	20% EX_{max} condition; 40% EX_{max} condition; 60% EX_{max} condition; con condition	Resting-state: Sit for five min Task state: Stroop task, exercise task	NR	MAP; HR	RPE
Kujach (2018)	21	HIE condition; con condition	Task state: Stroop task	Event-related	HR	RPE; TDMS
Miyashiro et al. (2021)	20–24	Meditation condition; ex condition; con condition	Task state: N-back task	NR	NA	NA
Byun et al. (2014)	20.6 ± 1	Ex condition; con condition	Task state: Stroop task	Event-related	NA	RPE; TDMS
Wen et al. (2015a)	23.6 ± 1.2	Ex condition; con condition;	Task state: Flanker task	Block	HR	RPE
Wen et al. (2015b)	58.7 ± 7.2	Ex condition; con condition;	Task state: Flanker task	Block	HR	RPE
Eggenberger et al. (2016)	74.9 ± 6.9	Video game dance group; balance and stretching group	Task state: Walking task	Block	NA	TMT-A; TMT-B; Stroop task; Executive Control task; MoCA; SPPB; FES-I; GDS
Jiang and Wang (2016)	20.6	Ex condition;	Task state: Flanker task	Block	NA	NA
Lambrick et al. (2016)	8.8 ± 0.8	CONT condition; INT condition	Task state: Stroop task	NR	HR; VO_2; V_E; RER; energy expenditure	Eston-Parfitt Scale
Chen et al. (2017)	22.5 ± 2	BMB group; con group	Task state: Flanker task	Block	NA	POMS (short version)
Coetsee and Terblanche (2017)	62.7 ± 5.7	RT group; HIIT group; MCT group; con group	Task state: Stroop task	NR	Walking endurance	NA
Hashimoto et al. (2018)	24.3 ± 3.5	40% VO_2 peak condition; 60% VO_2 peak condition; con condition	Task state: Paced Auditory Serial Addition Test	Block	NA	NA
Ji et al. (2019)	65.6 ± 1.32	CE condition; PE condition; CE + PE condition; RC condition	Task state: Stroop task	Block	NA	NA
Xu et al. (2019)	20.7 ± 1.6	Exp condition; con condition	Task state: Table-setting task	Block	NA	NA
Lai et al. (2020)	Boys: 72.3 ± 2.74 months Girls: 73.2 ± 1.30 months	Tennis group; con group	Task state: N-back task	Block	NA	Physical fitness
Stute et al. (2020)	68.26 ± 3.31 69.7 ± 4.23	Exp group; con group	Task state: N-back task	Block	HR	RPE

(Continued)

TABLE 2 (Continued)

References	Age	Group or condition comparison	fNIRS state and task	Task design	Physiological outcome index	Behavioral outcome index
Yang et al. (2020)	TCC Group: 66.31 ± 4.25 con Group: 65.92 ± 3.48	TCC group; con group	Task state: Flanker task	Block	NA	NA
Fujihara et al. (2021)	Young adults: 22.68 ± 1.38 Old adults: 68.72 ± 5.26	Young adult group; older adult group	Task state: Reverse Stroop task	NR	HRR	RPE
Kim et al. (2021)	22.5 ± 2.2	Moderate intensity condition; High-intensity condition	Task state: 2-back task	NR	NA	NA
Zhang et al. (2021)	Ex group: 22.10 ± 1.85 con group: 21.30 ± 2.54	Ex group; con group	Task state: Implicit cognitive reappraisal task	Block	NA	NA

HIE, high-intensity intermittent exercise; con, control; EX, exercise; HIIT, high-intensity interval training; RT, resistance training; MCT, moderate continuous training; EX_{max}, maximum voluntary exercise; INT, intermittent bout of exercise; CE, cognitive exercise; PE, physical exercise; CE + PE, cognitive + physical exercise; RC, reading control; exp, experimental; CONT, continuous bout of exercise; NR, not reported; NA, not applicable.

such as the inferior parietal cortex (IPC) and superior parietal lobule (SPL). Besides, two studies reported data on the prefrontal cortex (Stute et al., 2020; Yang et al., 2020), one study investigated temporal areas (Hashimoto et al., 2018), and one study assessed the inferior frontal gyrus (IFG). Nineteen studies exclusively assessed activation of the PFC (Yanagisawa, 2010; Hyodo, 2012; Endo et al., 2013; Byun et al., 2014; Wen et al., 2015a,b; Eggenberger et al., 2016; Jiang and Wang, 2016; Lambrick et al., 2016; Chen et al., 2017; Coetsee and Terblanche, 2017; Kujach, 2018; Ji et al., 2019; Lai et al., 2020; Yang et al., 2020; Fujihara et al., 2021; Kim et al., 2021; Miyashiro et al., 2021; Zhang et al., 2021). Details are listed in Table 4.

3.4.2 Measurements during exercise interventions

fNIRS was conducted during acute exercise interventions (see Table 5) using four distinct fNIRS devices were used. The device sampling frequency ranged from 1 to 1,000 Hz, and 8 emitting diodes and 8 laser diodes were employed in the majority of the studies. The number of channels ranged from 4 to 24.

Four studies focused on multiple cortical areas (Kurz et al., 2012; Kenville et al., 2017; Herold et al., 2019; Carius et al., 2020). All studies focused on motor areas, such as the PMC, primary motor cortex (M1), supplementary motor area (SMA), and precentral gyrus (PCG) (Kurz et al., 2012; Kenville et al., 2017; Herold et al., 2019; Carius et al., 2020). Among them, three studies reported findings on the parietal cortex (Kurz et al., 2012; Kenville et al., 2017; Carius et al., 2020), such as the IPC and SPL, one study reported data on the PFC (Herold et al., 2019), one study assessed brain areas related to auditory, frontal and visual functions (Kurz et al., 2012; Kenville et al., 2017), including the primary somatosensory cortex (SSC) and, postcentral gyrus (POCG). Lastly, four studies reported data on PFC activation (Endo et al., 2013; Auger et al., 2016; Kriel et al., 2016; Monroe et al., 2016).

3.5 Exercise intervention

All exercise interventions were categorized into three types according to their frequency and duration, regardless of study design. In other words, they were measured before and after long-term exercise interventions ($n = 5$), measured before and after one-time exercise interventions ($n = 17$), and measured during one-time exercise interventions ($n = 8$). Among them, merely one study presented data before, during, and after acute exercise interventions. Major confounding factors adjusted for across these studies included exercise type, duration, intensity, frequency, and duration of activity.

3.5.1 Design of measurements before and after exercise interventions

Five studies investigated hemodynamic changes before and after long-term exercise interventions. Since before-after tests were used, the influence of exercise on fNIRS imaging results was not considered. A broad range of exercise interventions was implemented in these studies, including walking (Coetsee and Terblanche, 2017), Tai Chi Chuan (TCC) (Yang et al., 2020), Baduanjin mind-body (BMB) (Chen et al., 2017), tennis (Lai et al., 2020) or interactive cognitive-motor video game dancing (DANCE), and balance and stretching training (BALANCE) (Eggenberger et al., 2016). The exercise intervention period lasted 8 weeks in most studies (Eggenberger et al., 2016; Chen et al., 2017; Lai et al., 2020; Yang et al., 2020), with only one study extending to 16 weeks (Coetsee and Terblanche, 2017). The frequency of exercise ranged from 2 to 5 times a week. Exercise intensity was classified into three categories: low, moderate, and high. Most studies employed moderate exercise intensity, except for one study that did not report data on intensity (Chen et al., 2017) and one that used moderate-vigorous (Coetsee and Terblanche, 2017) intensity.

TABLE 3 Study design of measurement during exercise interventions.

References	Age	Group or condition	fNIRS state and task	Task design	Physiological outcome index	Behavioral outcome index
Kurz et al. (2012)	23.7 ± 1.4	Walking forward condition; walking backward condition	Task state: walking	Block	NA	Stride time interval
Endo et al. (2013)	23 ± 1	20% EX_{max} condition; 40% EX_{max} condition; 60% EX_{max} condition; Control condition	Task state: cycling	NR	MAP; HR	RPE
Auger et al. (2016)	23.1 ± 2.4	40% POP condition; 80% POP condition; Rest condition;	Task state: cycling	Block	PPO	NA
Kriel et al. (2016)	23 ± 3	HIITPASS condition; HIITACT condition; REC condition	Task state: cycling	NR	VO_2; HR; HHb; power output	NA
Monroe et al. (2016)	21.3 ± 2.4	SIC condition CRC condition	Task state: cycling	NR	HR; oxygen uptake; peak power	POMS-B; RPE
Kenville et al. (2017)	25.7 ± 2.2	BS with 0% 1 RM (L0%) condition; BS with 20% 1 RM (L20%) condition; BS with 40% 1 RM (L40%) condition; BL condition	Task state: barbell squat	Block	NA	NA
Herold et al. (2019)	25.00 ± 3.00	Overground condition; treadmill walking condition	Task state: walking	Block	HR; LF/HF ratio	Walking speed
Carius et al. (2020)	24.61 ± 0.47	DH_{slow} condition; NDH_{slow} condition; AH_{slow} condition; DH_{fast} condition; NDH_{fast} condition; AH_{fast} condition	Task state: basketball dribbling	Block	HR	VAS

DH_{slow}, dominant right hand at slow walking pace; NDH_{slow}, non-dominant left hand at slow walking pace; AH_{slow}, alternating hands at slow walking pace; DH_{fast}, dominant right hand at fast walking pace; NDH_{fast}, non-dominant left hand fast walking pace; AH_{fast}, alternating hands at fast walking pace; SIC, sprint interval cycling; CRC, constant resistance cycling; BS, barbell squat; HIITPASS, HIIT with passive recovery; HIITACT, HIIT with active recovery; REC, recovery; BL, baseline values; NR, not reported; NA, not applicable.

The duration of a single intervention ranged from 30 min to 90 min. Details are listed in Table 6.

Seventeen studies measured cerebral blood flow before and after acute exercise interventions (see Table 7). Exercise types involved cycling and running in the majority of studies, with the exception of one study that incorporated push-ups (Miyashiro et al., 2021). The duration of a single intervention varied from 10 min to 30 min, with seven studies employing a 10-min duration (Yanagisawa, 2010; Hyodo, 2012; Byun et al., 2014; Wen et al., 2015a,b; Kujach, 2018; Kim et al., 2021), five studies opting for 15 min (Endo et al., 2013; Hashimoto et al., 2018; Ji et al., 2019; Stute et al., 2020; Fujihara et al., 2021), two studies using a 20-min duration (Jiang and Wang, 2016; Miyashiro et al., 2021), one study implementing a duration of 25 min (Xu et al., 2019), and two studies extending to 30 min (Lambrick et al., 2016; Zhang et al., 2021). Lastly, exercise intensity was mostly moderate.

3.5.2 Design of measurements during acute exercise intervention

In the one-time exercise interventions, eight studies measured fNIRS during the exercise intervention (see Table 8). These studies mainly selected exercise interventions involving minimal head movement, such as cycling (Endo et al., 2013; Auger et al., 2016; Kriel et al., 2016; Monroe et al., 2016), basketball slalom dribbling (Carius et al., 2020), barbell squats (Kenville et al., 2017), and walking (Kurz et al., 2012; Herold et al., 2019). Moreover, most studies implemented cycling and walking interventions, while four studies used cycling (Endo et al., 2013; Auger et al., 2016; Kriel et al., 2016; Monroe et al., 2016), and two studies used walking (Kurz et al., 2012; Herold et al., 2019). The duration of the intervention ranged from 10 min to 25 min. While moderate intensity was used in most of the eight studies, some studies did not report exercise intensity and instead reported data on the exercise load.

3.6 Main results

A total of 29 studies investigated oxyhemoglobin (oxy-Hb), deoxyhemoglobin (deoxy-Hb), and total hemoglobin (total Hb) levels following exercise interventions. Specifically, three studies measured oxy-Hb, deoxy-Hb, and total Hb levels (Auger et al., 2016; Lambrick et al., 2016; Coetsee and Terblanche, 2017), eight studies measured oxy-Hb and deoxy-Hb levels (Hyodo, 2012; Kurz et al., 2012; Endo et al., 2013; Byun et al., 2014; Monroe et al., 2016; Kenville et al., 2017; Herold et al., 2019; Carius et al., 2020),

TABLE 4 The fNIRS devices used in the study design for measurement before and after exercise intervention.

References	Instrument type	Sampling frequency	Diode	Laser	Channel
Yanagisawa (2010)	ETG-7000	100 ms	16	16	48
Hyodo (2012)	ETG-7000	10 Hz	16	16	48
Endo et al. (2013)	NIRO 200	1 Hz	NR	NR	NR
Kujach (2018)	ETG-7000	10 Hz	8	8	48
Miyashiro et al. (2021)	ETG-4000	10 Hz	8	7	22
Byun et al. (2014)	ETG-7000	10 Hz	16	16	48
Wen et al. (2015a)	ETG-4000	10 Hz	16	16	44
Wen et al. (2015b)	ETG-4000	10 Hz	16	16	44
Eggenberger et al. (2016)	Oxiplex TS tissue spectrometer	1 Hz	8	2	NR
Jiang and Wang (2016)	NR	NR	NR	NR	NR
Lambrick et al. (2016)	PortaLite	2 Hz	3	3	NR
Chen et al. (2017)	ETG-4000	NR	6	10	44
Coetsee and Terblanche (2017)	NIRO 200NX	5 Hz	2	2	2
Hashimoto et al. (2018)	ETG-4000	100 ms	8	8	24
Ji et al. (2019)	NIRScout	3.91 Hz	8	8	20
Xu et al. (2019)	NIRSport	7.81 Hz	8	8	14
Lai et al. (2020)	PortaLite	50 Hz	3	1	3
Stute et al. (2020)	NIRSport	3.47 Hz	16	16	38
Yang et al. (2020)	ETG-4000	NR	16	14	44
Fujihara et al. (2021)	OEG-16	NR	6	6	16
Kim et al. (2021)	NIRSIT	8.138 Hz	24	32	48
Zhang et al. (2021)	OMM3000/8	33 Hz	9	9	27

TABLE 5 The fNIRS devices used in the study design for measurement during exercise intervention.

References	Instrument type	Sampling frequency	Diode	Laser	Channel
Kurz et al. (2012)	ETG-4000	10 Hz	8	8	24
Endo et al. (2013)	NIRO 200	1 Hz	NR	NR	NR
Auger et al. (2016)	Custom built	NR	4	4	NR
Kriel et al. (2016)	PortaLite	10 Hz	NR	NR	NR
Monroe et al. (2016)	OxyMon MKIII	1,000 Hz	2	2	4
Kenville et al. (2017)	NIRSport	7.81 Hz	8	8	NR
Herold et al. (2019)	NIRSport	7.81 Hz	8	8	14
Carius et al. (2020)	NIRSport	7.81 Hz	8	7	22

16 studies measured oxy-Hb levels (Yanagisawa, 2010; Wen et al., 2015a,b; Eggenberger et al., 2016; Jiang and Wang, 2016; Chen et al., 2017; Hashimoto et al., 2018; Kujach, 2018; Ji et al., 2019; Xu et al., 2019; Lai et al., 2020; Yang et al., 2020; Fujihara et al., 2021; Kim et al., 2021; Miyashiro et al., 2021; Zhang et al., 2021), one study measured deoxy-Hb levels (Kriel et al., 2016), and one study computed the HBdiff (oxy-Hb minus deoxy-Hb) (Stute et al., 2020).

3.6.1 Changes in brain functional activity before and after exercise interventions

Five studies investigated cerebral blood flow after long-term exercise interventions (see Table 9). One study measured oxy-Hb, deoxy-Hb, and total Hb levels (Coetsee and Terblanche, 2017), whilst the remaining four studies measured oxy-Hb levels (Eggenberger et al., 2016; Chen et al., 2017; Lai et al., 2020; Yang et al., 2020). After the long-term intervention, oxy-Hb levels were

TABLE 6 Exercise protocol used in the study design for measurement before and after long-term exercise intervention.

References	Duration (weeks)	Sessions/week	Session length (min)	Exercise type	Exercise intensity
Eggenberger et al. (2016)	8 weeks	3	30 min	DANCE or BALANCE	Moderate-vigorous
Chen et al. (2017)	8 weeks	5	90 min	BMB	NR
Coetsee and Terblanche (2017)	16 weeks	3	30 min	Walking	Moderate-vigorous
Lai et al. (2020)	8 weeks	2	60 min	Tennis	Moderate
Yang et al. (2020)	8 weeks	3	45 min	TCC	Moderate

NR, not reported.

TABLE 7 Exercise protocol used in the study design for measurement before and after acute exercise intervention.

References	Duration (weeks)	Sessions/week	Session length (min)	Exercise type	Exercise intensity
Yanagisawa (2010)	NA	NA	10 min	Cycling	Moderate: 50% of VO_2 peak
Hyodo (2012)	NA	NA	10 min	Cycling	Moderate: 50% of VO_2 peak
Endo et al. (2013)	NA	NA	15 min	Cycling	20, 40, and 60% of EX_{max}
Kujach (2018)	NA	NA	10 min	Cycling	60% of MAP
Miyashiro et al. (2021)	NA	NA	20 min	Push-ups	Not reported
Byun et al. (2014)	NA	NA	10 min	Cycling	Light: 30% of VO_2 peak
Wen et al. (2015a)	NA	NA	10 min	Cycling	Moderate: 66% of HR_{max}
Wen et al. (2015b)	NA	NA	10 min	Cycling	Moderate: 66% of HR_{max}
Jiang and Wang (2016)	NA	NA	20 min	Cycling	Moderate intensity
Lambrick et al. (2016)	NA	NA	30 min	Running	Submaximal
Hashimoto et al. (2018)	NA	NA	15 min	Cycling	40% and 60% of the peak oxygen
Ji et al. (2019)	NA	NA	15 min	Cycling	65% of heart rate
Xu et al. (2019)	NA	NA	25 min	Cycling	Moderate intensity (65% of VO_2 peak)
Stute et al. (2020)	NA	NA	15 min	Cycling	Moderate: 50% of VO_2 peak
Fujihara et al. (2021)	NA	NA	15 min	Running	Moderate: HRR of 50%
Kim et al. (2021)	NA	NA	10 min	Running	Moderate-vigorous: 65% of VO_2 peak-vigorous 80% of VO_{2max}
Zhang et al. (2021)	NA	NA	30 min	Cycling	Moderate: 60%−69% of HR_{max}

VO_2 peak, peak oxygen intake; EXmax, maximum voluntary exercise; HRmax, maximal heart rate; VO_2max, maximal oxygen intake; NA, not applicable.

increased in the left PFC during the flanker and N-back tasks. Likewise, deoxy-Hb levels were increased in the left PFC during the Stroop task across almost all studies. One study used a walking task and described that oxy-Hb levels were higher in the left PFC and right PFC during walking.

Seventeen studies investigated brain function before and after the acute exercise intervention (see Table 10). One study measured oxy-Hb, deoxy-Hb, and total Hb levels (Lambrick et al., 2016), three studies analyzed oxy-Hb and deoxy-Hb levels (Yanagisawa, 2010; Endo et al., 2013; Miyashiro et al., 2021), 12 studies measured oxy-Hb levels (Yanagisawa, 2010; Wen et al., 2015a,b; Jiang and Wang, 2016; Hashimoto et al., 2018; Kujach, 2018; Ji et al., 2019; Xu et al., 2019; Fujihara et al., 2021; Kim et al., 2021; Miyashiro et al., 2021; Zhang et al., 2021), and one study calculated the HBdiff (oxy-Hb minus deoxy-Hb) (Herold et al., 2019). After the acute intervention, eight articles explored changes in the Stroop task (Yanagisawa, 2010; Hyodo, 2012; Endo et al., 2013; Byun et al., 2014; Lambrick et al., 2016; Kujach, 2018; Ji et al., 2019; Fujihara et al., 2021)

TABLE 8 Exercise protocol used in the study design measurement during acute exercise intervention.

References	Duration (weeks)	Sessions/week	Session length (min)	Exercise type	Exercise intensity
Kurz et al. (2012)	NA	NA	20 min	Walking	Walking at 0.45 m/s
Endo et al. (2013)	NA	NA	15 min	Cycling	20%, 40%, and 60% of EX_{max}
Auger et al. (2016)	NA	NA	10 min	Cycling	A constant power representing 40% and 80% of their individual PPO
Kriel et al. (2016)	NA	NA	18 min	Cycling	Vigorous
Monroe et al. (2016)	NA	NA	18 min	Cycling	The SIC of each 30-s sprint was summed across the four sprints to calculate the total work performed (Work SIC) to match the CRC at 70 rpm
Kenville et al. (2017)	NA	NA	25 min	Barbell load	0% 1 RM, 20% 1 RM, and 40% 1 RM for a BS
Herold et al. (2019)	NA	NA	~14.7 min	Walking	NR
Carius et al. (2020)	NA	NA	12.6 min	Basketball slalom dribbling	Slow walking pace (0.87 ms^{-1}) and fast walking pace (1.75 ms^{-1})

EX_{max}, maximum voluntary exercise; PPO, peak power output; 1RM, 1 repetition maximum; SIC, sprint interval cycling; CRC, constant resistance cycling; NA, not applicable; NR, not reported.

and observed an increase in oxy-Hb levels in the left dorsolateral prefrontal cortex (DLPFC) (Yanagisawa, 2010; Hyodo, 2012; Byun et al., 2014; Kujach, 2018; Ji et al., 2019), bilateral PFC (Endo et al., 2013), right frontopolar area (FPA) (Hyodo, 2012), left FPA (Byun et al., 2014), middle PFC (Fujihara et al., 2021), right ventrolateral prefrontal cortex (VLPFC) (Ji et al., 2019), and supraorbital ridge of the dominant side (Lambrick et al., 2016). Meanwhile, three articles explored changes in flanker task performance and observed that exercise resulted in an increase in oxy-Hb levels in the bilateral DLPFC (Wen et al., 2015b), right DLPFC, right FPA (Wen et al., 2015a), and left FPA (Wen et al., 2015b). Similarly, three articles explored fluctuations in performance on the n-back task and noted a rise in oxy-Hb levels in the bilateral orbitofrontal cortex (OFC) (Miyashiro et al., 2021) and left DLPFC (Kim et al., 2021) and a concomitant decrease in oxy-Hb levels in the right DLPFC during moderate-intensity exercise interventions (Kim et al., 2021), whilst HBdiff was decreased in both regions (frontal and parietal) and hemispheres (left and right) at almost all time points (Stute et al., 2020). One study applied the table-setting task (Xu et al., 2019) and found elevated oxy-Hb levels in the PMC, SPL, inferior frontal gyrus (IFG), and rostral inferior parietal lobule (IPL). Another study used the Paced Auditory Serial Addition Test (Hashimoto et al., 2018) and revealed that oxy-Hb levels in the left PFC increased with different exercise intensities. Finally, one study used the implicit cognitive reappraisal task but did not identify specific regions of interest (ROIs) with changes in activity after exercise and reported elevated oxy-Hb levels in channels 11, 16, 21, 23, and 27 (Zhang et al., 2021).

3.6.2 Changes in brain functional activity during exercise interventions

Eight studies investigated hemodynamic changes during exercise interventions (see Table 11). Studies using a one-time exercise intervention measured cerebral blood flow during exercise (Endo et al., 2013). Six studies analyzed both oxy-Hb and deoxy-Hb levels (Kurz et al., 2012; Endo et al., 2013; Monroe et al., 2016; Kenville et al., 2017; Herold et al., 2019; Carius et al., 2020), one study exclusively analyzed oxy-Hb, deoxy-Hb, and total Hb levels (Auger et al., 2016), and one study detected deoxy-Hb levels (Kriel et al., 2016).

During the acute intervention, eight studies explored changes in various exercise conditions. Three studies explored changes in different cycling intensities and noted that oxy-Hb levels were increased in bilateral PFC during exercise at the intensity of 60% EX_{max} (Endo et al., 2013) and that under all three conditions of rest, 40%, and 80% intensity levels. The subjects at rest exhibited significantly lower extracerebral and cerebral deoxy-Hb levels compared to values measured at the 80% intensity level of exercise. Furthermore, another study detected significant alterations in the hemodynamic response in almost all channels, with increased oxy-Hb in the bilateral SPL and left PMC after short-distance channel regression (Kenville et al., 2017). At the same time, two studies explored the effects of different levels of exercise difficulties on cerebral hemodynamics. Four studies varied exercise intensity and found an increase in oxy-Hb levels in the bilateral PFC, bilateral M1, SSC, SMA, SPL, left IPL, and right PMC and a concurrent decrease in deoxy-Hb levels in the PFC. One study compared forward walking with backward walking and documented that oxy-Hb levels were higher in the SMA, PCG, and SPL, whereas deoxy-Hb levels were decreased in the SMA. Another study compared brain function in overground and treadmill conditions and observed an increase in oxy-Hb levels in the L-PFC, R-PFC, L-PMC, R-PMC, and B-SMA. One study explored the effect of active recovery on brain function and detected an increase in PFC activity. An earlier study employed BSDT to explore brain function under different basketball dribbling conditions and found that IL-M1 (deoxy-Hb levels) and contralateral PMC-SMA (deoxy-Hb levels) activities were decreased. One study investigated the effect of active recovery on brain function and evinced a significant interaction

TABLE 9 Changes of brain functional activity before and after long-term exercise interventions.

References	Study design 1. Task 2. Oxygenation index	Exercise intensity	Region of interest (ROI)	Results
Coetsee and Terblanche (2017)	1. Stroop task (naming condition) 2. oxy-Hb; deoxy-Hb; total Hb	Moderate-vigorous	Bilateral PFC	**Pre vs. Post** **Con group:**↑ left PFC (oxy-Hb) **MCT group:** ↑ left PFC (deoxy-Hb); ↓ left PFC (total Hb) **Con group vs. HIIT group, MCT group, and RT group**: **post:** ↓left PFC, significant difference (oxy-Hb)
	1. Stroop task (executive condition) 2. oxy-Hb; deoxy-Hb; total Hb		Bilateral PFC	**Pre vs. Post** **RT group:**↓ left PFC (oxy-Hb), left PFC (total Hb);↑ left PFC (deoxy-Hb) **MCT group:** ↑left PFC (deoxy-Hb); ↓left PFC (total Hb) **Con group vs. HIIT group and MCT group:** post: ↓left PFC, significant difference (oxy-Hb)
Chen et al. (2017)	1. Flanker task 2. oxy-Hb	NR	Bilateral PFC	**Pre vs. Post** **Baduanjin intervention group:**↑ left PFC
Yang et al. (2020)	1. Flanker task 2. oxy-Hb	Moderate	Frontal_Sup_L, Frontal_Inf_L, Frontal_Sup_R, rontal_Inf_R.	**Pre vs. Post** **TCC group:**↑ Frontal_Sup_L, Frontal_Inf_L
Lai et al. (2020)	1.1-back task 2. oxy-Hb	Moderate	Left PFC	**Pre vs. Post** **Tennis intervention group:** ↑ left PFC **Tennis intervention group** (Time segment 1, 2, 3): ↑ left PFC
Eggenberger et al. (2016)	1. Walking task 2. oxy-Hb	Moderate-vigorous	Bilateral PFC	**Pre vs. Post** **Preferred t1-7:** ↓ left PFC, right PFC **Fast walking:** ↓ left PFC **Preferred vs. Fast Walking Speeds t1-7** **Post:** ↓ right PFC **Preferred vs. Fast Walking Speeds t10-25** **Post** ↓ left PFC **Baseline vs. Experimental** **Preferred and Fast Walking Speeds t1-7, t10-25, t26-34,** ↓ left PFC, right PFC **Referred and Fast Walking Speeds t35-46:** ↑ left PFC, right PFC

pre, pretest; post, posttest; ex, exercise; con, control; HIIT, high-intensity interval training; MCT, moderate continuous training; RT, resistance training; t1–7, The first timeframe was set at the initiation and acceleration of walking from the first to the seventh s of walking (t1–7); t10–25, the second timeframe t10–25 represented "steady-state" walking; t26–34, the end of walking with deceleration; t35-46 was chosen to analyze the decrease in oxy-Hb levels below the baseline during the rest phases. ↑, compared with the former, the latter was higher than the former; ↓, compared with the former, the latter was lower than the latter. Nonsignificant changes in brain activity were not reported. Frontal_Sup_L: the frontal superior left area, Frontal_Inf_L: the frontal inferior left area, Frontal_Sup_R: the frontal superior right area, Frontal_Inf_R: the frontal inferior area right.

between condition and bout (every 30 seconds of high-intensity exercise is termed a bout) for mean changes in Δ[HHb] across bouts. Within conditions, significant increases in mean Δ[HHb] were observed across bouts, with values progressively increasing over time under HIITPASS and HIITACT conditions.

4 Discussion

4.1 Study design

Most task-related fNIRS studies aimed to detect activation before and after exercise. Notably, relatively few studies have been conducted on resting-state hemodynamics in this field; only one study examined changes in resting-state hemodynamics before and after exercise (Endo et al., 2013) and did not identify significant changes. Studies performing measurements before and after exercise interventions provide evidence of the effects of exercise on an individual's neural mechanisms.

A minority of the included studies explored cerebral blood flow during exercise interventions (Kurz et al., 2012; Endo et al., 2013; Auger et al., 2016; Kriel et al., 2016; Monroe et al., 2016; Kenville et al., 2017; Herold et al., 2019; Carius et al., 2020), all of which were task-designed and used exercise type as an exercise task. Nevertheless, it is worth mentioning that there are limited available exercise-type options, and they are relatively fixed. Most exercise tasks in those studies adopted the same design as cognitive tasks and controlled the duration of each trial to approximately 30 to 40 seconds (Kurz et al., 2012; Kenville et al., 2017; Carius et al., 2020). However, from a practical perspective, exercise tasks lasting <30 seconds are challenging to implement. Thus, fNIRS should be implemented to develop an exercise task that combines the characteristics of the movement with the feasibility of fNIRS, and suitable methods should be selected to analyze the fNIRS data. Notably, although fNIRS is not as sensitive to motion artifacts as functional MRI and EEG, the rapid motion of any vibrating fiber may lead to substantial changes in the hemoglobin signal. Therefore, when designing exercise tasks, frequent and intense head movements should be avoided.

TABLE 10 Changes of brain functional activity before and after acute exercise interventions.

References	Study design 1. Task 2. Oxygenation index	Exercise intensity	Region of interest (ROI)	Results
Yanagisawa (2010)	1. Stroop task 2. oxy-Hb	Moderate: 50% of VO_2 peak	Anterior VLPFC; left DLPFC; left FPA; right DLPFC	**Pre vs. Post** **ex group and con group:** ↑ left DLPFC
Hyodo (2012)	1. Stroop task 2. oxy-Hb; deoxy-Hb	Moderate: 50% of VO_2 peak	Bilateral DLPFC, VLPFC, FPA	**Con group vs. ex group** **Pre:** ↑ bilateral DLPFC, VLPFC, FPA (oxy-Hb) ↑ DLPFC (deoxy-Hb) **Post:** ↑ right FPA (oxy-Hb)
Endo et al. (2013)	1. Stroop task 2. oxy-Hb; deoxy-Hb	20%, 40%, and 60% of EX_{max}	Bilateral PFC	**Baseline vs. during Stroop 1 (before exercise)** **Without exercise:** ↑ bilateral PFC (oxy-Hb) **20% EX_{max}, 40% EX_{max}, 60% EX_{max}:** ↑ bilateral PFC (oxy-Hb) **Baseline vs. during Stroop 2 (after exercise)** **40% EX_{max}:** ↑ bilateral PFC (oxy-Hb) **Pre vs. Post** **40% EX_{max}:** ↑ bilateral PFC (oxy-Hb) **60% EX_{max}:** ↑ bilateral PFC (oxy-Hb) **Without exercise vs. 40% EX_{max}** **after exercise:** ↑ bilateral PFC (oxy-Hb) **Without exercise vs. 60% EX_{max}** **after exercise:** ↑ bilateral PFC (oxy-Hb)
Kujach (2018)	1. Stroop task 2. oxy-Hb	60% of MAP	Bilateral DLPFC, VLPFC, FPA	**Resting control vs. HIE** **Post:** ↑ left DLPFC **Pre vs. Post** **HIE:** ↑ left DLPFC **resting control:** ↑ right VLPFC
Byun et al. (2014)	1. Stroop task 2. oxy-Hb; deoxy-Hb	Light: 30% of VO_2 peak	Bilateral DLPFC, VLPFC, FPA	**Con group vs. ex group** **Post:** ↑ left DLPFC (oxy-Hb) **Post:** ↑ left FPA (oxy-Hb)
Lambrick et al. (2016)	1. Stroop task 2. oxy-Hb; deoxy-Hb; total Hb	Submaximal	The supraorbital ridge of the participant's dominant side	**Pre vs. 1 min_post** **CONT and INT:** ↑ supraorbital ridge of the dominant side (oxy-Hb), supraorbital ridge of the dominant side (total Hb) **1 min_post vs. 15 min_post** **CONT and INT:** ↓ supraorbital ridge of the dominant side (oxy-Hb), supraorbital ridge of the dominant side (Total-Hb) **Pre vs. 15 min_post** **CONT and INT:** ↑ supraorbital ridge of the dominant side (oxy-Hb), supraorbital ridge of the dominant side (total Hb) **Pre vs. 30 min_post** **CONT and INT:** ↑ supraorbital ridge of the dominant side (oxy-Hb), supraorbital ridge of the dominant side (total Hb) **1 min_post vs. 30 min_post** **CONT) and INT:** ↓supraorbital ridge of the dominant side (deoxy-Hb)
Ji et al. (2019)	1. Stroop task (naming condition) 2. oxy-Hb	65% of heart rate	Bilateral VLPFC, and DLPFC	**RC condition vs. PE condition** ↑ right VLPFC
	1. Stroop task (executive conditions) 2. oxy-Hb		Bilateral VLPFC, and DLPFC	**RC condition vs. PE condition** ↑ left DLPFC, right DLPFC **CE condition vs. PE condition** ↑ right DLPFC
Fujihara et al. (2021)	1. Stroop task 2. oxy-Hb	Moderate: HRR of 50%	The left, middle, and right PFC	**Young adult group vs. older adult group** **Post:**↑ M-PFC
Wen et al. (2015a)	1. Flanker task 2. oxy-Hb	Moderate: 66% of HR_{max}	Bilateral DLFPC, FPA, VLFPC	**Con group vs. ex group** **Post:**↑ left PA
Wen et al. (2015b)	1. fFanker task 2. oxy-Hb	Moderate: 66% of HR_{max}	Bilateral DLFPC, FPA, VLFPC	**Con group vs. ex group** **Post:**↑ right DLPFC, right FPA
Jiang and Wang (2016)	1. Flanker task 2. oxy-Hb	Moderate intensity	Bilateral frontal area	**Pre vs. Post** **20 min of moderate-intensity aerobic ex group:** ↑ Bilateral frontal area

(Continued)

TABLE 10 (Continued)

References	Study design 1. Task 2. Oxygenation index	Exercise intensity	Region of interest (ROI)	Results
Miyashiro et al. (2021)	1. 2-back task 2. oxy-Hb	Not reported	DLPFC and OFC, Frontopolar prefrontalCortex	**Meditation-control pair and the exercise-control pair vs. the meditation-exercise** **Post:**↑ right and left OFC
Stute et al. (2020)	1. N-back task 2. HBdiff	Moderate: 50% of VO_2 peak	Bilateral DLPFC and VLPFC, IPL and SPL	**Con group vs. exp group** ↓ both regions (frontal and parietal) and hemispheres (left and right) at almost all time points
Kim et al. (2021)	1. 2-back task 2. oxy-Hb	Moderate-vigorous: 65% of VO_2 peak-vigorous 80% of VO_{2max}	Bilateral DLPFC, OFC	**Pre vs. Post** **Moderate Intensity:** ↓ right DLPFC **High Intensity:** ↑ left DLPFC
Hashimoto et al. (2018)	1. Paced auditory serial addition test 2. oxy-Hb	40% and 60% of the peak oxygen	Left frontal and temporal areas	**40% VO_2 peak and rest vs. 60% VO_2 peak** **Post:** ↑ left PFC
Xu et al. (2019)	1. Table-setting task 2. oxy-Hb	Moderate intensity (65% of VO_2 peak)	Left IFG, PMC, rostral IPL, and SPL	**Activation Pattern Assessed Using Channel-Based Group Analysis** **exec and obs components in the post-exp condition:** Activated in all channels (left IFG, PMC, SPL, rostral IPL) **Post-exp-obs condition:** Activated in channels 2, 6, 9, 11, and 13 (left IFG, PMC, and SPL) **Post-exp-obs components in the no-exercise conditions (post-ctrl, pre-exp, and pre-ctrl conditions):** Channels 3, 4, 5, 6, 7, 9, 11, 12, 13, and 14 (left IFG, PMC, rostral IPL, and SPL). According to the spatial map of the 23 subjects in the pre-exp condition and pre-ctrl condition, also found that channels 2, 3, 4, 5, 6, 7, 9, 10, and 13 (IFG, PMC, and rostral IPL), were activated during both action execution and observation. **Activation pattern assessed using ROI-based group analysis** **Action observation and execution in the post-exp condition:** Activated in left IFG, PMC, rostral IPL, and SPL, except SPL during action execution. **Action observation and execution in all the no-exercise conditions:** the IFG, PMC, rostral IPL, and SPL were significantly activated. Only the activation of the SPL during action execution in the post-ctrl condition and the rostral IPL during action execution in the post-ctrl condition were not significantly activated **ROI-based group analysis for the effect of moderate-intensity exercise** **In action observation, during the post-sessions (exp/ctrl)**, there were significant differences between the exp and ctrl conditions in all four ROIs. **In action execution, post-ctrl vs. post-exp:** ↑left IFG
Zhang et al. (2021)	1. Implicit cognitive reappraisal task 2. oxy-Hb	Moderate: 60%−69% of HR_{max}	NR	**Con group vs. ex group** ↓ channels 1, 25 **Baseline vs. Implicit cognitive reappraisal task** ↓ channels 3 and 8 ↑ channels 11, 16, 21, 23, and 27 **Pre vs. Post** **ex group:** ↑ channels 7 and 13

NR, not reported; pre, pretest; post, posttest; ex, exercise; con, control; exp, experimental; EX_{max}, maximum voluntary exercise; HIE, high-intensity intermittent exercise; CONT, an acute bout of continuous exercise; INT, an acute bout of intermittent exercise; PE, physical exercise; CE, cognitive exercise; exec, action execution; obsc, action observation.↑, compared with the former, the latter was higher than the former; ↓, compared with the former, the latter was lower than the former. Nonsignificant changes in brain activity were not reported.

In addition, numerous studies have explored the effects of exercise interventions on behavioral and physiological indicators before, during, and after exercise. Most of the behavioral indicators are related to cognition (Yanagisawa, 2010; Hyodo, 2012; Endo et al., 2013; Byun et al., 2014; Wen et al., 2015a,b; Jiang and Wang, 2016; Lambrick et al., 2016; Chen et al., 2017; Coetsee and Terblanche, 2017; Hashimoto et al., 2018; Kujach, 2018; Ji et al., 2019; Xu et al., 2019; Lai et al., 2020; Yang et al., 2020; Fujihara et al., 2021; Kim et al., 2021; Miyashiro et al., 2021) and emotion (Zhang et al., 2021), while the primary physiological indicator is heart rate, which is closely related to exercise. However, studies examining the relationship between functional brain activity and the three behavioral and physiological domains were scarce.

Future studies can combine real-time changes in cerebral blood flow before, during, and after exercise in a more in-depth and comprehensive manner to establish the relationship

TABLE 11 Changes of brain functional activity during acute exercise interventions.

References	Study design 1. Task 2. Oxygenation index	Exercise intensity	Region of interest (ROI)	Results
Kurz et al. (2012)	1. Walking task 2. oxy-Hb; deoxy-Hb	Walking at 0.45 m/s	SMA, SPL, precentral gyrus (PCG), postcentral gyrus (POCG)	**Forwards vs. backward walking** ↑SMA, PCG, SPL (oxy-Hb), ↓SMA (deoxy-Hb)
Endo et al. (2013)	1. Cycling taskv 2. oxy-Hb; deoxy-Hb	20%, 40%, and 60% of EX_{max}	Bilateral PFC	**Baseline vs. during cycling task** **60% EX_{max}:** ↑ bilateral PFC (oxy-Hb) **Without exercise vs. 60% EX_{max} :** ↑ bilateral PFC (oxy-Hb)
Auger et al. (2016)	1. Cycling task 2. oxy-Hb; deoxy-Hb; total-Hb	A constant power representing 40% and 80% of their individual PPO	PFC	**Rest vs. 80%PPO** ↑ PFC (deoxy-Hb)
Kriel et al. (2016)	1. Cycling task 2. Δdeoxy-Hb	Vigorous	PFC	**HIITPASS and HIITACT and REC** For the mean Δdeoxy-Hb for each bout, differences were found between conditions for Bout 2, Bout 3, and Bout 4; however, no significant differences in PFC were found between the two HIIT conditions. For the mean Δdeoxy-Hb within conditions, there were significant increases across bouts, with values increasing over time in the HIITPASS and HIITACT conditions.
Monroe et al. (2016)	1. Cycling task 2. Oxy-Hb; Deoxy-Hb	The SIC of each 30-s sprint was summed across the four sprints to calculate the total work performed (Work SIC) to match the CRC at 70 rpm	DLPFC	**Baseline vs. exercise** ↑DLPFC(Oxy-Hb) **CRC vs. SIC** ↑DLPFC(Oxy-Hb) **During SIC:** ↑DLPFC (Deoxy-Hb)
Kenville et al. (2017)	1. Barbell squat task 2. oxy-Hb; deoxy-Hb	0% 1RM, 20% 1RM, and 40% 1RM for a BS	M1, PMC, SMA, IPL, SPL, and brain areas that are related to auditory, frontal, and visual areas	**Alterations in the haemodynamic response within sensorimotor areas:** **L0% vs. L20%** ↑ bilateral M1, right PMC, SMA, left IPL, right SPL (oxy-Hb) **L0% vs. L40%** ↑ significant alterations in the hemodynamic response in all channels, except channels 12, 18, and 22 (oxy-Hb) ↑ left SSC and IPL (deoxy-Hb) **L20% vs. L40%** ↑ significant alterations in the hemodynamic response in all channels, except channels 4, 9, 12, and 18 (oxy-Hb) **BL vs. BS during L0%** ↑ bilateral M1, SSC, SMA, SPL, left IPL, and right PMC (oxy-Hb) **BL vs. BS during L20% and L40%** ↑ bilateral M1, SSC, SMA, SPL, left IPL, and right PMC (oxy-Hb)
				Alterations in the haemodynamic response outside sensorimotor areas: **L0% vs. L20%** ↑ bilateral M1, IPL, SMA, and PMC (oxy-Hb) **L0% vs. L40%** ↑ significant alterations in the hemodynamic response in all channels, except channels 1, 12, and 13 (oxy-Hb) **L20% vs. L40%** ↑ significant alterations in the hemodynamic response in all channels, except channels 1 and 13 (Oxy-Hb) **BL vs. BS during L0%, L20% and L40%** significant alterations in the hemodynamic response in terms of HbO_2 levels in all fNIRS channels, except channels 1 and 13 (oxy-Hb)

(Continued)

TABLE 11 (Continued)

References	Study design 1. Task 2. Oxygenation index	Exercise intensity	Region of interest (ROI)	Results
				Alterations in the haemodynamic response within sensorimotor areas after Short Distance Channel Regression: **L0% vs. L40%** ↑ bilateral SPL (oxy-Hb) **L20% vs. L40%** ↑ bilateral SPL (oxy-Hb) ↑ left PMC (deoxy-Hb) **BL vs. L40%** ↑ left PMC (deoxy-Hb)
Herold et al. (2019)	1. Walking task 2. oxy-Hb; deoxy-Hb	NR	Bilateral PFC, PMC, SMA	**During walking** ↑left PFC, right PFC, left PMC (oxy-Hb) **Overground vs. treadmill walking** ↑ left PFC, right PFC, left PMC, right PMC, bilateral SMA (oxy-Hb)
Carius et al. (2020)	1. Basketball dribbling task 2. oxy-Hb; deoxy-Hb	Slow walking pace (0.87 ms^{-1}) and fast walking pace (1.75 ms^{-1})	Bilateral PMC-SMA, SAC, M1, IPC	**AH_{slow} vs. DH_{slow}** ↓ IL-M1 (deoxy-Hb) **slow vs. fast** **dominant right hand (DH):** ↓ contralateral PMC-SMA (deoxy-Hb)

PMC-SMA, premotor and supplementary motor cortex; SAC, somatosensory association cortex; SSC, primary somatosensory cortex; IL-M1, ipsilateral M1; pre, pretest; post, posttest; Bout (every 30 seconds of high-intensity exercise is called a bout); L0%, 0% 1 RM (repetition maximum); EX_{max}, maximum voluntary exercise; BS, barbell squat; BL, baseline values; HIITPASS, HIIT with passive recovery periods between four bouts; HIITACT, HIIT with active recovery periods between four bouts; REC, HIITACT with four HIIT bouts replaced with passive periods; FH, the prefrontal cerebral cortex; AH, alternating hands; DH, dominant right hand; AH_{slow}, slow alternating hands; DH_{slow}, slow dominant right hand; SIC, sprint interval cycling; CRC, constant resistance cycling. ↑, compared with the former, the latter was higher than the former; ↓, compared with the former, the latter was lower than the former. Nonsignificant changes in brain activity were not reported.

between exercise and brain plasticity. In addition, the benefits and mechanisms of exercise interventions on the health of individuals should be explored from multiple perspectives, combining behavioral, physiological, and cerebral assessments.

4.2 fNIRS equipment and parameter settings

The included studies measured cerebral hemodynamics before and after exercise employing a relatively large number of channels. In studies designed to measure cerebral hemodynamics during exercise, the number of channels was relatively low, with the maximum number of channels in the included studies being 24 (Kurz et al., 2012). Attributed to its task specificity, studies that measured cerebral hemodynamics during exercise intervention all used portable devices.

Besides, the selection of ROIs also varied with the study design. Studies designed to measure cerebral hemodynamic changes before and after exercise activity explored the effects of exercise on cognition, with the prefrontal lobe being a key region. In contrast, studies designed to measure cerebral hemodynamics during exercise intervention targeted more locations in the sensorimotor areas (Endo et al., 2013; Auger et al., 2016; Kriel et al., 2016; Monroe et al., 2016; Kenville et al., 2017; Herold et al., 2019; Carius et al., 2020) or other brain areas.

Several exercise processes require a combination of physical activity and cognitive engagement. Hence, it is critical not only to place channels in the motor cortex but also to consider its impact on the prefrontal cortex. Advances in technology have led to an increase in the number of channels for portable devices, thus enabling the measurement of cerebral hemodynamics in multiple ROIs. Given the potential for signal quality issues for measurement during exercise, it is recommended to establish a short-distance channel and instruct participants to minimize head movement during the testing procedure.

4.3 Exercise intervention

Among studies designed to measure fluctuations in cerebral hemodynamics before and after exercise interventions, both long-term exercise interventions and short-term exercise interventions were available. Conversely, few long-term interventions were investigated, most likely due to challenges in conducting the assessment over extended periods. Exercise protocols for long-term interventions were flexible, featuring a diverse range of exercise protocols without overlap between studies and a uniform exercise frequency of 2 to 3 sessions per week (Eggenberger et al., 2016; Coetsee and Terblanche, 2017; Lai et al., 2020; Yang et al., 2020). Only one study applied an exercise frequency of 5 times per week (Chen et al., 2017). Similarly, exercise intensity and duration were relatively consistent, with all being of moderate intensity (Eggenberger et al., 2016; Chen et al., 2017; Coetsee and Terblanche, 2017; Lai et al., 2020; Yang et al., 2020) and each session lasting over 30 min (Chen et al., 2017; Lai et al., 2020; Yang et al., 2020).

At present, studies focusing on the effects of long-term exercise interventions on brain functional activity using fNIRS predominantly aim to detect changes in cognitive-task-related brain functional activity before and after exercise interventions but do not involve the detection of brain functional activity during the exercise task. In studies designed to measure changes in cerebral

hemodynamics during acute exercise intervention, all exercise types were relatively easy to implement in the laboratory, requiring minimal activity space and offering flexibility, such as cycling and running. These factors may account for the fact that only three exercise programs were used. In the future, it might be possible to further explore changes in cerebral blood flow during other commonly practiced exercises that involve minimal head movement, such as Tai Chi Chuan and yoga.

The length of the single exercise session, on the other hand, did not exceed 30 min (Yanagisawa, 2010; Hyodo, 2012; Endo et al., 2013; Wen et al., 2015b; Lambrick et al., 2016; Coetsee and Terblanche, 2017; Hashimoto et al., 2018; Kujach, 2018; Ji et al., 2019; Xu et al., 2019; Stute et al., 2020; Fujihara et al., 2021; Miyashiro et al., 2021; Zhang et al., 2021), with the majority lasting for only 10 min (Yanagisawa, 2010; Hyodo, 2012; Byun et al., 2014; Wen et al., 2015a,b; Kujach, 2018; Kim et al., 2021). Consequently, changes in cerebral hemodynamics during prolonged exercise sessions remain enigmatic.

To explore hemodynamic changes during exercise, future studies may extend the duration of exercise sessions to 30 min to determine the effect of long exercise session durations on cerebral cortical blood flow.

4.4 Effect of exercise on cerebral cortical blood flow changes

In the exploration of task designs, the activation of hemoglobin was frequently discussed, with most studies using oxygenated hemoglobin as an indicator to evaluate brain activation (Yanagisawa, 2010; Wen et al., 2015a,b; Eggenberger et al., 2016; Jiang and Wang, 2016; Chen et al., 2017; Hashimoto et al., 2018; Kujach, 2018; Ji et al., 2019; Xu et al., 2019; Lai et al., 2020; Yang et al., 2020; Fujihara et al., 2021; Kim et al., 2021; Miyashiro et al., 2021; Zhang et al., 2021).

Achieving consistent results with long-term exercise interventions was challenging due to the diversity of the tasks performed. Interestingly, although the adopted tasks were different, most studies identified changes in the left PFC during inhibitory control tasks (Chen et al., 2017; Coetsee and Terblanche, 2017; Yang et al., 2020). In general, higher hemoglobin activity was observed in the cortical region after the cessation of one-time exercise compared with baseline cortical activity, similar to changes in cortical activation during cognitive tasks. Besides, alterations in the prefrontal cortex and motor cortex were observed during one-time exercise sessions.

Considering that fNIRS signals are significantly impacted by physiological artifacts of the system (Caldwell et al., 2016), the influence of exercise on the cerebral cortex is assumed to mainly arise from physiological confounders after exercise. According to the findings of a methodological investigation, fNIRS signals are affected by systemic physiological artifacts for up to approximately 8 min after stopping cycling for 10 min (Byun et al., 2014). Therefore, the results of studies that performed fNIRS tests after exercise ($< \sim$8 min) should consider the effect of physiological confounds. However, a reasonable hypothesis suggests that some fNIRS signals observed post-exercise originated from neuronal activity. The entire prefrontal cortex should be impacted by systemic physiological changes if the greater cortical activity observed after exercise is primarily a result of systemic physiological artifacts. The fact that greater cortical activity was observed only in specific regions of the prefrontal cortex rather than the entire prefrontal cortex is significant because it supports the hypothesis that the fNIRS signals were at least partially derived from neuronal activity. The positive neurobehavioural correlation between cognitive ability and cortical activity in various regions of the prefrontal cortex further supports this notion.

The review indicated that exercise interventions alter oxygenated hemoglobin levels in the prefrontal cortex and motor cortex, which are associated with improvements in higher cognitive functions such as inhibitory control and working memory. These findings further support the hypothesis that exercise promotes changes in the prefrontal and motor cortex, which may be key regions for exercise to promote brain health. To deepen our understanding of the fundamental processes by which exercise modifies the brain, future studies should concentrate on alterations in cerebral blood flow during physical exertion.

4.5 Limitations

Nevertheless, this review has limitations that merit acknowledgment. To begin, this review only explored studies involving exercise durations over 10 min, but future studies should expand their scope to explore durations of exercise that contribute to brain health. The primary purpose of this review was to conduct subgroup analysis based on different research designs (measuring fNIRS before, during, and after exercise intervention). Future analyses should aim to stratify group populations or exercise types into different subgroups. The systematic search, dual-author screening, eligibility assessment, and quality appraisal were employed to minimize biased selection of studies, whilst dual-author auditors ensured a thorough search. However, this review was not preregistered and not available for inspection by other researchers, and future reviews can be registered with PROSPERO in advance. A meta-analysis was not conducted due to the high degree of heterogeneity across studies and the low number of studies examining each outcome.

5 Conclusions and future perspectives

Overall, fNIRS is a promising neuroimaging tool that provides insights into changes in exercise-induced hemodynamics before, during, and after exercise interventions.

Studies using fNIRS to measure cerebral blood flow before and after exercise interventions have predominantly incorporated relatively few long-term interventions and predominantly featured short-term interventions. These studies have mainly focused on the effects of exercise on brain activity during cognitive tasks such as inhibitory control. However, the study equipment and study intervention protocols were less stringent and relatively more flexible. All studies on this topic have focused on changes in oxygenation in the prefrontal area of interest.

Few of the included studies measured hemodynamic changes during exercise, with all of them employing short-term interventions, relatively fixed exercise intervention protocols, minimal head motion, and short exercise durations. Of note, the exercises were easy to execute in the laboratory setting, and the fNIRS systems had a limited number of channels.

Exercise protocols for long-term interventions encompassed a wide range of exercise protocols and an exercise frequency ranging from 2 to 3 sessions per week. The exercise intensity was moderate, and the duration of a single session exceeded 30 min. Exercise types for long-term interventions were those that necessitated minimal space and were flexible, such as cycling and running. The duration of a single exercise session did not exceed 30 min, with most sessions lasting for 10 min. Finally, exercise intensities were maintained at a moderate level.

The results of this review signaled that exercise interventions alter oxygenated hemoglobin levels in the prefrontal cortex and motor cortex, which are associated with improvements in higher cognitive functions such as inhibitory control and working memory. The frontal cortex and motor cortex may be key regions for exercise to promote brain health. Future research could further focus on changes in cerebral blood flow during exercise to better understand the underlying mechanisms by which exercise influences brain function.

Moreover, due to its insensitivity to motion, the fNIRS is ideally suited for research during exercise interventions. It is paramount to thoroughly scrutinize the study design, fNIRS device parameters, and exercise protocols. Cerebral blood flow during exercise intervention represents a future research direction that has the potential both to identify cortical hemodynamic changes and elucidate the relationship between exercise and cognition.

Future studies can combine two study designs that measure blood flow before, during, and after exercise in a more in-depth and comprehensive manner. Additionally, they can utilize multiple indicators, such as functional connectivity, to accurately reflect the effects of exercise on brain functional networks.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

Q-QS: Writing – original draft, Writing – review & editing. J-MH: Writing – review & editing. TX: Writing – review & editing. J-YZ: Writing – review & editing. D-LW: Writing – review & editing. YY: Writing – review & editing. RL: Writing – review & editing. Z-LX: Writing – review & editing. H-cY: Supervision, Writing – review & editing, Funding acquisition, Project administration. LC: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Themes and trends in marathon performance research: a comprehensive bibliometric analysis from 2009 to 2023

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Background: When marathon runners break the 2-h barrier at the finishing line, it attracts global attention. This study is aimed to conduct a bibliometric analysis of publications in the field of marathon running, analyze relevant research contributors, and visualize the historical trends of marathon performance research over the past 15 years.

Methods: On 8 December 2023, we extracted high-quality publication data from the Web of Science Core Collection spanning from 1 January 2009 to 30 November 2023. We conducted bibliometric analysis and research history visualization using the R language packages biblioshiny, VOSviewer, and CiteSpace.

Results: A total of 1,057 studies were published by 3,947 authors from 1,566 institutions across 63 countries/regions. USA has the highest publication and citation volume, while, the University of Zurich being the most prolific research institution. Keywords analysis revealed several hotspots in marathon research over the past 3 years: (1) physiology of the elite marathon runners, (2) elite marathon training intensity and pacing strategies, (3) nutritional strategies for elite marathon runners, (4) age and sex differences in marathon performance, (5) recovery of inflammatory response and muscle damage.

Conclusion: This study presents the first comprehensive bibliometric analysis of marathon performance research over the past 15 years. It unveils the key contributors to marathon performance research, visually represents the historical developments in the field, and highlights the recent topical frontiers. The findings of this study will guide future research by identifying potential hotspots and frontiers.

KEYWORDS

marathon, performance, Bibliometrics, athletes, review

Abbreviations: CK, creatine kinase; EIMD, exercise-induced muscle damage; IAAF, the International Association of Athletics Federations; WOSCC, Web of Science Core Collection; peakVO2, maximum oxygen uptake; cTnT, cardiac troponin T; NT-proBNP, N-terminal pro-brain natriuretic peptide; SCA, sudden cardiac arrest; SCD, sudden cardiac deaths; LDH, lactate dehydrogenase.

Background

When marathon runners break world records of 2-h barrier, it will likely attract significant global attention (Joyner et al., 2011; Hoogkamer et al., 2017). As reported by the International Association of Athletics Federations (IAAF), Kelvin Kiptum and Tigst Assefa set new world records with completion times of 02:00:35 and 02:11:53, respectively, in 2023 (Competition Performance Rankings, 2024). These exceptional and outstanding achievements in this field directing renewed interest in improving marathon performance.

Previous research established that peak oxygen uptake, anaerobic threshold velocity, and running economy play pivotal roles in endurance performance (Joyner and Coyle, 2008; van der Zwaard et al., 2021) as well as marathon performance (Jones et al., 2021; Haugen et al., 2022). Elite marathon runners are highly skilled and well-conditioned athletes characterized by exceptional running economy and observed with cardiovascular and cardiopulmonary capacity. Historically, the majority of marathon performance investigations were conducted within topics of physiological bio-markers associated with these core metrics, including anthropometry, heart size, hemoglobin content, and capillary density among top marathon runners (Billat et al., 2001; Joyner and Coyle, 2008). Recent research has delved deeper, revealing that 35 years old of age marks the pinnacle of endurance performance for proficient marathon runners (Lepers et al., 2020). Additionally, high altitude training and high-intensity exercise lead to an increase in endomembrane folds and enhanced mitochondrial efficiency in the lower extremity muscles of elite endurance athletes (King, 2021). Furthermore, the discovery of veillonella, a microorganism leveraging lactate metabolism to bolster performance, has provided insights at the microscopic level (Scheiman et al., 2019). Studies exploring the interaction between external environment factors and marathon performance particularly performance over longer distances are increasing. Notably, in August 2023, physicists unveiled that a grouping of seven pacers arranged in a three-swordfish formation could reduce air resistance for the targeted pacer by approximately 60%, thus enhancing performance (Physicists find a way to set a new marathon record, 2023). Advances in footwear technology aimed at enhancing the running economy have also garnered significant attention in recent years (Muniz-Pardos et al., 2021). Investigations into the impact of weather conditions have revealed that elite runners accelerate as humidity and daylight hours increase (Weiss et al., 2022). The factors influencing marathon performance are intricate and multifaceted, underscoring the criticality of staying abreast of the latest information for the scientific training of marathon runners. Researchers must identify prevailing hot research topics and future trends, and given the proliferation of marathon performance research, the adoption of novel approaches to literature analysis has become indispensable.

Bibliometrics, a methodology that qualitatively and quantitatively analyzes publications in a specific field, allows for the identification of influential countries, authors, institutions, journals, and publications (Donthu et al., 2021). Furthermore, it enables the analysis of the knowledge structure within the field and the exploration of cutting-edge research hotspots and trends (Mukherjee et al., 2022). In the realm of kinesiology, bibliometric studies are limited, and no comprehensive analysis of marathon has been conducted.

This study employs bibliometric methods to comprehensively analyze and summarize the most influential countries, institutions, authors, publications, and keywords in marathon performance literature from the past 15 years, identifying the development of hotspots and trends in marathon performance research.

Materials and methods

Data source and search strategy

In this study, we mainly searched three high-quality citation databases, SCI-Expanded, SSCI, and A&HCI, in the Web of Science Core Collection (WOSCC) database platform, the search time is up to 2023-11-30. The specific search strategy is illustrated in Figure 1A. Data inclusion and exclusion criteria were as follows:

(1) The search interval was from 2009-01-01 to 2023-11-30.
(2) The search strategy was "TS=(marathon) AND (TS=(performance) OR TS=(pace) OR TS=(finish time) OR TS=(speed) OR TS=(velocity))";
(3) The search type was "article" and "review";
(4) The search language was "English".

Based on our search results, we identified 1,347 papers. Upon reviewing the titles and abstracts of these papers, we excluded 290 that were deemed irrelevant to our research. Finally, we obtained a total of 1,057 documents comprising 988 articles and 69 reviews.

Data analysis and visualization

Data analysis and visualization were conducted using various tools and techniques. The R language package biblioshiny, VOSviewer, and CiteSpace were employed to investigate various facets of the research.

Specifically, the biblioshiny tool served as the primary instrument for the comprehensive summarization and organization of data pertaining to marathon performance research. This encompassed the analysis of annual publications, predominant countries, institutions, and individual authors, along with the top 10 co-cited references. Additionally, biblioshiny facilitated the synthesis of information on the top 30 most frequently occurring keywords and their distribution across the years 2009–2023. It further aided in examining the thematic evolution of keywords in the year 2023. VOSviewer played a pivotal role in visualizing collaboration patterns among countries, institutions, and authors. It also facilitated the depiction of co-occurrence networks pertaining to keywords. Meanwhile, CiteSpace was predominantly utilized for identifying research frontiers through the application of the citation burst function, unveiling influential literature and keywords.

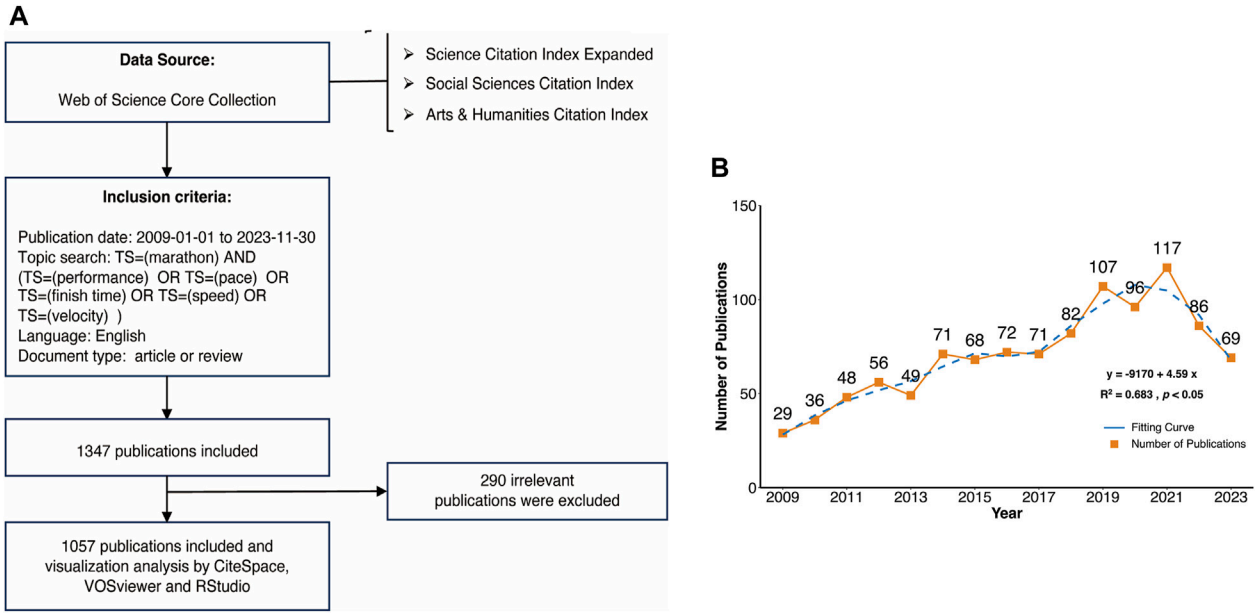


FIGURE 1
(A) The data collection and search strategy. **(B)** Annual publications in marathon performance research during 2009-2023.

Results

Number of publications over the years

The annual literature production reflects the dynamics of research development. Figure 1B shows that the overall marathon performance research has increased steadily at an annual growth rate of 6.39%. The number of publications per year was below 70 until 2014, and then rose sharply after 2018, reaching a peak of 117 in 2021. However, the fitting of the variables 'publications' and 'year' using the loess function ($R^2 = 0.683$, $p < 0.05$) revealed a slight decrease in research output in this field over the last 5 years.

Countries/regions distribution in marathon performance

The Marathon Performance Study involved researchers from 63 countries/regions. Supplementary Table S1 displays the 10 countries with the most publications, with the United States leading (652 publications, 5,133 citations), followed by Switzerland (423 publications, 3,122 citations) and Spain (335 publications, 1,208 citations). The co-authorship analysis of countries/regions reveals international collaborations.Supplementary Figure S1 uses VOSviewer's built-in function co-authorship analysis to analyze the collaboration among 28 countries/regions with over 10 publications. Co-authorship analysis can unveil the strength and level of connection among various entities by examining the frequency and patterns of collaboration among countries, institutions, and authors who have jointly authored papers (Donthu et al., 2021). The results reveal a division of the cooperation network into four distinct color clusters, with the red and green clusters being the largest and centered on the United States and Switzerland, respectively. Specifically, the United States primarily collaborates with countries/regions including England and Australia, whereas Switzerland's main collaborators are countries/regions such as France and Greece.

Institutions distribution in marathon performance

As depicted in Supplementary Figure S2, a total of 1,566 institutions have engaged in marathon performance issuance, with 36 institutions producing more than 10 articles. Among these, the University of Zurich in Switzerland emerges as the leading contributor, generating 174 articles, followed by the University of West Attica with 30 articles. Co-authorship analysis of 119 institutions, each with a publication frequency exceeding 5, was conducted using VOSviewer. The findings depicted in Supplementary Figure S3 demonstrate that the collaborative network is segmented into eight distinct color clusters. Notably, the largest and most interconnected cluster, represented by purple, is centered on the University of Zurich. This cluster exhibits rich collaborations and maintains closely-knit relationships with several institutions, such as the University of Western Attica and the University of Malaga.

Authors distribution in marathon performance

The contribution of scholars with a high volume of publications and citation frequency is crucial for the advancement of the field of marathons. Supplementary Table S2 displays the top 10 authors in the field of marathon performance based on publication volume, along with their corresponding H-index and citation frequency. The



FIGURE 2
(A) The top 30 occurrences keywords word clouds. **(B)** The top 30 most occurrences keywords distribution over 2009-2023.

H-index is a crucial metric for evaluating the academic impact of scholars. Higher values signify a more significant impact, calculated mainly using all of an author's publications. Over the past 15 years, marathon performance research has been primarily led by 3,947 authors, with Knechtle B (171 articles) emerging as the top scholar in terms of publication count, H-index, and citation frequency. VOSviewer was employed to analyze co-authorship patterns of 89 authors with a frequency greater than 5. Supplementary Figure S4 presents the results, depicting a collaboration network divided into eight clusters represented by different colors, with the largest collaboration cluster in green consisting of 10 authors centered on Knechtle B, Rosemann T. Among these collaborations, Knechtle B has the highest number of partners, totaling 29.

The top 10 most co-cited references in marathon performance

Co-citation analysis is a scientific mapping technique that posits publications frequently cited together as thematically similar. This method is effective for identifying the most influential publications within a dataset (Cheuvront et al., 2005; Knechtle et al., 2020). Supplementary Table S3 presents the top 10 most co-cited references in the field. The most frequently cited reference, with a total of 67 citations in our dataset, is Lepers R et al., 's 2012 publication in the journal of AGE. This study explored that master runners (men aged ≥65 years and women aged ≥45 years) may not yet have reached the limits of marathon performance (Lepers and Cattagni, 2012). A reference by Matthew, comprising 60 citations in our dataset, indicates that marathon running tends to decelerate in warm weather (Ely et al., 2007). The remaining references predominantly examine various aspects of marathon performance, including the impact of factors such as body composition, training techniques, pacing strategies, gender differences, and temperature regulation. Altmetric attention scores reflect research impact, social influence, and dissemination effectiveness (van der Zwaard et al., 2020). Among the top 10 most co-cited references, the American College of Sports Medicine's studies on exercise and fluid replacement, gender differences in the age of elite marathon runners, and the impact of weather on marathon events demonstrate significant influence and academic attention within both the public and scholarly communities.

The top 30 most occurrences keywords and their distribution over 2009-2023

Keyword frequency serves as an indicator of research hotspots to a certain extent. We utilized the biblioshiny package in R to extract the 30 most frequently occurring author keywords and simultaneously generated the word cloud map using R, depicted in Figure 2A. Among these keywords, "running", "performance", "endurance", and "marathon" emerge as the most prominent, with frequencies of 196, 119, 113, and 98 times, respectively. In Figure 2B, the frequency trends of these 30 author keywords over the last 15 years are depicted by using R package ggplot2. It is evident from the figure that these keywords were less prevalent before 2016. Notably, studies on marathon performance, particularly those related to ultra-marathons, gender, running economy, training, age, and nutrition, have gained increased prominence in the last 3 years, spanning from 2021 to 2023.

Keywords co-occurrence and thematic evolution in marathon performance

Keywords co-occurrence analysis is primarily utilized to examine the concurrent frequency of two or more keywords in a specified dataset, unveiling the semantic correlations among keywords, and pinpointing the research theme (Donthu et al., 2021). Supplementary Figure S5 illustrates the results of the co-occurrence analysis conducted using VOSviewer on 53 keywords with a frequency greater than 10. The co-occurrence network is segmented into five distinct clusters. The largest cluster, denoted by the red color, predominantly encompasses studies on marathon performance, economy of motion, and the risks associated with sports injuries, such as fatigue, inflammation, muscle injury, and dehydration. In contrast, the green cluster primarily focuses on analyzing the effects of marathon running on echocardiography, heart rate, and other relevant factors. The blue cluster pertains to research investigating differences in athletic performance by gender and age in marathon runners. The yellow cluster explores the relationship between marathon performance and anthropometry as well as body composition. Lastly, the purple cluster delves into studies on marathon biomechanics and stride frequency.

The thematic evolution analysis of 53 keywords with a frequency greater than 10 is depicted in Supplementary Figure S6. This analysis was conducted using the Walktrap Clustering Algorithm in biblioshiny. The Weight index was utilized as an inclusion index, weighted by word occurrence. This analysis provides insights into the temporal trends of research interests within the field. Each node in the Sankey plot corresponds to the keyword with the highest frequency of occurrence, and its size is directly proportional to the number of keywords associated with the topic. The flow of nodes signifies the direction of the evolution of the topic complex, visually depicting the overall flow and transition of themes across categories over time (Schmidt, 2008). The Sankey diagram depicts a stable and compact shift in keyword hotspots, with many current studies deriving from previous periods. For instance, the research on marathon runners' heart rates was a prominent research focus from 2009 to 2015, persisting until 2016 to 2020. Additionally, the study of pacing strategies and inflammatory responses in marathon runners emerged as a research hotspot from 2009 to 2015 and regained attention as a hotspot from 2021 to 2023. Notably, research conducted in the past 3 years has focused on age-related performance decline, gender differences, pacing strategies, inflammation, and recovery, indicating their status as trending topics.

References bursts and keywords bursts in marathon performance

The identification of reference bursts and keyword bursts primarily relies on CiteSpace's built-in burst detection algorithm, employing a gamma value and a minimum duration of 1.0. Reference bursts can facilitate the identification of key literature and keywords in the field of marathon running. The red line segments in Supplementary Figure S7 indicate the time periods of literature/keyword bursts, while strength measures the intensity of the bursts. The figure displays the top 15 references with the highest citation bursts, among which the 2012 article on male (≥65 years) and female (≥45 years) master runners did not reach their limits of performance has the strongest burst (Lepers and Cattagni, 2012). Most of the references have reached their peak citation rates by 2018, except for four recent studies that remain influential: Hoogkamer et al. (2018) studied the effects of different running shoes on energy expenditure (Hoogkamer et al., 2018), Knechtle and Nikolaidis (2018) performed a review of ultramarathon physiology and pathophysiology (Knechtle and Nikolaidis, 2018), Scheer (2019) observed the exponential growth of ultra-marathon participation and the increasing involvement of women (Scheer, 2019), and Vitti et al. (2020) on the rising marathon participation in New York City over the last 50 years, with more significant trends among women and the best performances by Ethiopians and Kenyans (Vitti et al., 2020).

Supplementary Figure S8 presents the top 20 keywords associated with the citation outbreak. Among these keywords, "running performance" stands out as the keyword with the highest outbreak intensity in marathon performance field, aligning with the focus of our research. Additionally, keywords such as "sex differences", "intensity", "nutrition", "running economy", "health", "physiology", and "impact" continue to receive significant attention as hot topics within the field in 2021-2023.

Discussion

General distribution

This study conducts a bibliometric analysis of research papers on marathon performance spanning the past 15 years. The analysis reveals a consistent growth trend in the annual number of publications on marathon performance. Notably, there was a significant surge in publications from 2009 to 2014, although a decline was observed in the last 2 years. A total of 3,947 authors affiliated with 1,566 institutions across 63 countries/regions contributed to marathon performance research articles, underscoring widespread scholarly interest. The collaboration network, spanning countries/regions, institutions, authors, and scholars, reflects extensive academic exchanges and cooperation, breaking geographical constraints. The United States emerges as the leading country in both publications and citations. The University of Zurich and Knechtle B from the University of Zurich stand out as the most productive institutions and scholars, respectively. Knechtle B is further recognized as the most influential scholar and a frequent collaborator in the field. His 2018 review on ultramarathon physiology and pathophysiology is a top 15 reference with the strongest citation bursts, garnering sustained attention (Knechtle and Nikolaidis, 2018).

Research hotspots and trends

Based on keyword occurrences, time distribution, co-occurrence, thematic evolution, citation bursts analysis, and the results of a comprehensive analysis of research hotspots in the past 3 years, we have organized the findings into the following thematic chapters.

Physiology of the elite marathon runners

Maximum oxygen uptake (peakVO_2), anaerobic threshold speed, and running economy are three crucial factors that impact marathon performance (Joyner and Coyle, 2008; Haugen et al., 2022). In 2017, a study demonstrate a peakVO_2 can reach 83 mL/kg/min (Lucia et al., 2008). A study conducted in 2021 indicated that elite marathoners need to achieve a maximal oxygen uptake of 71.0 ± 5.7 mL/kg/min, an anaerobic threshold velocity of 18.9 ± 0.4 km/h, and an oxygen consumption of 191 ± 19 mL/kg/km to maintain a running speed of 21.1 km/h (Jones et al., 2021). However, data on anaerobic threshold velocities for men below 2:10:00 and for women below 2:25:00 are still lacking (Joyner et al., 2020).

Running economy plays a critical role in determining marathon speed while keeping energy expenditure in check, making it essential for elite marathon runners to possess an excellent running economy for success (Saunders et al., 2004). For elite runners with similar maximal oxygen uptake, running economy was a better predictor of marathon performance than maximal oxygen uptake. In the 1960s and 1970s, top marathoners Frank Shorter and Derek Clayton exhibited oxygen consumption ranging from 70-71 mL/kg/min, which aligns with the anaerobic threshold speed (Saltin et al., 1995). Limited data is available regarding running economy for top marathoners. Environmental and biomechanical factors also appear to affect the running economy of elite runners. Recent research has focused on enhancing the performance of elite marathoners by improving running economy through various means, such as utilizing shoes that are 100 g lighter, employing four lead runners to alternately block wind in the latter half of the race, or leveraging a tailwind of 6.0 m/s (Hoogkamer et al., 2017). Furthermore, studies on marathon shoes and the running economy have emerged as popular research topics, exploring improvements in landing time and suggesting that world-class athletes are the primary beneficiaries of enhanced footwear technology. In general, footwear technology has demonstrated moderate benefits in improving running economy (Muniz-Pardos et al., 2021).

Elite marathon runners training intensity and pacing strategies

Elite distance runners typically undergo 8-10 years of prolonged exercise training before achieving international standards (Haugen et al., 2022). Prior research has shown that a moderate amount of high-intensity training (approximately 40 km/week) can stimulate the body's potential for maximal exercise loads (Gibala et al., 2012). Additionally, several hours of daily exercise can enhance the anaerobic threshold velocity of elite marathon runners by increasing mitochondrial content and capillary density in their leg muscles (Hughes et al., 2018). Training at altitude and engaging in high-intensity training are effective methods for promoting mitochondrial catabolism and regeneration, leading to the production of more efficient mitochondria in the leg muscles of elite endurance athletes (King, 2021). A recent study involving top male and female marathoners who underwent 8 weeks of high-intensity training, covering distances of 180 ± 27 km and 155 ± 19 km, respectively, before a race revealed improved peakVO_2 among the athletes. Although their running economy remained unchanged, they exhibited reduced peakVO_2 utilization at a marathon pace (Doherty et al., 2020).

Pacing represents one of the primary factors influencing a marathoner's performance on race day, and a consistent pace, determined by characteristic training volume, the number of races of the marathon distance, and average training pace, significantly contributes to enhanced marathon performance (Leslie et al., 2023). A perfectly uniform pace is highly desirable, with successful marathoners generally achieving a faster pace in the first half of the race and a slower pace in the second half. Comparing the pacing of marathon record holders from different eras, it was observed that those from 1988 to 2018 demonstrated relatively slower pacing in the first half and faster pacing in the second half, with less overall variation in pacing (Casado et al., 2021). This trend may continue in the future. Furthermore, an analysis of top-level runners during the 2016 Rio Olympics and the 2017 IAAF World Championships revealed that women exhibited less variation in pace changes compared to men throughout the race (Casado et al., 2021).

Nutritional strategies for elite marathon runners

Nutrient supplementation is essential for athletes to achieve optimal athletic performance. Carbohydrates serve as the primary energy source for marathon runners, accounting for 90% of their energy expenditure, and their consumption has been linked to improved race performance (Stellingwerff, 2013). Elite marathon runners require rapid uptake of external glucose during running, insulin release to deliver glucose to muscle cells, electrolyte replenishment, and promotion of fluid retention (Ravindra et al., 2022). Incrementally increasing carbohydrate intake ensures the replenishment and maximization of muscle glycogen reserves. Typically, carbohydrate intake during marathon training ranges from 5 to 7 g/kg/day, with higher intake closer to the race (Drewnowski, 1998). While some studies have suggested that fat intake may help marathon runners conserve carbohydrates, it is unclear whether this contributes to endurance performance. Sufficient protein intake from external sources is necessary to maintain skeletal muscle mass, and Thomas and colleagues recommend that endurance athletes consume at least 20 g of protein every 3-4 h (Ravindra et al., 2022).

Marathon exercise is associated with significant water and electrolyte deficits, and dehydration-induced weight loss is a key factor in performance decline. Hydrating according to thirst is the best approach for maintaining proper hydration in athletes. Consuming 5-10 mL of carbohydrate-containing water per kilogram 2-4 h prior to exercise is also advised (Ravindra et al., 2022). Furthermore, hyponatremia, a serious complication resulting from faulty nutritional strategies, is associated with a BMI of less than 20 kg/m^2, excessive water intake, and weight gain during competition (Schrier et al., 2013).

Age and sex differences in marathon performance

The relationship between age and running time in elite marathoners follows a "U" shape, with faster running times observed between the ages of 15-25 and an increase in running times after the age of 35 (Lepers et al., 2020). Generally, peak endurance performance for marathon athletes occurs around the age of 35. As individuals age, cardiovascular and muscular function gradually declines, leading to a decrease in metabolism. This decline is associated with lower maximal heart rate, cardiac output, maximal oxygen uptake, running economy, and anaerobic threshold speed. Differences in maximal oxygen consumption contribute to 40%–77% of the variation in marathon performance, resulting in a decline of 7%-10% in endurance performance per decade for marathon runners (Trappe, 2007). However, studies suggest that elite or world-class master athletes can mitigate this decline through intense training. Some findings indicate that they can maintain a maximal oxygen uptake of 64.5 mL/kg/min at age 60 and 46.9 mL/kg/min at age 70, while also maintaining a comparable running economy to younger runners (Haugen et al., 2022). Additionally, high-level marathoners can sustain 90% of their maximal oxygen uptake for up to 2 h (Lepers et al., 2020).

With the increasing participation of women in marathons, gender differences in marathon performance have been studied since 1990 (Helgerud et al., 1990). Men generally exhibit faster running times due to physiological factors. Data from the Boston Marathon between 1972 and 2017 reveals that the annual 10 fastest men averaged an 18.3% faster time than women, with men also displaying higher maximal oxygen uptake compared to women (Knechtle et al., 2020). However, it is important to note that both men and women can maintain 90% of their maximal oxygen uptake during training when their performances are comparable (Helgerud et al., 1990). In a study comparing physiological indicators of 12 male and female runners with equivalent performances between the ages of 20 and 30, J. Helgerud found that performance-matched male and female marathoners exhibited similar maximal oxygen uptake (Helgerud et al., 1990). The difference lay in females having twice the amount of kilometers in their best 2-month training program but were less economical runners (Zavorsky et al., 2017). Recent studies indicate no significant difference in the age-related decline of physiological factors between male and female marathoners. However, marathon finishing times for female age group winners decline at a faster rate, approximately 27 s per year, after the age of 35 (Zavorsky et al., 2017).

Recovery of inflammatory response and muscle damage

The heightened biomarkers of myocardial injury, such as cardiac troponin T (cTnT) and N-terminal pro-brain natriuretic peptide (NT-proBNP), subsequent to marathon exercise, have been a subject of considerable debate in the field. To date, no study has definitively clarified their clinical significance (Niemelä et al., 2016). A study conducted in 2006 involving 60 non-elite marathon runners, using pre- and post-event echocardiography and serum biomarkers, revealed that 40% of participants exhibited cardiac troponin levels equivalent to acute myocardial infarction (≥0.03 ng/mL) (Neilan et al., 2006). Subsequent studies indicated that elevated biomarkers, including cardiac troponin, normalized within 72 h (Scherr et al., 2011). This response was even more pronounced among amateur marathoners. Additionally, it is imperative to note sports-related sudden cardiac arrest (SCA). The Race Associated Cardiac Arrest Event Registry documented a higher risk of SCA among marathon runners compared to non-marathon participants, based on data from 10.9 million individuals involved in U.S. marathons between 1 January 2000, and 31 May 2010. Furthermore, males were found to have a greater incidence of SCA (0.90 vs 0.16/100,000) and accounted for 50% of all sudden cardiac deaths (SCD) in the last mile (Franklin et al., 2020).

Skeletal muscle damage commonly occurs as a complication of strenuous exercise, with studies revealing significant elevation of markers of skeletal muscle damage, such as lactate dehydrogenase (LDH), myoglobin, and creatine kinase (CK) following strenuous exercise (Bernat-Adell et al., 2021). Exercise-induced muscle damage (EIMD) can also impact running performance by altering stride length, consequently increasing the oxygen consumption rate while running. However, the potential alteration of other physiological parameters by EIMD remains uncertain. Furthermore, limited research has been conducted on the effect of exercise-induced muscle damage on marathon performance, particularly over longer durations and distances, indicating a crucial area for future investigation (Howatson and van Someren, 2008).

Limitations

This study encountered several limitations. Firstly, it solely relied on literature sourced from the WoSCC database, excluding high-quality studies available in PubMed, Scopus, and other databases. Secondly, the study exclusively considered English literature, potentially introducing research bias by excluding studies in other languages.

Conclusion

To the best of our knowledge, this is the first bibliometric study conducted in the field of marathon athletics. Our study aims to review the significant contributors, collaborative models, research hotspots, and trends observed in marathon performance publications over the past 15 years. Recent research focuses on marathon performance physiology, training strategies, nutrition, age and gender differences and inflammatory response. Overall, this study serves as a valuable reference for marathon performance researchers, providing insights into more focused future research directions, and informed scientific decisions.

Author contributions

LY: Writing–original draft. ZC: Writing–original draft. XZ: Writing–original draft. QH: Methodology, Writing–review and editing. JZ: Writing–review and editing. QW: Conceptualization, Project administration, Writing–review and editing. ZZ: Conceptualization, Project administration, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2024.1388565/full#supplementary-material

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Employing emerging technologies such as motion capture to study the complex interplay between genotype and power-related performance traits

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Exercise genomics has progressed alongside advancements in molecular genetic technologies that have enhanced our understanding of associations between genes and performance traits. This novel field of research incorporates techniques and tools from epidemiology, molecular genetics, exercise physiology and biostatistics to investigate the complex interplay between genotype and specific quantitative performance traits, such as muscle power output. Here I aimed to illustrate how interdisciplinary training can ensure the effective use of new emerging technologies, such as motion capture, to examine the influence of genetic and epigenetic factors on power-related quantitative performance traits. Furthermore, this study raises awareness about the present research trends in this field, and highlights current gaps and potential future developments. The acquired knowledge will likely have important future implications in the biotech industry, with a focus on gene therapy to combat age-related muscle power decline, personalized medicine and will drive advancements in exercise program design.

KEYWORDS

cross-field, genomics, physiology, biomechanics, epigenetics

Introduction

The ground-breaking polymerase chain reaction (PCR) method was invented by Kary Mulis in 1983, and in the decades since that discovery, remarkable advancements have been made in genetic research. Cutting-edge molecular technologies have refined our approach to investigating how genetic predisposition influence performance traits. Innovative genetic research tools led to the formal recognition of the field of exercise genomics in the late 2000s. Initial research primarily focused on common genetic polymorphisms,[1] with studies mainly using the case-control approach, without incorporating quantitative performance measures as relevant biomarkers (Woods et al., 2001; Yang et al., 2003; Papadimitriou et al., 2008; Papadimitriou et al., 2009; Mikami et al., 2013). Subsequent molecular genetic

1 Common genetic polymorphisms, most often single-nucleotide polymorphisms (SNPs), are heritable nucleotide differences between individuals that occur in at least 1% of the population (Karki et al., 2015).

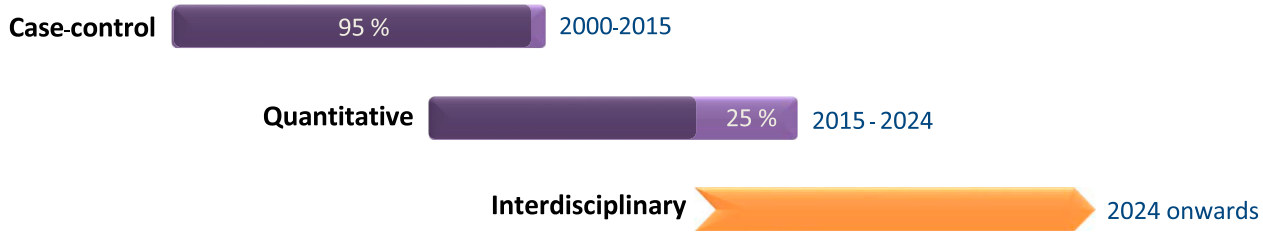


FIGURE 1
The timeline of different types of research conducted in the field of exercise genomics, as well as the future direction.

research enabled us to investigate the quantitative contribution (Papadimitriou et al., 2016; Contrò et al., 2018; Papadimitriou et al., 2018; Wei, 2021), gain genetic insights into physical characteristics, such as muscle strength (Clarkson, 2005; Broos et al., 2015; Willems et al., 2017) and explore the mechanistic pathways (Papadimitriou et al., 2019) that explain the interactions between genes and exercise training Figure 1.

While these methods have shown some effectiveness (Papadimitriou et al., 2016; Willems et al., 2017; Contrò et al., 2018), their implementation to explore complex performance characteristics—such as speed and muscle power—has proven to be more challenging (Hanson et al., 2010; Ruiz et al., 2011; Broos et al., 2015). One possible explanation is that the contributions of common genetic polymorphisms to these performance characteristics typically have small effect sizes, and these approaches lack the sensitivity required to detect such minor effects. Furthermore, considering that the majority of athletic outcomes involve multi-joint movements, the suitability of a number of the technologies that were previously employed may be questioned. Moreover, complex quantitative traits commonly exhibit further epigenetic influence from factors that regulate gene expression, such as DNA methylation (Raleigh, 2012).

Determining how common genetic polymorphisms influence athletic performance and human locomotion is challenging for several reasons—including the difficulty of accurately defining precise biomarkers; challenges in identifying or measuring the influences of environmental, epigenetic, and anthropometric factors; inadequate sample sizes; and technological limitations in obtaining sufficient and high-quality genetic and performance data. Rapid advancements in technology have yielded new and improved research tools that enable us to overcome these limitations. These tools enhance the accuracy and specificity of measurements, and improve the quality of created databases. These advancements enable us to more efficiently and precisely identify and quantify how common genetic variants and epigenetic factors influence physical performance.

Exercise physiologists now have access to several new emerging technologies, as it will be discussed in the paper. These include motion capture, which enhances the accuracy and specificity of performance measurements, bead-based DNA isolation methods that yield efficiently high-quality DNA, and novel microarray-based assays that enable rapid measurement of large numbers of genetic and epigenetic markers.

Motion capture technology enables the precise detection and analysis of specific performance characteristics, such as torque and velocity. Initially, this technique was used in life sciences for gait analysis. Today, motion capture is utilized in additional fields, including neuroscience and robotics. As motion capture systems continue to improve and expand, they hold great potential for applications in exercise genomics (Htet et al., 2023) and future use in epigenetics.

To fully enable the potential of today's highly skilled exercise physiologists and sport geneticists, we must support them in integrating the latest technologies, with emphasis on the crucial role of interdisciplinary research.

Motion capture technology in sport genomics: a guide for incorporating an emerging technology

Over the past 50 years, a wide range of vision-based methods have been developed to track human movement. An in-depth review of these approaches is available in the work of (Moeslund et al., 2006). Here, I aim to provide a brief overview of the evolution of the techniques used in the field, with an emphasis on the potential for revolutionized future applications in genomic and epigenomic research. The differences between these systems lie in the camera configuration, representation of recorded data, and types of tracking algorithms employed (Lee and Chen, 1985; Narayanan et al., 1995; Kakadiaris and Metaxas, 1998; Wagg and Nixon, 2004).

While there are notable differences in the technical characteristics of these techniques (Richards, 1999), they all share the same fundamental concept. They involve identifying spots of interest in sequential image frames, converting them into real-space coordinates, and using this information to determine the three-dimensional (3D) position of the visualizing skeleton (Corazza et al., 2006; Baran and Popović, 2007).

Prior to the introduction of digital technology, film analog cameras were commonly employed for tracking human movement during athletic activities (Procter and Paul, 1982; Bobbert et al., 1986; Lees et al., 1993). Some of this technology proved helpful in analyzing explosive body movements due to its greater resolution and enhanced recording frequency. However, the effectiveness of this approach was hindered mainly by lengthy processing times and complex data interpretation.

Over the last decade, there has been a remarkable progress in the study of human movement. This is largely due to the utilization of cutting-edge optoelectronics (Windolf et al., 2008). Faster computing power, larger memory, and hardware shrinkage have

TABLE 1 The table provides a summary of the most relevant physiological and biomechanical parameters that arise from these techniques and that can be linked to genetic and epigenetic factors along with their calculation formulas.

	Variables	Formulas	Technology	References
Angular	Relative torque	$RT = \frac{Segmental\ mass\ (kg)^{*}Angular\ acceleration\ (\deg s^{-2})}{Total\ body\ mass\ (kg)}$	Motion capture	Knudson (2007)
	Power	$P = Relative\ torque\ (N_m)^{*}Angular\ velocity\ (\deg s^{-1})$		Sayers et al. (1999)
Dynamic	Peak power	$PP = Force\ at\ peak\ velocity\ (N)^{*}Peak\ velocity\ (ms^{-1})$	Integration of motion capture systems with force plate dynamometry	Turner et al. (2012)
	Rate of force development	$RFD = \frac{Peak\ Force\ (N)}{Time\ to\ peak\ Force\ (s)}$		Comfort et al. (2011)
Reactive	Reactive strength index	$RSI = \frac{DJ\ Height\ (m)}{Ground\ Contact\ Time\ (s)}$		Riggs and Sheppard (2009)
	Index of reactive force	$IReaF = \frac{DJ\ Height - SJ\ Height\ (m)}{SJ\ Height\ (m)}$		Papadopoulos et al. (2009)

further facilitated these advances. Due to these exciting developments, research methodologies made significant improvements and a plethora of innovative techniques of automatic recognition of body movements have been developed. Most of these systems employ numerous cameras that emit infrared radiation, together with reflective markers that reflect this radiation back to the cameras. This enables the recording devices to determine the 3D position of the markers fast and accurately (Mündermann et al., 2006; Maletsky et al., 2007). Recent technological advancements have even made it feasible to detect motion without the need for reflective markers (Saini et al., 2015). These marker-less techniques often have much faster processing times and an improved recording range. However, they demonstrate reduced accuracy and precision, making them unsuitable for research applications (Klous et al., 2010). Currently, marker-based optoelectronic measurement systems are often regarded as the gold standard in motion capture. They outperform all other technologies in terms of the accuracy and precision required for prospective usage in research environments (Corazza et al., 2010; McGuirk et al., 2022; Johnson et al., 2023).

While motion capture is already prevalent in the life sciences industry, there remains potential for growth in research settings including in the fields of exercise genomics, physiology, and epidemiology. There is great demand for highly accurate motion capture technology in research. Current advancements in hardware have overcome previous limitations, but for this potential to be realized, it is important to educate and raise awareness among researchers who may have little experience working with motion tracking data. In particular, exercise physiologists and geneticists can benefit from using this high-quality data in their investigations. Ultimately, to fully harness the advantages of motion capture technology in research, we must increase acceptance and understanding among a range of researchers and their respective fields.

Moreover, motion capture alone may not be sufficient to qualify the performance levels of individuals. To successfully qualify and quantify the genetic and epigenetic influences it is necessary to evaluate dynamic performance characteristics, such as ground reaction forces and the rate at which force is developed incorporating additional technologies such as force plate dynamometry.

My research team integrated motion capture technology with force plate dynamometry in hopes of identifying novel power-related outcomes that are more sensitive to allele-specific differences. The study we conducted presents evidence that there is a connection between allele-specific differences and specific performance characteristics in certain joints during explosive body motions, such as sprinting or jumping (Htet et al., 2023). The physiological and biomechanical parameters identified from these analyses are shown in Table 1. These variables can serve as biomarkers in future studies to reveal subtle associations between performance traits and genetic or epigenetic factors.

The angular parameters quantify relative torque and power during explosive body movements, such as jumps and sprints, as recorded by motion capture technology. On the other hand, the dynamic variables represent power related characteristics of the force-time curve as measured by force plate dynamometry. Furthermore, the reactive parameters quantify the elastic utilization during vertical jumps with very short ground contact time, and increased muscle contraction velocity combining an explosive coupling between an eccentric and concentric muscle action, commonly known as stretch-shortening cycle (SSC) (Nicol et al., 2006). These parameters are determined based on participants' performance in Squat Jump (SJ) and Drop Jump (DJ), which was measured using motion capture technology (Htet et al., 2023).

Motion capture technology allows sport geneticists and exercise physiologists to incorporate biomechanical biomarkers into studies of allele-specific performance traits, thereby improving the accuracy and specificity of the measurements. The potential to include a biomechanical marker that reflects the genetic effect on a specific joint represents an advancement compared to traditional approaches for assessing speed and power-related performance in genetic research.

Compared to previous research approaches, the potential widespread utilization of motion capture technology in sport genomics offers several advantages. Firstly, it enables a focus on specific joints without influence by the overall anthropometric parameters of the human body. Secondly, it facilitates the analysis of full-body movements. Furthermore, it enables detailed analysis of more specific performance characteristics, such as peak torque and velocity, with regards to individual joints.

Before motion capture technology can be implemented in exercise genomic research, exercise physiologists must thoroughly assess the characteristics and reliability of this new laboratory approach. This requires analyzing the sensitivity, specificity, and other aspects that could affect the accuracy of the measurement. A series of preliminary and validation studies must be conducted (Moe et al., 2022) before these biomarkers can be used in large-scale genetic investigations. For example, researchers must determine how much of the variation in allele-specific measurements can be attributed to individual differences, intra-individual variability, or laboratory error. Each stage of this investigation process requires a foundation in exercise genomics, as well as expertise in various academic fields, potentially including physiology, biomechanics, and biostatistics. Thus, a sport geneticist or an exercise physiologist must have a comprehensive understanding and involvement in all components of the study, even those that extend beyond traditional exercise physiology or genomic training.

Other emerging technologies with potential application in the field

Bead-based DNA separation methods

Microarrays have been extensively utilized as platforms for SNP detection (Bumgarner, 2013). These technologies require high quality sample preparations, and the process of DNA isolation for sport genomic research continues to be a time-consuming task, relying on various extraction and centrifugation steps (Head et al., 2014).

Magnetic DNA isolation is an emerging technology that utilizes the power of magnetism for fast and effective DNA extraction and purification (Haddad et al., 2016). Column-based procedures involve the centrifugation of the lysate, followed by the addition of the supernatant to a silica membrane for the purpose of binding nucleic acids. The DNA is then washed and finally released in an adequate volume of elution buffer. These steps present a significant risk of causing mechanical damage to the DNA. Magnetic bead-based procedures have a reduced number of handling stages, and certain protocols eliminate the need for centrifugation, which reduces the risk of shearing compared to column-based methods (Chacon-Cortes and Griffiths, 2014; Ali et al., 2017). This improvement in efficiency also leads to lower costs.

Exercise geneticists can benefit from using this high-quality DNA in their studies, but in order to take full advantage of this potential, it is crucial to promote awareness among researchers who might lack familiarity working with this methodology.

DNA micro-array based methylation assays

In recent years, there has been growing interest in health-related fitness epigenetics. Complex power-related quantitative traits commonly exhibit varying degrees of genetic influence, as well as further influence from the epigenome. The epigenome serves as the interface connecting the environment with the genome.

Epigenetic modifications involve changes of gene expression that occur without any alternations to the DNA sequence and include DNA methylation, histone modifications, and microRNA expression (Ling and Groop, 2009). An explanation of all types of epigenetic modifications is beyond the scope of this mini review study and may be obtained elsewhere (Portela and Esteller, 2010). Here I aim to raise awareness and understanding of newly developed technologies employed in research examining DNA methylation and their potential application in exercise genomics.

DNA methylation involves the attachment of a methyl group to the 5-carbon position of the pyrimidine nucleotide cytosine. This mark predominantly appears within the context of a CpG dinucleotide (Brait et al., 2008). This kind of regulation changes the gene expression by functioning as a bidirectional valve. Once a particular CpG reaches a specific CpG location, it leads to the suppression of gene expression, whereas its demethylation facilitates gene expression.

In order to investigate this process, several laboratory techniques have been created to assess different aspects of DNA methylation (Laird, 2003). The utilization of these methods originated in the field of cancer research and includes global methylation, which characterizes an individual's general methylation profile (Zhang et al., 2011), and methylation that is specific to a particular gene, which regulates how certain genes are expressed (Deneberg et al., 2010).

The introduction and extensive use of epigenome-wide DNA methylation technologies—such as Illumina Infinium Human Methylation 450K assay—allowing rapid and simultaneous measurement of methylation levels at around 480,000 CpG sites across the genome (Wang et al., 2015), led to the development of DNA methylation-based biomarkers for various types of health related fitness characteristics (Yousefi et al., 2022; Jokai et al., 2023). Biomarkers of methylation levels may have future applications in large-scale studies to assess the complex relationships between genotype, gene expression, and specific quantitative performance characteristics such as muscle torque and power.

Discussion

This work highlights the potential for a future utilization of novel biomarkers and technologies in the context of exercise genomic research. With the growing acceptance of emerging technologies, such as motion capture, there is a significant opportunity to improve our understanding of the relationship between common genetic variants and certain quantitative performance traits, such as muscle power output, as well as identify the potential influence of epigenetic factors.

Most quantitative genetic studies have demonstrated that specific common genetic variants typically account for only about 2%–3% of the variation in muscle speed and power performance (Papadimitriou et al., 2016). The remaining variability is influenced by a diverse array of genetic, epigenetic, and environmental factors—the majority of which are not well understood, especially the genetic and epigenetic factors.

The presently available data support the conclusion that the genetic predisposition to power-related performance traits and responses to physical training are determined by the interplay of numerous genes and non-genetic factors, rather than by a single

gene or few alleles. Elucidating the effects of common genetic variations on human movement and athletic performance is a difficult task. Challenges include the precise detection of common variations in DNA, the determination and quantification of anthropometric and epigenetic variables, technological constraints in procuring genetic and performance data of sufficient quantity and quality, and the complex characteristics inherent in conducting research with humans.

Future research in the field of exercise genomics should be composed of a larger amount of functional quantitative research and a smaller fraction of case-control studies as illustrated in Figure 1. Case-control studies have played a key role in the initial stage of exercise genomics research, as they constitute a useful approach for investigating the association between common genetic variations and athletic performance. However, they have several drawbacks, including being prone to bias, and the majority of published candidate gene studies suffer from limited sample numbers and insufficient statistical power. Therefore, it is important to confirm the findings of case-control studies through replication with improved quantitative research designs (Papadimitriou et al., 2016; Contrò et al., 2018).

The potential use of motion capture technology in sport genomics provides several advantages compared to earlier research analyses in this field (Moran et al., 2007; Ruiz et al., 2011). Firstly, it enables a focus on specific joints without being affected by general anthropometric factors of the human body. Furthermore, it facilitates a comprehensive full-body examination of specific performance characteristics, including the peak torque and power generated at individual joints during explosive body movements. Such methodological and technological advancements have facilitated the identification of more precise phenotypes, and improved study designs for detecting and measuring the effects of common genetic variants on complex phenotypes, such as those associated with muscle speed and power (Htet et al., 2023).

Further research is necessary to expand beyond common genetic variants, combining transcriptomics with genomics and utilizing motion capture technology to investigate the potential influence of DNA methylation markers on training adaptations in specific performance characteristics important for speed and power.

Moreover, motion capture alone may not be sufficient to qualify the performance levels of individuals. Integrating additional technologies like force plate dynamometry is crucial. Muscular, body related signals and cerebral activities are also essential elements to be able to refine the intrinsic quality of the movement and today accompany the measurement of movement in the field (Cosendey et al., 2023).

Future exercise geneticists must thoroughly understand diverse disciplines to determine the appropriate use of emerging technologies and novel biomarkers, to assess their validation, and to ensure their meaningful interpretation. In a way, an exercise geneticist can be viewed as the stage director of a scientific project, which includes physiologists, biomechanical research scientists, computer vision analysts, laboratory technicians and bioinformatics experts. Just as it is impractical for a stage director to be involved in every role in a theater performance, it is also unrealistic for an exercise geneticist to be an expert in every role required for modern genomic research. However, like a stage director, an exercise geneticist must have a thorough understanding of each discipline, in order to coordinate and synthesize their contributions. Thus, in addition to expertise in genomic research, an exercise geneticist must also have a multidisciplinary skill set. Embracing interdisciplinary education in exercise genomics will cultivate an appreciation for different perspectives and methodologies within traditional fields of study and will facilitate the effective utilization of new emerging technologies to shed light on complex interplay between genome, epigenome and power-related performance traits.

This integrated knowledge has the potential to greatly impact the biotech industry, particularly in terms of age-related muscle power decline, and future applications in personalized exercise training programs, that aim to tailor training based on an individual's genetic makeup (Amato et al., 2018). Overall, this field of research can greatly enhance human health and well-being.

Lastly, incorporating rapidly emerging technologies can be a daunting task due to the overwhelming amount of data they produce. Prior to conducting further research in the field, it is imperative to employ discovery-based strategies to sort through the vast amount of data generated and pinpoint specific markers. This challenge led to emergence of the bioinformatics field, and it is now essential to have a biostatistician or an expert in data interpretation as a collaborator. Furthermore, artificial intelligence has the capacity to discover novel approaches to analyze biomarker and genomic data, equipping us with cutting-edge tools for predicting genes or epigenetic factors associated with performance traits and to address challenges associated with evaluating and understanding vast quantities of genomic and biomechanical data (Nguyen et al., 2022). Moreover, the large quantity of data being generated fundamentally changes the validation process, which now necessitates both discovery and hypothesis testing.

In a nutshell, exercise geneticists can greatly benefit from incorporating emerging technologies, like motion capture, into their studies. However, to fully realize this potential, it is crucial to raise awareness while improving acceptance and comprehension among researchers from various fields.

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Conflict of interest

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A meta-analysis of the intervention effect of mindfulness training on athletes' performance

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Objective: To explore the intervention effect of mindfulness training on athletes' performance using meta-analysis method.

Methods: A total of 11 articles and 23 effect sizes were included through retrieval of Chinese and English databases, with a total sample size of 582.

Result: Mindfulness training improves the level of mindfulness [SMD =1.08, 95%CI (0.30, 1.86), $p < 0.01$], fluency (The optimal competitive psychological state of the athlete, the athlete's attention is all focused on the task, and other things no longer attract their attention) [SMD =1.47, 95%CI (0.87, 2.08), $p < 0.001$] and performance [SMD =0.92, 95% CI (0.40, 1.43), $p < 0.01$], reduced psychological anxiety [SMD = -0.87, 95% CI (−1.54, −0.20), $p < 0.05$], and all reached the level of large effect size.

Conclusion: The effect of mindfulness training on athletes' sports performance is effective, and it can be used as an effective psychological skill intervention method to improve athletes' sports performance. In the future, we should further expand the sample size, strengthen the comparative study of different sports and intervention modes, and pay attention to the difference between the time effect and trait mindfulness level in fluency state.

KEYWORDS

an athlete, mindfulness training, meta-analysis, sports performance, fluency

1 Introduction

Athletic performance is the focus of attention in the field of competitive sports and competitions, and good athletic performance is the key to obtain excellent competition results. Athletes are highly stressed groups, and how to overcome adversity to obtain the best sports performance is one of the most difficult tasks in their sports career (Birrer and Morgan, 2010). Theoretical models related to sports performance, such as inverted U-shaped hypothesis, personal optimal functional area theory, drive theory, processing efficiency theory, attention control theory, etc., focus on the relationship between anxiety and sports performance under competition pressure from a specific aspect (Sun and Li, 2013, 2021). The integrated model of sports performance more comprehensively and systematically explains the different stages of sports performance and their influencing factors. The theoretical model holds that sports performance is determined by four factors, including physical fitness, environmental stimulation and requirements, personality and behavioral self-regulation, and sports performance is divided into preparation stage, performance stage and reaction stage after sports. In the preparation stage, athletes mainly face the internal and external demands that affect their competitive behavior. The cognitive, emotional and behavioral responses of individuals in the performance stage are easily affected by external events; The post-exercise reaction phase involves reactions to performance-related external

consequences and internal processes (Gardner and Moore, 2007). As a result, sports performance refers not only to the athletic level behavior on the field, but also to the mental state and performance before, during and after the competition. The negative aspects of mental performance include anxiety, depression and Choking phenomenon, and the positive aspects include positive emotion, self-esteem, mindfulness level and fluency experience. Therefore, based on the integrated model of sports performance and the test indicators of quantitative intervention research, this study conducted a more comprehensive investigation of athletes' sports performance from two aspects: psychological performance (psychological anxiety, level of mindfulness, fluency experience) and behavioral performance (performance).

In order to improve the athletic performance of athletes, the traditional control-based psychological skills training has been gradually applied to the field of sports, and has achieved certain results in reducing the "negative internal experience" and increasing the "positive state," but its significant effect on the athletic performance of athletes has not been effectively supported, and it is faced with many difficulties (Noetel et al., 2019). First of all, the theoretical foundation is not solid. The "optimal state" theory holds that sports performance is dominated by potential psychological traits (such as anxiety, trait, self-confidence) or mental states (such as mood state, arousal state, fluency state), and the change of mental characteristics and mental states will also lead to the change of sports performance. The influence of environmental and learning factors on sports performance is ignored (Si, 2006; Moore, 2009). Secondly, the empirical effect is not ideal. Some researchers have used traditional psychological skills training to improve the performance of athletes, but there is no consistent empirical conclusion. Gardner and Moore conducted a qualitative study on the improvement of competitive sports performance by traditional mental skill training, and the results were not well proved. Finally, the practical operation is not strong (Gardner and Moore, 2006). What is the standard of optimal state for different individuals? How to operate to get the best state of mind? This is difficult to define in the actual application environment. In view of this, in recent years, in order to make up for the possible shortcomings of traditional mental skills training, mindfulness-based mental training has attracted more and more attention from sport psychology practitioners (Song and Zhang, 2020).

Derived from the Eastern Zen thought, mindfulness is closely related to religion, but it does not have the mysterious color of religion and has the characteristics of science. It is relatively popular in the West, mainly applied in clinical medicine, psychological intervention and other fields (Brensilver, 2011). Kabat-Zinn defines it as "mindfulness is the process of purposefully focusing attention on the present moment and becoming aware without judgment of the experience presented one moment after another" (Kabat-Zinn, 2003). With the rise of the third wave of cognitive behavioral therapy, mindfulness training has been widely used in the field of sports competition. From the perspective of theoretical models, attention control theory, interference theory and mind wandering theory all emphasize that athletes' attention is susceptible to irrelevant information interference and lack of attention to the current movement process, which will cause anxiety and thus affect sports performance (Duan and Zhang, 2017). The mindfulness theory does not emphasize the control of the internal state and the acquisition of the best state, but focuses on the attention of their own situation and internal state without judgment and evaluation, so that athletes can focus on the current sports tasks, so as to effectively improve the psychological state of athletes and enhance their behavior. The main representatives are the mindfulness-accept- engagement training proposed by Moore and Gardner (2001) and Gardener and Moore (2004), the mindfulness exercise performance enhancement training proposed by Kaufman et al. (2009), the exercise mindfulness meditation training established by Baltzell and Akhtar (2014), and the mindfulness - acceptance - awareness - engagement training proposed by Si et al. (2014). A growing number of studies refer to the use of emerging technologies in mindfulness training. AI is expected to play a key role in future mental health programs. Artificial intelligence, through machine learning algorithms, can provide personalized recommendations, record progress, and provide real-time feedback to users. By identifying cognitive and behavioral patterns, AI applications can adapt based on real-time data from users. AI can identify the user's personal preferences and interests and provide appropriate triggers to increase the user's motivation to continue working toward the training goals (Mitsea et al., 2023). Mindfulness training based on virtual reality technology usually uses virtual reality technology to design and develop mindfulness training software, which is conducive to designing personalized courses, intelligent monitoring, emotion tracking and interesting games for patients' individual conditions, so that patients have a high acceptance of mindfulness training based on virtual reality technology, which can improve patients' negative emotions and fatigue (Wenjuan et al., 2024). From the perspective of empirical research, mindfulness training plays a positive role in helping athletes to accept their negative emotions (John et al., 2011), reduce anxiety (Watson, 2008; Zhao and Zhang, 2013) and improve experience acceptance (Gardner and Moore, 2006). In the field of competitive sports, mindfulness training intervention can effectively improve athletes' mindful attention and awareness ability (Bernier et al., 2009), fluency experience, and athletic performance level (Wolanin, 2005). Mindfulness meditation is also able to improve attentional resource allocation (van den Hurk et al., 2010a), enhance working memory and executive ability (van den Hurk et al.,2010b; Jha et al., 2010), improve attention levels and motor skills (Cascante-Rusenhack et al., 2016). Foreign studies have shown that mindfulness is negatively correlated with job burnout, emotional/physical exhaustion, and will decline. Mindfulness training can alleviate burnout and chocking phenomenon (Vealey et al., 2014), improve athletes' emotional state, enhance sports awareness and performance ability (Walker, 2013; Baltzell et al., 2014), and increase the frequency and duration of fluency (Aherne et al., 2011). Relevant domestic evidence also shows that mindfulness training can reduce pre-competition anxiety (Feng and Si, 2015), improve emotional state (Yang and Zhang, 2014), improve mindfulness level and sports performance (Zhong et al., 2013).

Overall, in recent years, the field of competitive sports has widely begun to apply mindfulness training to improve sports performance, and has achieved certain results. However, due to the short period of entry into this field, relative empirical studies are less than clinical intervention fields, and athletes belong to a special group with limited sample access, so the sample size of a single study is not large. In view of this, this study used meta-analysis method to obtain a larger sample and integrate relevant research results to systematically evaluate the

intervention effect of mindfulness training on athletes' sports performance, with a view to providing a basis for reasonable and effective psychological intervention methods for athletes.

2 Research methods

2.1 Literature screening

This meta-analysis was conducted according to PRISMA guidelines (Page et al., 2021), and the searching protocol and inclusion criteria (detailed below) were decided by research team in regular meetings. Two researchers from the team conducted the literature screening. The key words for screening of English literature were selected from prior studies, and the variants of the terms were obtained from academic dictionary (e.g., Collins English Thesaurus). The terms of mindfulness, training, meditation, athletic performance, randomized controlled trail (RCT) and their variants were searched using Boolean formula in Chinese (i.e., CNKI, Wanfang, and VIP) and English sources (i.e., Web of Science, EBSCO, Science Direct, and Pubmed), please see Supplementary Table 1 for details of searching strategies. The literature screening phase ended on June 10, 2020. The title and abstract literature screening returned 181 Chinese literatures (limited core journals, CSSCI), 250 English literatures and 22 other sources were obtained Details of the procedure was presented in Figure 1.

2.2 Inclusion and exclusion criteria

2.2.1 Inclusion criteria

The inclusion criteria were strictly in accordance with PICOS criteria (Amir-Behghadami and Janati, 2020). (1) The subjects were athletes, not limited to sports; (2) The interventions are mindfulness training, meditation or mindfulness-based methods; (3) The experimental design part of the included literature was randomized controlled experiment (RCT); (4) The outcome indicators were mindfulness level, happiness flow, competition pressure or anxiety, sports performance and achievement; (5) Sample size, average and standard deviation of experimental group and control group can be obtained.

2.2.2 Exclusion criteria

The main exclusion criteria are: (1) experimental design non-randomized controlled experiment; (2) Non-athletes; (3) Non-mindful intervention; (4) Conference abstracts, dissertations, review articles, meta-analyses, duplicate publications, inability to obtain full text, etc.; (5) Inconsistent with the research theme; (6) Outcome indicators are inconsistent; (7) The data is incomplete, and the data needed for research cannot be obtained.

2.3 Literature screening and data extraction

The literature initially retrieved was imported into the literature management software, the duplicate literature was eliminated, and then the title and abstract were read to exclude irrelevant literature, and the full text was further read to determine the final literature included in the study. In the whole process, the two researchers independently screened and extracted the literature. In case of any disagreement, the included literature and its related information were finally determined through discussion or with the assistance of a third party (Figure 1). The extraction content mainly includes the first author, publication years, research methods, research objects, gender, age, sample size, intervention measures of the experimental group and control group, outcome indicators, etc.

Literature retrieval in the database was as follows: CNKI ($n = 31$), VIP ($n = 5$), WanFang ($n = 145$), Web of Science ($n = 107$), PubMed ($n = 60$), Science Direct ($n = 74$), EBSCO (n = 9).

2.4 Quality evaluation

The quality of the included literature was evaluated according to the evaluation criteria of the Cochrane Handbook 5.1.0. The evaluation includes the following aspects: (1) random sequence generation; (2) Distribution hiding; (3) Implement blind method for the implementers and participants; (4) Implement blind method for results evaluators; (5) Integrity of data results; (6) Selective reporting of research results; (7) Other sources of bias. A detailed description of those criteria can be found elsewhere (Higgins and Altman, 2008). The evaluation was completed by two researchers, and if there was any disagreement, the third researcher would discuss and decide together. The results are shown in Figure 2.

The three options of risk assessment were coded as followings: high risk (red; 0), unclear (yellow; 1), low risk (green; 2); the total score is ranged between 0 and 27, with higher score indicated higher study quality. The quantification of this assessment was used to examine whether the study quality contributes to the variance of the main outcomes. The meta regression was conducted for synthesis with more than five observations (i.e., mindfulness, sport anxiety, and performance), and permutation test was conducted to avoid the risk of overfitting. The results indicated that the quality of the study does not affect the main outcomes.

2.5 Outcome variables

The concept of "flow" refers to a highly desired but elusive state of mind characterized by total focus on the task at hand as well as enhanced skill performance. Elite athletes with high levels of personality mindfulness tend to experience flow. Some flow experts believe that flow can be difficult to achieve when a person is anxious because anxiety triggers negative self-conscious focus that disrupts concentration (Csikszentmihalyi, 1990; Jackson and Csikszentmihalyi, 1999), some flow literature suggests that the cognitive component of anxiety, rather than the physiological component, may be the most important cause of anxiety's negative impact on flow (Jackson and Wrigley, 2004). Mindfulness may be a catalyst for flow, while mindfulness can also reduce the likelihood of anxiety, and a review of the mindfulness and sports literature has shown that increased mindfulness may lead to altered relationships with internal experiences such as anxiety (Gardner and Moore, 2012).

2.6 Data analysis

R (version 4.3.1) software was used to analyze outcome indicators of the included literatures. For continuous variables, Weighted Mean

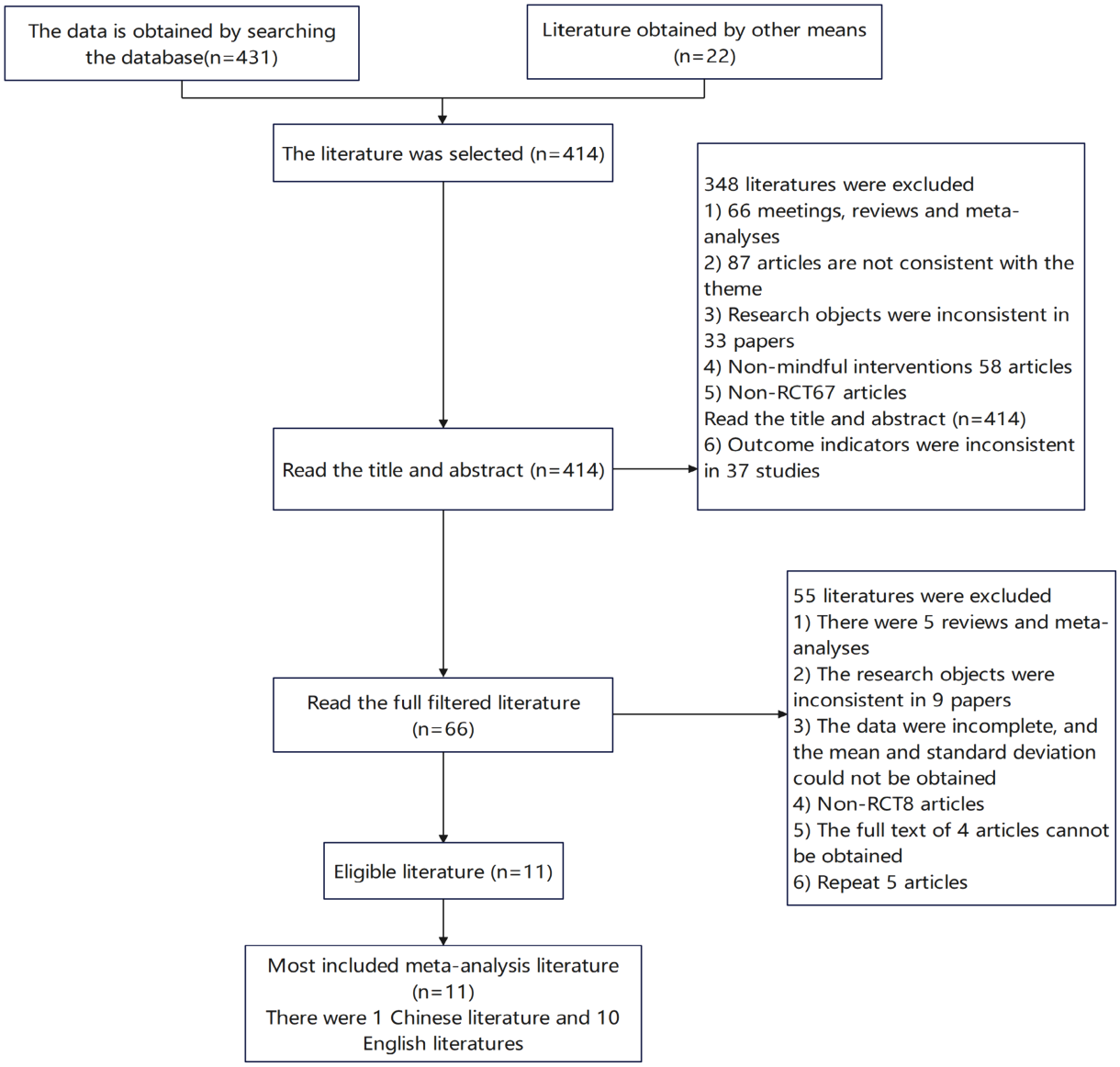


FIGURE 1
Flow chart of inclusion of literature screening.

Difference (WMD) was used if the same measurement tools were used. If the measurement tools used are different, the Standard Mean Difference (SMD) is used. There are differences in the measurement tools used in the study, so the standardized mean difference (SMD) is used as the effect size indicator. Heterogeneity was tested by I^2 statistic. When $p \geq 0.1$ and $I^2 \leq 50\%$, fixed-effect model was used for analysis. When $p < 0.1$ and $I^2 > 50\%$, the heterogeneity between the studies was indicated, and the random effects model was used for analysis.

3 Research results

3.1 Basic characteristics of the included research literature

A total of 453 literatures were preliminarily retrieved. Through the formulation of inclusion criteria and exclusion criteria, the search results were screened and read, and a total of 11 eligible randomized controlled trials were included (Table 1). Three studies included only men, one study included only women, and the rest included both men and women. All participants were athletes with an average age range of 16 to 67 years. The sample size was 582 people, including 305 men and 116 women. There were two literatures that did not report the number of gender column. The main intervention methods were mindfulness-accept-input training, mindfulness-stress reduction therapy, mindfulness-meditation training and other mindfulness-related intervention methods, while the control group mostly adopted no intervention, psychological skills training and educational lectures. Outcome indicators: level of mindfulness, fluency, psychological anxiety (degree) and academic performance. According to the definition of effect size by Cohen et al. effect size ($0.2 \leq ES < 0.4$) is a small effect, effect size ($0.4 \leq ES < 0.6$) is a medium effect, and effect size ($ES \geq 0.6$) is a large effect, and $p < 0.05$ (Cohen, 1962; Wu et al., 2013).

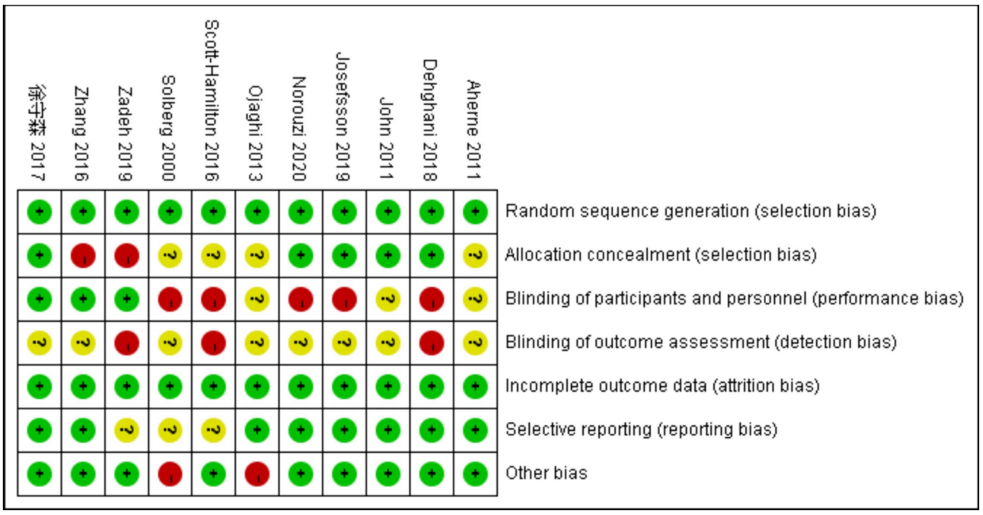


FIGURE 2
Risk assessment of the included literature.

3.2 Publication bias test

Generally, in meta-analysis, only when the number of studies is greater than 10 can a funnel plot be made to observe the publication bias of an article (Liu, 2011). A total of 11 literatures and 24 studies were included in this study, and publication bias test could be conducted if the conditions were met (Figure 3). As can be seen from Figure 3, the funnel plot is basically symmetrical, indicating that there is no significant publication bias in the study.

3.3 Sensitivity analysis

Sensitivity analysis was used to check the stability and reliability of meta-analysis or systematic review results, so as to provide guarantee for effective research. This study mainly adopted the method of gradually excluding literatures and changing the analysis model. The sensitivity analysis was carried out on 11 literatures and 24 studies included in the study, and the effect size was recalculated after each article was excluded to observe the heterogeneity. It was found that after the Scott-Hamilton study was excluded, and statistical heterogeneity decreased to a non-significant level, $I^2 = 0\%$ ($I^2 <= 50\%$), chi-square test $p = 0.93$ ($p > 0.1$), see section 3.2 for details. There was no significant change in other results, indicating that the results of the meta-analysis in this study were credible.

4 Results of meta-analysis

4.1 Meta-analysis of mindfulness training on athletes' mindfulness level

Seven studies demonstrated the impact of mindfulness training on the level of mindfulness in athletes, including a total sample size of 293 people. There was heterogeneity in the included studies ($p < 0.01$, $I^2 = 88\%$), which was analyzed by random effects model. The results showed (Figure 4) that there was a statistically significant difference in the level of mindfulness between the experimental group and the control group [SMD =1.08, 95%CI (0.30, 1.86), $p < 0.01$], and the average effect size was 1.08, $p < 0.01$, reaching the level of large effect size.

4.2 Meta-analysis of mindfulness training on athletes' fluency status

Two studies demonstrated the effect of mindfulness training on the fluency of athletes, with a total sample size of 56 people. No heterogeneity was identified after the removal of the study by Scott-Hamilton ($p = 0.93$, $I^2 = 0\%$), which was analyzed by fixed effects model. The results showed (Figure 5) that the experimental group and the control group had a significant difference margin in fluency [SMD =1.47, 95%CI (0.87, 2.08), $p < 0.001$], and the average effect size was 0.99, $p = 0.05$, reaching the level of large effect size.

4.3 Meta-analysis of mindfulness training on psychological anxiety of athletes

Seven studies demonstrated the effects of mindfulness training on psychological anxiety in athletes, including a total sample size of 283 people. There was heterogeneity in the included studies ($p < 0.1$, $I^2 = 81\%$), which was analyzed by random effects model. The results showed (Figure 6) that there was a statistically significant difference between the experimental group and the control group in psychological anxiety (degree) [SMD = -0.87, 95%CI (−1.54, −0.20), $p < 0.05$], and the average effect size was 0.83, $p < 0.01$, reaching the level of large effect size. "-" indicates that the psychological anxiety of the individual has been relieved after the experiment.

TABLE 1 Basic features of the literatures included in this study.

Author and year of publication	Research method	Research object	N		Sex		Age (M ± SD)	Intervention measure		Outcome index
			E	C	male	female		E	C	
Zadeh et al. (2019)	Randomized control	Football player	22	22	44	0	E:23.77 ± 1.95C:24.86 ± 4.68	MAC 45 min/time 6 sessions/week 7 weeks	NT	①Mindfulness (MSPQ) ②Team performance
Norouzi et al. (2020)	Randomized control	Football player	20	20	40	0	34.05 ± 1.72	MBSR 90 min/time 16 sessions/week 8 weeks	NT	Anxiety (BAI)
Scott-Hamilton et al. (2016)	Randomized control	Cyclist	27	20	42	5	E:38.96 ± 12.40C:40.65 ± 10.88	MiCBT 65 min/time 7session/week 8 weeks	NT	① Mindfulness (FFMQ) ② Flow (DFS-2) ③ Anxiety (SAS-2)
Ojaghi et al. (2013)	Randomized control	Table tennis player	20	20	Failure to report		Failure to report	Mindfulness	NT	① Mindfulness (MAAS) ② Anxiety (CSAI) ③ Sport performance
Aherne et al. (2011)	Randomized control	Elite athlete	6	7	9	4	21.00 ± 1.68	Mindfulness and CD 60 min/time 2 days/week 6 weeks	NT	① Mindfulness (CAMS-R) ② Flow (FSS-2)
Solberg et al. (2000)	Randomized control	runner	11	10	Failure to report		39 ± 7	Acem Meditation 2.5 h/session 1session/week 7 weeks	ATPS	Anxiety (STAI)
Josefsson et al. (2019)	Randomized control	Elite athlete	36	32	25	33	E:20.9 ± 4.24C:21.0 ± 4.16	MAC 50 min/session 1session/week 7 weeks	PST	① Mindfulness (AMQ) ② Anxiety (DERS) ③ Sport performance
John et al. (2011)	Randomized control	shooter	48	48	96	0	29.5 ± 4.3	MMT 20 min/day 6 days/week 4 weeks	NT	Shooting performance
Zhang et al. (2016)	Randomized control	College darts thrower	22	21	16	27	19.23 ± 1.27	MAC 80-90 min/session 1session/week 8 weeks	SPL	① Mindfulness (FFMQ) ② Flow (SDFS) ③ Dart throwing performance
Dehghani et al. (2018)	Randomized control	College women's basketball player	14	15	0	29	E:23.44 ± 0.49C:23.34 ± 0.34	MAC 1.5 h/session 8sessions	NT	Anxiety (SCAT)
Xu et al. (2017)	Randomized control	Collegiate golfer	33	18	33	18	E:21.55 ± 1.42C:21.78 ± 0.88	MAC 70 min/week 1session/week 6 weeks	NT	① Mindfulness (FFMQ) ② Anxiety (CSAI) ③ Sport performance

(1) E, Experimental group; C, Control group; M, Mean value; SD, Standard deviation. (2) MAC, Mindfulness-Acceptance-Commitment Approach; MBSR, Mindfulness-based Stress Reduction; MMT, Mindfulness Meditation Therapy; NT, No Treatment; ATPS, Autogenic Training Problem Solving; PST, Psychological Skill Training; SPL, Sport Psych Lectures; MiCBT, Mindfulness-integrated Cognitive Behavior Therapy program. (3) MAAS, Mindful Attention and Awareness Scale; FFMQ, Five Facet Mindfulness Questionnaire; MSPQ, Mindful Sport Performance Questionnaire; CAMS-R, The Cognitive and Affective Mindfulness Scale-Revised; AMQ, Athletic Mindfulness Questionnaire; DFS-2, Dispositional Flow Scale-2; FSS-2, Flow State Scale-2; SDFS, Short Dispositional Flow Scale; BAI, Beck Anxiety Inventory; SAS-2, Sports Anxiety Scale-2; CSAI, Competitive State Anxiety Inventory; STAI, State–Trait-Anxiety-Inventory; SCAT, Sport Competition Anxiety Test; DERS, Difficulties in Emotion Regulation Scale.

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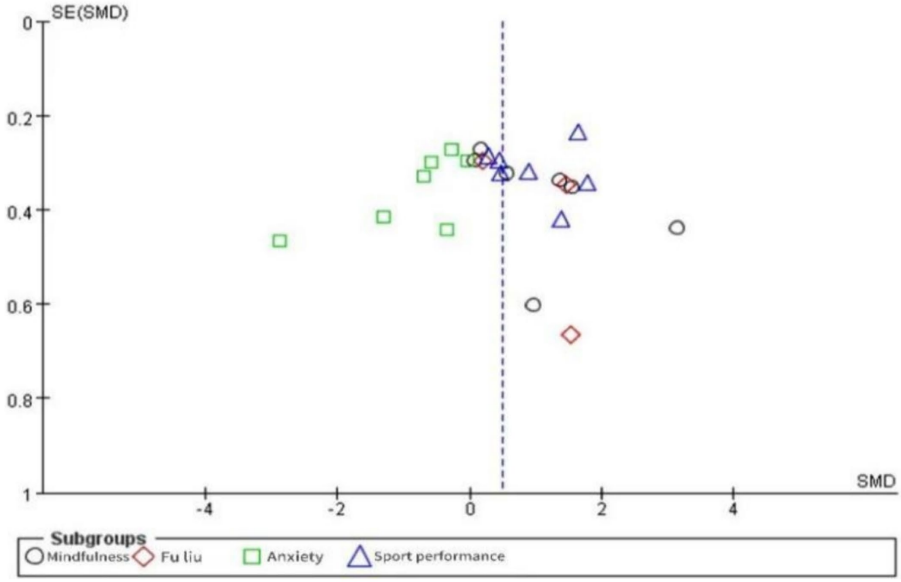


FIGURE 3
Shows a biased funnel diagram.

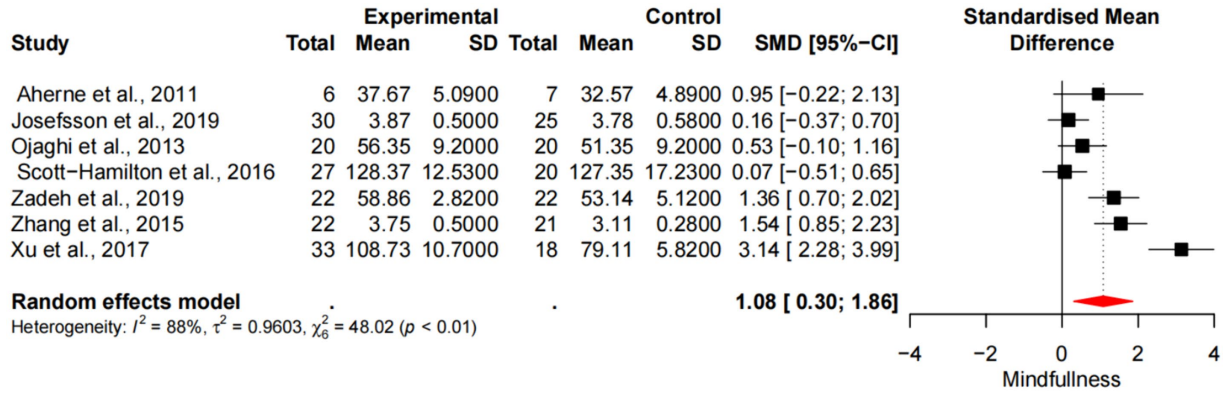


FIGURE 4
Forest diagram of the effect of mindfulness training on the level of mindfulness of athletes.

4.4 Meta-analysis of mindfulness training on athletes' performance

Six studies demonstrated the impact of mindfulness training on athlete performance, including a total sample size of 329 people. There was heterogeneity in the included studies ($p < 0.1$, I2 = 80%), which was analyzed by random effects model. The results showed (Figure 7) that the difference in performance between the experimental group and the control group was statistically significant [SMD =0.92, 95%CI (0.40, 1.43), $p < 0.01$], and the average effect size was 0.92, $p < 0.001$, reaching the level of large effect size.

5 Discussion

5.1 Impact of mindfulness training on the level of mindfulness of athletes

Mindfulness intervention has been widely used in medical and health care systems and has made a positive contribution to promoting health levels (Kiely, 2016). As more and more research confirms the beneficial effects of mindfulness, the use of mindfulness training methods in competitive sports and sports has been surging in recent years. Mindfulness is an open, accepting, non-judgmental state of

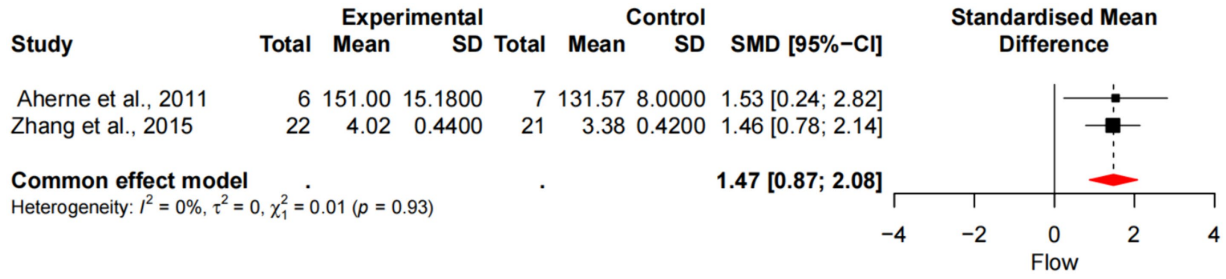


FIGURE 5
Forest diagram of the effect of mindfulness training on athletes' fluency.

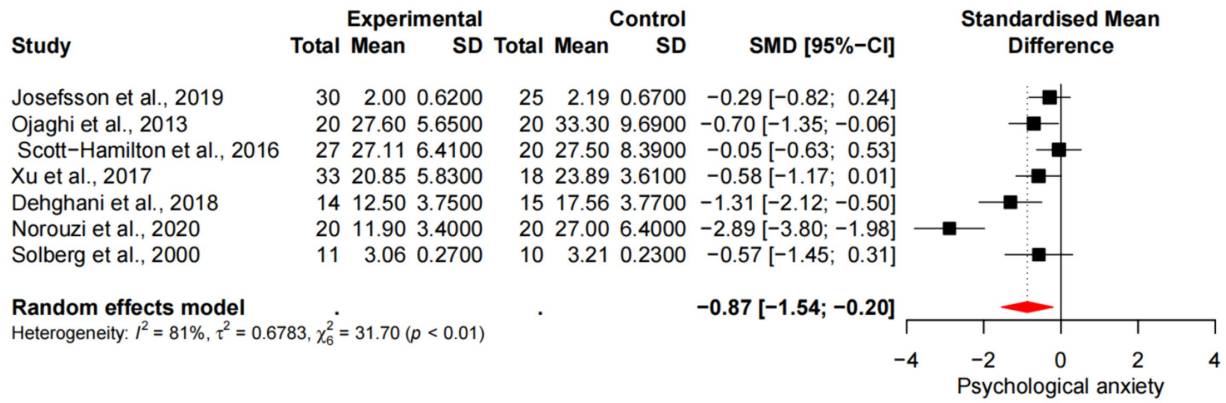


FIGURE 6
Forest diagram of the effect of mindfulness training on psychological anxiety of athletes.

awareness in which individuals focus their attention on the present moment, on internal and external things and experiences. The ease with which the individual maintains this state of awareness is a manifestation of good control of attention. Mindfulness is a psychological tactic whose main purpose is to increase an individual's attention to the present moment through a variety of methods (Davis and Hayes, 2011). Individuals with high levels of mindfulness are able to separate their attention from the meditative state and focus highly on the task at hand (Gardner and Moore, 2007). Attention control, mental adjustment and mental toughness are the three key areas for athletes. At present, most athletes realize the necessity of physical and technical training, but the recognition of the benefits of mental training is not yet in place (Ferraro and Rush, 2000). Bishop et al. believe that mindfulness consists of two parts: one is to focus attention on the current task; the other is to adapt to the situation in the present moment according to the individual's experience ability, and the whole process is full of curiosity, openness and acceptance (Bishop et al., 2004). Holzel pointed out that mindfulness meditation can enhance attention control, emotional regulation, and self-awareness (Hölzel et al., 2011a). Studies on the mechanism of attention control and self-awareness have shown that both short-term and long-term mindfulness training can cause changes in the structure of the brain's white matter and gray matter. It can be seen that mindfulness training can affect the brain and nervous system and promote the learning and mastery of motor skills (Hölzel et al., 2011b). Chinese scholar Yang Shu et al. pointed out in a study on the Impact of mindfulness cognitive Intervention on psychological indicators related to stress coping in high-level athletes that mindfulness cognitive intervention training for athletes can effectively improve their mindfulness level (Yang and Zhang, 2014). Li Jieling et al. conducted a sustained attention intervention study on badminton team athletes and college students, and found that mindfulness training can effectively cope with mental wandering, thus improving athletes' sports performance (Li et al., 2017). Duan Zaifu et al. also came to the same conclusion in his article "A New Perspective for Choking in Competition: the Wandering Theory of Mind" (Duan and Zhang, 2017). This study integrates 7 data related to the impact of mindfulness training on the level of mindfulness of athletes, and also confirms that mindfulness training is an effective way to improve the level of mindfulness of athletes [SMD =1.08, 95%CI (0.35, 1.82), p = 0.004], and can improve the attention of athletes when applied to sports. Promote athletes to achieve good performance in the arena.

5.2 Influence of mindfulness training on athletes' fluency

The fluid experience proposed by Csikszentmihalyi has contributed greatly to positive psychology and is now an important branch of the field (Csikszentmihalyi, 1990). In the process of skill display, athletes will have a peak moment of high concentration of attention, focus on the current moment, physical and mental

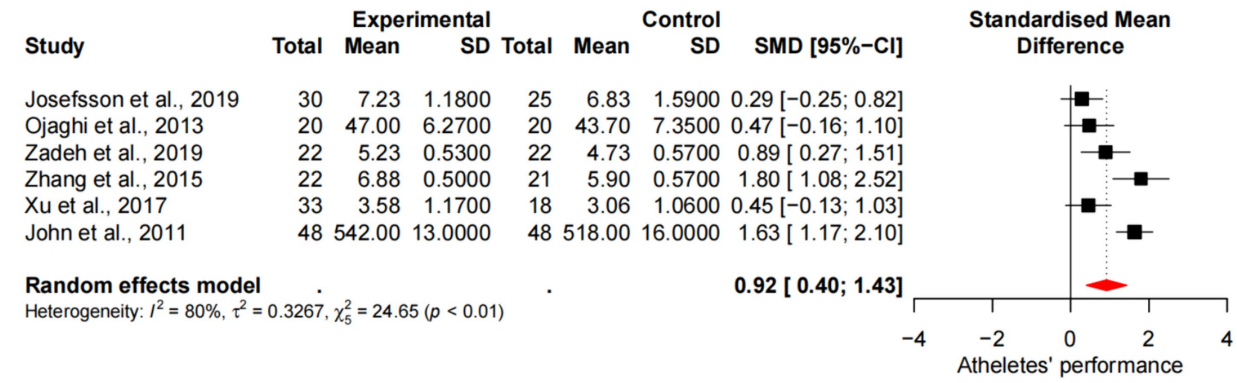


FIGURE 7
Forest diagram of the effect of mindfulness training on athletes' performance.

integration, self-confidence doubling, mental relaxation, and performance beyond normal. This state is usually called the "best zone," and the state in this region is the state of fluency (Young and Pain, 1999). The so-called state of fluency is the state of consciousness in which the athlete is fully engaged in an athletic task and performs at the best athletic level (Jackson and Marsh, 1996). Fluid state is an optimal psychological state, which is closely related to sports performance and performance. Therefore, it is very important to promote the appearance of athletes' optimal psychological state in the field of competitive sports. In college physical education, smooth experience has been proved to play a role in the field of sports for many times (Jackson and Roberts, 1992; Zhang and Ma, 2007). Participants experience the state of flow, which is conducive to increasing their interest and enthusiasm in sports activities and improving their participation behavior (Mandigo and Thompson, 1998). As for the research on mindfulness training and fluency experience, (Hasker, 2010) conducted mental skill training of mindfulness training and imagery training on athletes of different disciplines, and found that athletes in the mindfulness group obtained a higher sense of peak experience, and the group's subjective assessment performance improved significantly. Bernier et al. (2009) pointed out that focused athletes are more likely to experience smooth experience and feel the fun and satisfaction brought by sports. Schwanhausser (2009) suggests that the increase in propensity and fluency is related to the mindfulness-acceptance intervention style. Foreign studies have also found that fluency experience is negatively correlated with anxiety, perfectionism and thought disruption, and positively correlated with confidence and mindfulness (Russell, 2001), and the significant correlation between the two has positive significance for the use of mindfulness psychological intervention (Kee and Wang, 2008). Based on MAIC, Chinese scholar Bu Danran tested the impact of mindfulness intervention on tennis players' mindfulness level, fluency experience and sports performance. According to the data, athletes' mindfulness level, mood state and fluency experience of traits have been significantly improved (Bu, 2015). For the relationship between the two, Yin Yuanmei intervenes in shooting athletes with the help of mindfulness training program, introduces emotional regulation self-efficacy, and confirms its regulatory role between mindfulness and smooth experience (Yin, 2015). In summary, using different mindfulness training methods to intervene athletes in different sports, the results all show that mindfulness training can improve athletes' fluency (Li and Sun, 2000; Hasker, 2010; Liu et al., 2016). In this study, meta-analysis method was used to integrate relevant data for quantitative analysis, and the results showed that mindfulness training was conducive to improving athletes' fluency state and experience [SMD =0.99, 95%CI (0.02, 1.96), p = 0.05]. Both of them showed marginal significance (p = 0.05), which may be related to the fluency state being a higher psychological state of competitive sports psychology, and it may also be related to the level of athletes' trait mindfulness and the time effect of mindfulness training. It is suggested to increase the relevant empirical research in this field.

5.3 Influence of mindfulness training on psychological anxiety of athletes

The arena is like a battlefield, and athletes inevitably have pressure in this special environment, resulting in anxiety (Anshel and Wells, 2000). Competition pressure has a negative impact on athletes' competitive performance on the arena. Therefore, it is particularly important to find out the source of pressure and relieve pressure and anxiety. The source of pressure mainly comes from internal and external factors, including coaches, referees, players, opponents, spectators, time, environment, competition results, etc. The main internal factors are the athlete's ability level, concentration, self-awareness, self-confidence, sports recovery and so on. Some of these factors are uncontrollable, in the face of uncontrollable factors, the most important thing is to learn and have the ability to self-regulate the physiological and psychological state, give full play to their own level, and achieve the best sports performance (Scoffier et al., 2010). Daily mental training is a compulsory course for every athlete, and having a good mental state is the premise of excellent performance in the competition. As a psychological intervention method, mindfulness training makes up for the shortcomings of traditional psychological skills training. It does not emphasize the establishment of the best psychological state, does not control and change the internal negative state, and advocates the attention to the present and acceptance without judgment. The mindfulness re-perception model holds that mindfulness contains three elements: attention, purpose and attitude, and its core mechanism is re-perception (Shapiro et al., 2006). Later, Brown et al. concluded that through re-perception or

de-self-centralization, mindfulness training can strengthen non-judgmental evaluation of experience, weaken emotional bias toward stimulus perception, and help individuals avoid ineffective and counterproductive adverse emotional states as much as possible (Brown et al., 2007). Relevant foreign studies have shown that mindfulness meditation training can enhance positive emotions, and with the increase of trait mindfulness, positive emotions are gradually enhanced (Nyklíček and Kuijpers, 2008; Zautra et al., 2008; Orzech et al., 2009). Relevant meta-analysis found that mindfulness training, as a clinical intervention, can help patients alleviate a variety of mental health problems and improve mental function (Baer, 2003). Thompson et al. confirmed that mindfulness training can improve athletes' mental state during sports, increase their acceptance of experience, improve happiness and mobility, and reduce the risk of anxiety, stress and burnout (Thompson et al., 2011). Studies have found that MAC training can alleviate and reduce state anxiety during competition (Piet et al., 2012; Forsyth and Eifert, 2016). Domestic research has also found that mindfulness training can reduce the level of trait anxiety and self-awareness of athletes, and improve the tendency to deal with problems and emotions (Zhao and Zeng, 2013). With the enhancement of mindfulness tendency during sports, the brain will focus on the current sports task, ignore the factors unrelated to the game, temporarily forget the pain, anxiety, pressure and other factors, and devote themselves to it, so as to obtain the best sports performance (Brotto et al., 2012). It can be seen that mindfulness has a regulating effect on athletes' emotions (Chen et al., 2011). This study sorted out the data of the included literature, and 7 studies discussed the impact of mindfulness training on the psychological anxiety of athletes. Through the integration of the data, it was found that mindfulness training could reduce the psychological anxiety of athletes, and the result was statistically significant ($p = 0.006$), which was consistent with previous studies by scholars. Therefore, mindfulness training can be applied to the field of sports as an alternative psychological intervention to traditional mental skill training.

5.4 Impact of mindfulness training on athletes' performance

Competitive sports are full of competition and challenges, athletes are under various pressures and events at the same time, but also constantly improve their motor skills, in order to obtain good sports performance and excellent sports results. Sports performance is most intuitively reflected in the athletic performance of the athletes, therefore, to improve the athletic skill level of the athletes and promote their athletic performance is the main goal of the coach and the team. Mindfulness training in the field of sports began with the article "Mindfulness Meditation Training in University and Olympic Rowing" by Western scholars such as Kabat Zinn. The emergence of mindfulness training methods has gradually become an alternative to mental skill training in the traditional sense of improving sports performance (Moore, 2003). The application of mindfulness training in sports environment can improve athletes' performance, mental state and overall happiness (Gardner and Moore, 2012). At present, domestic and foreign studies have proved the positive role of mindfulness in improving attention, regulating emotional status, and improving sports performance (Sappington and Longshore, 2015; Huang and Ning, 2017) conducted a systematic review of relevant studies on the intervention of mindfulness training on athletes, and concluded that mindfulness-based mental training methods can help improve athletes' competitive performance. Jouper and Gustafsson (2013) uses mindfulness training with shooters to help them regain their confidence and be fully engaged (John et al., 2011). Timothy conducted a questionnaire survey on the rowers' self-efficacy, team efficacy belief, mindfulness and fluency. The research showed that self-efficacy and team efficacy belief were significantly correlated with mindfulness, fluency and sports self-confidence, and the higher the level of mindfulness, the higher the level of self-efficacy and team efficacy belief. It is more helpful for athletes to improve their performance (Pineau et al., 2014). Wan Chunmei conducted an 11-week intervention on the young athletes of the national diving team with mindfulness training, and the results showed that after the intervention, the level of mindfulness of the athletes was improved, and the test scores were also improved, indicating that mindfulness training is conducive to improving sports performance (Wan, 2019). This study conducted data integration of the included studies. Six studies discussed the intervention effect of mindfulness training on athletes' sports performance. The comparison between the mindfulness training experimental group and the control group also showed consistent research conclusions with other scholars, which proved that mindfulness training can improve athletes' sports performance and performance [SMD =0.92, SMD =0.92, SMD =0.92, SMD =0.92, SMD =0.92, SMD =0.92, SMD =0.92, SMD =0.92, SMD =0.92, SMD =0.92, SMD =0.92, SMD =0.92. 95% CI (0.39, 1.45), $p = 0.0006$], the results were statistically significant. Therefore, the application of mindfulness-based psychological intervention to the field of competitive sports has achieved remarkable results and can be regarded as an effective way to improve performance.

5.5 The effect of different mindfulness training on training results

In order to make the course schedule fit with the time characteristics of sports training, different mindfulness training courses are also arranged differently. Table 2 summarizes and compares the course schedule design of these training methods:

From the findings of the research results, the effects of the four training methods on the level of mindfulness and acceptance have been effectively proved, but the empirical research results related to the effects of different mindfulness training methods are also different. For example,

TABLE 2 Course time design of main mindfulness training methods.

	MAC	MSPE	MMTS	MAIC
Time span	7 ~ 12 weeks	4 weeks	6 weeks	7 ~ 8 weeks
Class hour	7 ~ 12	4	12	7 ~ 8
Length per class hour	1 h	2.5 h	0.5 h	1 h

it is found that both MAC training and MAIC training are effective in improving athletic performance. Long-term follow-up studies have also proved that MSPE training is effective in improving athletic performance (Thompson et al., 2011). However, MMTS training is not designed to directly target the impact on sports performance, so the results of relevant studies do not reflect its impact on sports performance.

Athletes who participate in mindfulness training must meet the criteria of not having any physical or mental illness, hearing impairment, and not smoking, taking drugs and drinking alcohol. There are also potential risks in the experiment. Participants did not consume caffeine or alcoholic beverages in the 12 h before the experiment, and did not exercise in the 12 h before the experiment, especially during the test period (John et al., 2011). In fact, multiple studies have shown that raising awareness too closely during mindfulness practices can make mental health conditions worse, including increasing the risk of depression, anxiety, schizophrenia, or substance abuse, and decreasing the ability to tolerate pain. Mindfulness researchers and project developers have recognized that while reversing the flaws in MRPs can improve well-being, little attention has been paid to the negative effects of overdoing these processes on well-being (Britton, 2019). Therefore, the duration and frequency of mindfulness training should be strictly grasped during the experiment to minimize the probability of risk.

6 Limitations and future studies

6.1 Limitations

This study integrates the research results of mindfulness training on athletes' sports performance through meta-analysis, which is larger than the sample size of a single empirical study and the research results are more convincing. However, there are also shortcomings in this study: (1) Only published literatures were included in this study, and unpublished studies were not taken into account. The research data are not comprehensive enough, which will affect the reliability of the research results to some extent. (2) The athletes included in the study were engaged in different sports, and the intervention methods, intervention cycles, time and frequency were also different, which may be the reason for the high heterogeneity. (3) The protocol of this meta-analysis was not registered, which may affect the quality and replicability of the findings. However, this study applied stringent strategies to maximize the retrieval of relevant articles and to prevent the inclusion of duplicated studies. For example, articles authored by the same individuals, affiliated with the same institution, or sharing the same trial registration ID were considered at high risk of duplication. Additionally, full information regarding sources and corresponding search strategies were reported to facilitate perfect replication of this study, thus mitigating this limitation to some extent. (4) The number of studies included in this meta-analysis was limited, especially for the outcome of flow. The power to detect dose–response effects was similarly limited for this reason. Specifically, it remains unclear to what extent mindfulness could maximize its effects on sports performance. Only a few studies examined this feature(Wang et al., 2023)., which warrants further investigations to validate, the heterogeneity was high in most of the syntheses, which may affect the external validity of our findings.

6.2 Future studies

Based on the research prospects of this study: (1) It is suggested to further strengthen the practical application research of mindfulness training, expand the sample size, and strengthen the comparative study between different exercise items and intervention modes. (2) Studies on mindfulness training and sports performance mostly focus on athletes. Future studies may consider focusing on college students majoring in physical education to provide more powerful evidence for mindfulness training and sports performance. (3) It is suggested to strengthen the empirical research on fluency from the differences in trait mindfulness level and time effect of mindfulness training. (4) Future studies should try the relevant studies and compare the effects of different mindfulness training on the end goal and whether there are different effects on the training program. (5) The application of the new technology is still limited, and it is hoped that future research will apply VR to mindfulness training.

7 Conclusion

Meta-analysis evidence shows that mindfulness training can significantly improve athletes' sports performance, which is embodied in the level of mindfulness, fluency, psychological anxiety and other psychological performance, as well as performance and other behavioral performance. As a psychological intervention method, mindfulness training can improve the level of mindfulness, fluency and performance of athletes, reduce the level of psychological anxiety, and the effect size reaches the level of large effect value. The course span is 7 to 12 weeks, the number of lessons is 7 to 12 times, each lesson length of 1 h mindfulness training is effective in improving athletic performance, and helps athletes to be in the best condition. It is worth noting that mindfulness training has a marginal effect on improving fluency.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

XS: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. ZY: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. XF: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1375608/full#supplementary-material

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Effect of aerobic exercise on the improvement of executive function in children with attention deficit hyperactivity disorder: a systematic review and meta-analysis

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Objective: Aerobic exercise (AE) interventions are beginning to be used as an emerging adjunctive treatment modality in the treatment of children with Attention Deficit Hyperactivity Disorder (ADHD). However, to date, there is no substantial evidence to support the improved effects of aerobic exercise intervention in children with ADHD aged 6–12 years. This study aims to investigate the effect of aerobic exercise therapy on executive function in children with attention deficit hyperactivity disorder aged 6–12 years.

Method: We conducted a systematic review and meta-analysis using PubMed and Web of Science. The cut-off date was June 1, 2023. The aim was to assess the impact of aerobic exercise interventions on children with ADHD and all randomized controlled trials eligible for aerobic exercise interventions for children with ADHD were included. Nine randomized controlled trials were screened for eligibility for systematic evaluation, and the nine studies were assessed for risk of bias using the PEDro score and the GRADE Quality of Evidence Evaluation System for quality grading of outcome indicators. After testing for heterogeneity, a random-effects model was selected for analysis. Finally, meta-analyses and regression analyses were performed on the core functions (inhibitory control, cognitive flexibility, and working memory) and subgroups of the nine studies on executive function using Revman 5.4 and Stata 16.0.

Results: The risk of bias evaluation showed a mean PEDro score of 7.78, and of the nine studies, two were rated as having excellent methodological quality, while the remaining seven had a good level of evidence, and the GRADE evidence evaluation showed that the outcome indicators were all of moderate quality. Inhibitory control [SMD = 0.83,95% CI (0.37–1.29), Z = 3.51, $p = 0.0005$], cognitive flexibility [SMD = 0.65,95% CI (0.37–0.93), Z = 4.58, $p < 0.00001$], and working memory [SMD = 0.48,95% CI (0.02–0.95), Z = 2.03, $p = 0.04$] were statistically significant, with effect sizes of moderate or higher; furthermore, in subgroup analyses type of intervention, duration, intensity, and medication use had different effects on inhibitory control and cognitive flexibility, and the combined IC, CF statistic found that a single category of aerobic exercise ($\beta = 0.867$, $p < 0.001$), moderate intensity ($\beta = 0.928$, $p < 0.001$), 6–12 weeks

(β = 0.804, $p < 0.001$), 60-90 min ($\beta = 0.894$, $p < 0.001$), and the use of medication ($\beta = 1.202$, $p = 0.002$) were better for overall improvement in EF.

Conclusion: Aerobic exercise therapy significantly improved executive functioning in children with ADHD, showing above moderate effect sizes especially in inhibitory control, cognitive flexibility, and working memory. Aerobic exercise therapy can be used as a reference in improving executive function in children with ADHD, but given the limitations of this study, it should be used with caution when applied in clinical settings.

KEYWORDS

aerobic exercise, ADHD, executive functions, children, meta-analysis

1 Introduction

Attention deficit hyperactivity disorder (ADHD) is one of the most common neurodevelopmental disorde (Brassell et al., 2017; Thapar et al., 2017; Du Rietz et al., 2021). The prevalence of ADHD is approximately 5.29% worldwide (Posner et al., 2020). Up to 7.2% of children have ADHD and the symptoms of ADHD affect 60% of children into adulthood (Thomas et al., 2015; Sibley et al., 2017). According to the Diagnostic and Statistical Manual of Mental Disorders, fifth edition, people with ADHD mainly present with symptoms of hyperactivity, impulsivity, and inattention (American Psychiatric Association, 2013), often with a learning disorder, conduct disorder, or coexisting oppositional defiant disorder mental illnesses (Biederman and Faraone, 2005). Inconsistency with normal developmental levels can cause various problems in academic and social activities in children with ADHD (American Psychiatric Association and DSM Task Force, 2017), resulting in learning difficulties, impaired social skills, and strained family–parent relationships (Harpin, 2005), such as difficulty completing studies, lower social skills, and increased family conflict. In addition, they are more likely to develop comorbidities such as depression, anxiety, and developmental coordination disorders (Barnard-Brak et al., 2011).

Executive functioning (EF) is the regulation of basal cognition through top-down higher mental processes that are essential for reaching goal-directed adaptive behaviors and maintaining attention (Diamond, 2013, 2020). The core symptoms of ADHD stem from major deficits in EF, with most patients exhibiting one or more such deficits (Nigg et al., 2005; Willcutt et al., 2005). The key components of EF, including control over updating the content of working memory (WM), shifting (i.e., task switching), and inhibitory control (IC), form the infrastructure of EF (Miyake et al., 2000). Central to the psychological and behavioral characteristics of ADHD patients and closely related to their performance in school, work, and social settings are the three core functions of IC, cognitive flexibility (CF), and WM. Among them, cognitive flexibility is mainly divided into two subtypes: reactive and spontaneous (Eslinger and Grattan, 1993), reactive CF refers to an individual's ability to quickly adjust his or her thinking strategies and behavioral patterns in response to changes in the external environment, whereas spontaneous CF refers to an individual's ability to generate a diverse range of new ideas on his or her own without external pressures to make changes, explore the unknown and the ability to adjust their thinking (Ebersbach and Hagedorn, 2011). Deficits in these three core functions are directly linked to the everyday performance of ADHD patients, such as the extent of their learning difficulties, social challenges, and behavioral problems (Diamond, 2013), which play an important role in ADHD patients' physical and mental health, behavioral management, learning efficacy, and social interaction (Diamond, 2013; Mueller et al., 2017). Thus, improvement of EF in children with ADHD is extremely important. Commonly used treatments use medication (methylphenidate or atomoxetine) or behavioral interventions (Tantillo et al., 2002; Barnard-Brak et al., 2011), and traditional treatments are expensive, making them unaffordable for patients' families (Cornelius et al., 2017). It also has potential risks such as slowed growth, appetite suppression, abdominal pain, headache, and difficulty sleeping (Swanson et al., 2007; Newcorn et al., 2010), and lacks significant long-term effects (Molina et al., 2009; Cornelius et al., 2017).

An alternative intervention is aerobic exercise (AE). AE is a physical activity in which inhaled oxygen adequately meets the body's energy requirements during exercise through aerobic metabolism (William, 2006) by performing low-to-high-intensity movements for long periods (Sharon, 2007). In recent years, numerous studies have found (Liu et al., 2022) that improvement in EF deficits in children with ADHD can be achieved with AE (Chang et al., 2014; Brassell et al., 2017; Miklos et al., 2020). Chang et al. (2014), Brassell et al. (2017), and Miklos et al. (2020), conducted trials with aerobic fitness (Brassell et al., 2017), swimming exercise (Chang et al., 2014), and running exercise (Miklos et al., 2020) respectively, and found significant improvement in IC or CF. In addition, some studies have found that cerebral oxygenation and cerebral blood volume improve at higher levels of exercise intensity, which in turn lead to improvement in prefrontal-dependent cognitive performance (Gondoh et al., 2009; Hwang et al., 2016). However, in Diamond and Ling (2019), AE and resistance intervention training were considered the least effective among the methods to improve executive function (Diamond and Ling, 2019), and similarly, another study concluded that AE had no significant effect on EF improvement (Takacs and Kassai, 2019).

Currently, most research has focused on exploring the effects of exercise interventions on ADHD improvement (Cerrillo-Urbina et al., 2015; Seiffer et al., 2022), and only some have explored the improvement effect of exercise interventions on EF (Welsch et al., 2020; Sung et al., 2022). Moreover, some found positive evidence of improvement after reviewing AE interventions in children or

adolescents with ADHD in subgroups (Liang et al., 2021). However, both randomized controlled trials (RCT) and non-RCT experimental studies were included in these studies, which also included children, adolescents, and adults of different ages. Only a few explored the effects of AE on IC, CF, and WM core functions in EF (Liang et al., 2021). Thus, there is a lack of a systematic evaluation of the effectiveness of AE interventions to improve IC, CF, and WM functioning in 6–12-year-old children with ADHD. Therefore, the main objectives of this review were (1) to systematically evaluate the effects of AE on core functions in EF in ADHD patients aged 6–12 years and (2) to explore the effects of AE intervention type, intensity, medications taken, duration and periodicity on the improvement of EF in children with ADHD.

Therefore, the participants in this study comprised children aged 6–12 years diagnosed with ADHD. Children in this age group are the key target of ADHD intervention research and effective interventions are particularly important for their learning and social development. The interventions were AE in either a combination of movements or a single event, including AE with added neurocognitive training. To accurately assess the effects of AE on EF in children with ADHD, we compared an experimental group undertaking an AE intervention with a control group undertaking conventional or other exercise treatments. We then measured the effects of AE on EF in children with ADHD, particularly IC, CF, and WM, and their significance in subgroup analyses. The study design was based on an RCT of an ADHD intervention to ensure the validity and reliability of the findings and minimize bias through random assignment.

Our systematic review and meta-analysis aimed to evaluate the effects of AE on EF in children with ADHD aged 6–12 years and provide more definitive intervention guidelines for this group of children. Analyzing the effect of AE on the improvement of core functions in EF should not only enhance the findings in the literature, but also provide a scientific basis for the adjunctive treatment of EF in children with ADHD. In addition, this study explores the effects of the type, intensity, medication taken, and time and period of the AE intervention on the improvement effect of EF, further refining the application of AE interventions used in ADHD treatment.

2 Methods

In this study, we did not pre-register for meta-analysis. We will do our best to ensure the credibility and transparency of the study by providing a detailed description of the study methodology, interpretation of results, and data sharing. Readers are welcome to share any questions or suggestions regarding our research methods and are willing to provide further explanations and discussions.

2.1 Search strategy

In this study, a systematic evaluation and meta-analysis were conducted according to the criteria specified in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Liberati et al., 2009). Literature searches were conducted in the PubMed and Web of Science databases with a publication deadline of June 1, 2023. To search for relevant topics, titles, and abstracts, the following keywords were used in both databases: "children," "physical activity," "exercise," "running," "cycling," "swimming," "executive functioning," "ADHD," and "attention deficit hyperactivity disorder." For example, the following search strategy was used in Web of Science: #1: (TS = ("ADHD" OR "Attention Deficit Disorder with Hyperactivity")); #2: (TS = ("aerobic exercise" OR "physical activity" OR "exercise" OR "children" OR "running" OR "cycling" OR "swimming")); #3: (TS = ("executive function")); and #4: #1–#3. Additionally, the literature was searched and screened by two reviewers (GY and HS) independently.

2.2 Selection criteria and screening

Studies eligible for inclusion in this study were selected using the following criteria: (1) study design: RCT based on ADHD intervention; (2) study population: children aged 6–12 years with confirmed ADHD; (3) type of intervention: the experimental group used a combination of movement-based or single-item AE (e.g., "Shape Up," combined aerobic and neurocognitive, cycling, running, table tennis, swimming AE, etc.) as interventions in the study, and the control group was treated with conventional or other exercise treatment; (4) Intervention time: the experimental group conducted more than one aerobic exercise session; (5) Outcome indicators: using tools related to task testing (e.g., Tower of London, Digit Span Forward, Backward Test, Go-No-Go Task, Flanker Task Stroop Task, Trail Making Task, Wisconsin Card Sorting Test) to investigate inhibition switching, CF, and WM indicators in EF in children with ADHD.

Exclusion criteria for this study: (1) literature not written in English; (2) case reports; (3) reviews; (4) conference abstracts; (5) book chapters or other; (6) studies containing other case patients; (7) exclusion of peer-reviewed articles.

2.3 Data extraction

Two reviewers (GY and QL) extracted EF test data from the full text of the included studies, and issues of disagreement were discussed and resolved by two other reviewers (QL and JL). Basic characteristics of children with ADHD (mean age in different groups, gender/number), experimental site, exercise intensity, medication use or not, intervention design (type of AE, intervention period, intervention frequency, intervention intensity), and outcome indicators (IC, CF, WM) of the task tests were extracted from the included literature. As well as extracting data on the occurrence of adverse events, this includes, but is not limited to, any physical discomfort, injuries, or other health problems that may result from participation in aerobic exercise. We extracted the mean (Mean) and standard deviation (SD) of each task test performed before and after the intervention in the experimental and control groups of ADHD children with EF from the included studies, while recording the sample size (n) of the two groups and performing meta-analysis of raw scores of the different task tests (e.g., color-word, the sum of correct responses, non-perseverative errors, total correct, accuracy, etc.), for meta-analysis. If the exact data were not provided in the article, they were obtained by contacting the authors, or they could be calculated from the data provided in the article. In addition, if experimental data were reported in graphical form in the article, Get Data Graph Digitizer software was used to

measure the data to obtain the mean and SD of the test before and after the two groups.

2.4 Data analysis

The amount of change in inhibitory control, cognitive flexibility and working memory from pre to post intervention was extracted, and if the original study directly reported means and standard deviations for the outcome variables, these reported values could be used directly. If the original studies did not directly report means and standard deviations for the outcome variables, we then needed to take Corr as 0.40 or 0.50 according to the guidelines in section 16.1.3.2 of the Cochrane Handbook 5.0.2 and follow the Mean E, change = Mean E, final-Mean E, baseline, $SD\,E,change = \sqrt{SD^2_{E,baseline} + SD^2_{E,final} - \left(2 * Corr * SD_{E,baseline} * SD_{E,final}\right)}$ formula to calculate the mean and standard deviation of the pre- and post-intervention outcome variables to meet the data requirements needed to perform Meta-analysis. Meta-analysis as well as meta-regression analyses were then performed using Review Manager Software V.5.4 and stata/map 16.0 on the means and standard deviations extracted for changes in outcome variables before and after the intervention. Standardized mean difference (SMD) was used as the combined statistic for this study due to the different outcome indicators of the test instruments, and 95% confidence interval was used as the combined data effect (Liu et al., 2022). For data on adverse events, descriptive statistics will be used to summarize the reporting of adverse events in the included studies. To improve the robustness of the results, we analyzed the data using a random-effects model, which more accurately reflects differences in effects across studies and provides a more representative estimate of the combined effect. And Hedges' g method was used to quantify the effect sizes of the exercise interventions, which were categorized into three classes according to the common criteria for effect size estimation: a small effect of 0.2 at least less than 0.5, a medium effect of 0.5 at least less than 0.8, and a large effect of 0.8 and above (Hanley et al., 2003). After combining the statistics, if $p < 0.05$, there was statistical significance; if $p > 0.05$, there was no statistical significance.

2.5 Qualitative analysis

In this study, to ensure the reliability of the cited evidence, the PEDro scoring system was used to evaluate the risk of bias of the nine selected papers (Yang et al., 2022). The PEDro scoring system consists of eleven criteria: explicitly setting the inclusion criteria for the study participants, the randomization of the participant selection process and the concealment of the allocation in the grouping, the similarity at baseline and blinding of participants, therapists, and evaluators, a follow-up rate of greater than 85%, the use of intention-to-treat analysis, statistical comparisons between groups, and accurate reporting of data points and indicators of variability are all key factors in ensuring the reliability and validity of the study results. According to the PEDro scale, each item is scored out of 1 and is based on a yes or no response, with scores between 6–8 considered good, 9–10 considered excellent, 4–5 considered acceptable, and less than 4 indicating quality of evidence. 4 indicated that the evidence was of low quality (Maher et al., 2003). Two independent reviewers (GY and QL) were responsible for performing the assessment of the risk of bias of the literature included in the study, and any disagreements were resolved by consulting the corresponding author (JL).

2.6 Assessment of the certainty of evidence

GRADE (Grading Recommendations to Assessment Development and Evaluation system) is a system for categorizing and evaluating the quality and strength of evidence, which is one of the international standards today (Liu et al., 2020). The studies included in the study were RCTs with high-grade evidence, and we rated the level of evidence based on five aspects: risk of bias, indirectness, inconsistency, imprecision, and publication bias (Zhang et al., 2019). The quality of evidence was graded in 4 levels of high (high), moderate (moderate), low (low), and very low (very low) for the main outcome indicators (IC, CF, and WM).

3 Results

3.1 Identification of studies

We retrieved 309 studies from Web of Science data and 121 studies from the PubMed database. Two reviewers (GY and QL) went through a rigorous screening process, excluding studies unrelated to the study design after the title and abstract screening, and removing duplicate studies, review articles and conference-type studies. Forty potential studies were entered into the full-text evaluation screening, 19 unrelated studies were excluded after the full-text screening, and two studies without EF outcome indicators were excluded. Eighteen studies were screened for full-text review, data from 5 studies were excluded without contacting the authors, and four studies that were AE interventions but not RCT trials were excluded. After the screening, nine studies met the criteria for inclusion in the systematic evaluation and meta-analysis, and the detailed study screening process is shown in Figure 1.

3.2 Description of included studies

A total of nine RCT trials were included in this study for analysis, and Table 1 shows the relevant characteristics of the included studies. The studies involved 377 children with ADHD (300 boys and 77 girls), with a mean age ranging from 9.31 ± 1.33 years; 133 of the children with ADHD used medication, with one study not reporting medication use (Nejati and Derakhshan, 2021). The trials included in this study were from 3 different countries, and all studies were conducted in Asia and Europe, namely China (Chang et al., 2012, 2022; Pan et al., 2015, 2016; Liang et al., 2022), Switzerland (Benzing et al., 2018; Benzing and Schmidt, 2019), and Iran (Memarmoghaddam et al., 2016; Nejati and Derakhshan, 2021).

Of the blinding of patients and trialists implemented in the nine included RCT studies, one was single-blinded (Benzing et al., 2018), four studies were unblinded (Chang et al., 2012; Pan et al., 2015; Memarmoghaddam et al., 2016; Benzing and Schmidt, 2019), and the remaining four study designs were not reported (Pan et al., 2016; Nejati and Derakhshan, 2021; Chang et al., 2022; Liang et al., 2022).

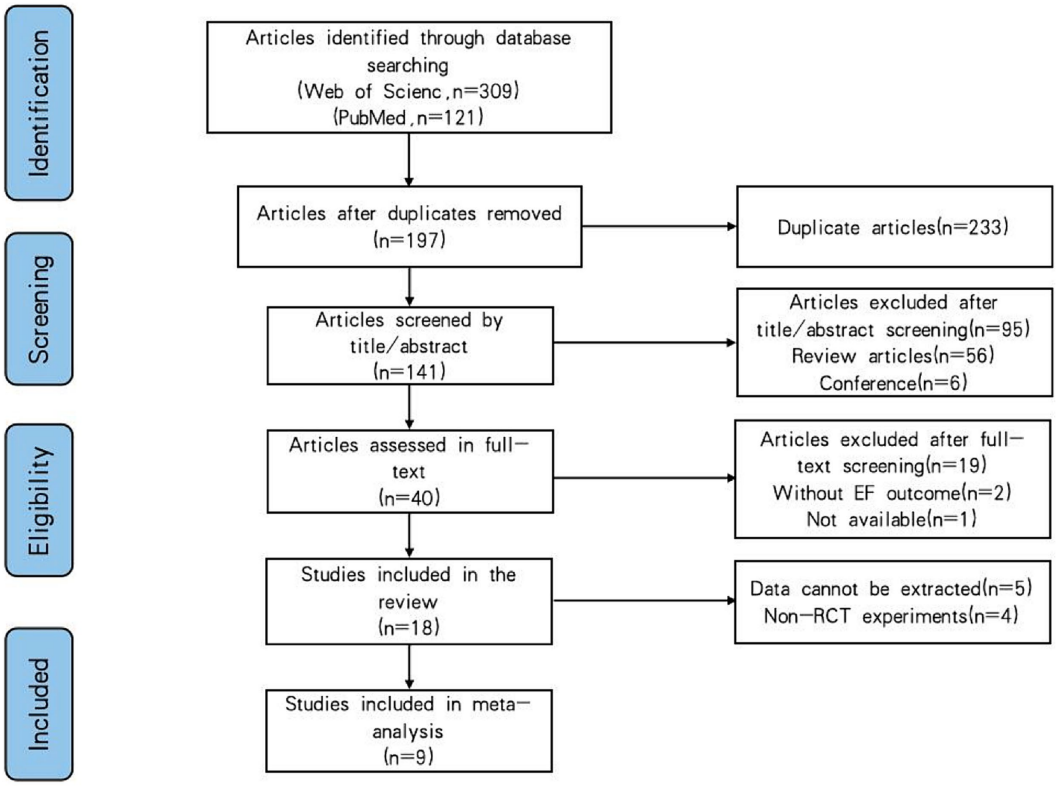


FIGURE 1
Flowchart of the selected literature.

Regarding intervention duration, two studies used a single 15–30 min intervention (Chang et al., 2012; Benzing et al., 2018) and the other seven studies were 4–12 weeks (Pan et al., 2015; Memarmoghaddam et al., 2016; Pan et al., 2016; Benzing and Schmidt, 2019; Nejati and Derakhshan, 2021; Chang et al., 2022; Liang et al., 2022). In terms of intervention frequency, studies were 2–3 times per week for 30–90 min each time. In addition, all nine studies performed the intervention as a single category of AE, combined with a combination of AE classes. Four studies used a single-category AE intervention (Chang et al., 2012, 2022; Pan et al., 2015, 2016), using table tennis (Pan et al., 2015, 2016; Chang et al., 2022), and running (Chang et al., 2012), respectively, and five studies used a combination category AE intervention (Memarmoghaddam et al., 2016; Benzing et al., 2018; Benzing and Schmidt, 2019; Nejati and Derakhshan, 2021; Liang et al., 2022), using a game console for "Shape Up" AE with a combination of 6 types of movements (Benzing et al., 2018; Benzing and Schmidt, 2019), AE with a combination of different sports (e.g., soccer, basketball, etc.) (Memarmoghaddam et al., 2016), and AE with a combination of movements designed to enhance cognitive performance (Nejati and Derakhshan, 2021; Liang et al., 2022). Among the nine RCT trials in the control group, there were five not receiving any treatment (Pan et al., 2015; Memarmoghaddam et al., 2016; Benzing and Schmidt, 2019; Chang et al., 2022; Liang et al., 2022), two studies conducted with Watch the sports video (Benzing et al., 2018; Chang et al., 2012) and 2 studies were conducted with running and not receiving new sport activities (Pan et al., 2016; Nejati and Derakhshan, 2021), and it is worth mentioning that in the study by Pan et al. (2016) both experimental and control groups performed aerobic exercise workouts, but there was no cognitive load in the control group's exercise program. Participants' heart rates were controlled within 50 to 80% of heart rate reserve (HRR) when they received the intervention in nine trials. Of these, intervention intensity was designated as moderate (moderate intensity) in 4 studies (Chang et al., 2012, 2022; Pan et al., 2015, 2016) and between moderate to vigorous intensities (moderate to vigorous intensities) in another 4 studies (Memarmoghaddam et al., 2016; Benzing et al., 2018; Benzing and Schmidt, 2019; Liang et al., 2022). In addition, one study did not report a specific intervention intensity in the original literature (Nejati and Derakhshan, 2021).

As shown in Table 2. The included RCT studies all used at least one or more EF testing instruments, with pre-and post-tests of IC, CF, raw scores of WM (correctness and error rate scores), and reaction time in the EF of children with ADHD. Of these, six studies used the Stroop Task, three studies used the Flanker Task and two studies used the Go-No-Go Task to test IC; two studies and four studies tested CF using the Flanker Task, Wisconsin Card Sorting Test, respectively; two studies used the Color Span Backwards Task, and two other studies used the N-Back Test, Tower of London Test to test WM.

In addition, we observed that no adverse events were reported in the experimental groups participating in aerobic exercise in all nine included studies. This observation emphasizes the reliability of aerobic exercise for children with ADHD in terms of safety. It can provide a solid theoretical basis for future research and evidence for clinical practice regarding the safety and efficacy of aerobic exercise interventions to complement other treatment options in improving executive function in children with ADHD.

TABLE 1 Characteristics of included trials in this review.

Author, year (country)	N (M/F)	Age (M ± SD)	RCT design	Drug use	Measurement stools/indicator	Intensity	Intervention method	Exercise categories	Frequency of exercise	Main effect
Pan et al. (2016) (Taiwan, China)	*N* = 32 (M = 32/F = 0)	EG:8.93 ± 1.49 CG:8.87 ± 1.56	NR	EG = 7 CG = 7	IC:ST	MI	EG: table tennis exercise CG: Not receiving new sport activities	SAE	12 weeks, 2 times/ week,70 min/each	IC:RS improves ($p < 0.01$)
Benzing et al. (2018) (Switzerland)	*N* = 46 (M = 38/F = 8)	EG:10.46 ± 1.35 CG:10.50 ± 1.41	SB	EG = 19 CG = 17	IC:FT CF:FT WM:CSBT	MVI	EG: "Shape Up "exergaming exercises CG: Watched a documentary report about mountain running	CAE	One session 15 min	IC:RT with potential to improve ($p < 0.05$); CF:RT with potential to improve ($p < 0.05$); WM:RS no improves ($p > 0.05$)
Benzing and Schmidt (2019) (Switzerland)	*N* = 51 (M = 43/F = 8)	EG:10.46 ± 1.30 CG:10.39 ± 1.44	NB	EG = 20 CG = 17	IC:ST CF:FT WM: CSBT	MVI	EG: "Shape Up" exergaming exercises CG: Not receiving any treatment (waiting-list)	CAE	8 weeks, 3 times/ week, 30 min/each	IC:RT improves ($p < 0.05$); CF:RT improves ($p < 0.05$); WM:RS no improvement ($p > 0.05$)
Memarmoghaddam et al. (2016) (Iran)	*N* = 36 (M = 36/F = 0)	EG:8.31 ± 1.29 CG:8.29 ± 1.31	NB	EG = 0 CG = 0	IC:ST, GNGT	MVI	EG: Exercise program (such as football, basketball, for aerobic exercise) CG: Did not receive any intervention	CAE	8 weeks, 3 times/ week, 90 min/each	IC:RS and RT improves ($p < 0.05$)
Pan et al. (2015) (Taiwan, China)	*N* = 30 (M = 30/F = 0)	EG:9.08 ± 1.43 CG:8.90 ± 1.66	NB	EG = 9 CG = 9	IC:ST CF:WCST	MI	EG: table tennis exercise CG: Not receive any intervention	SAE	12 weeks, 2 times/ week, 70 min/each	IC:RS significantly improves ($p < 0.01$) CF:RS improves ($p < 0.05$)
Chang et al. (2022) (Taiwan, China)	*N* = 32 (M = 26/F = 6)	EG:8.31 ± 1.30 CG:8.38 ± 1.31	NR	EG = 4 CG = 4	IC:ST CF:WCST	MI	EG: Actual table tennis training CG: No additional training	SAE	12 weeks, 3 times/ week, 60 min/each	IC:RS improves; CF:RS improves ($p < 0.01$)
Nejati and Derakhshan (2021) (Iran)	*N* = 30 (M = 30/F = 0)	EG:9.43 ± 1.43 CG:9.43 ± 1.43	NR	EG = NR CG = NR	IC: GNGT CF: WCST WM: NBT	NR	EG: Exercise for cognitive improvement and rehabilitation (EXCIR) CG: Running	CAE	4–5 weeks, 3 times/ week, 40–50 min/ each	WM: Improved RS and response time ($p < 0.05$); CF: RS improve ($p < 0.05$); IC: RS improve ($p < 0.05$), RT no difference ($p > 0.05$)
Liang et al. (2022) (China)	*N* = 80 (M = 28/F = 52)	EG:8.37 ± 1.42 CG:8.29 ± 1.27	NR	EG = 0 CG = 0	IC: FT CF: TMT WM: TOLT	MVI	EG: Combined aerobic and neurocognitive-exercise CG: Without taking any additional exercise program or medical treatment	CAE	12 weeks, 3 times/ week, 60 min/each	IC: RT improves, RS no significant effect ($p < 0.01$); WM:RS no significant effect, RT improves ($p < 0.001$); CF: RS no significant effect, RT improves ($p < 0.05$)
Chang et al. (2012) (Taiwan, China)	*N* = 40 (M = 37/F = 3)	EG:10.42 ± 0.95 CG:10.4 ± 0.875	NB	EG = 10 CG = 10	IC:ST CF: WCST	MI	EG: run on a treadmill CG: Watched a running/exercise-related video	SAE	One session 30 min	IC:RS improves ($p < 0.05$) CF:RS improves ($p < 0.05$)

N, Number; M, Male; F, Female; M, Mean; SD, Standard Deviation; NR, No report; SB, Single-blind; NB, Non-blind; EG, experimental group; CG, control group; IC, inhibitory control; CF, cognitive flexibility; WM, working memory; ST, Stroop task; WCST, Wisconsin card sorting test; FT, flanker task; CSBT, color span backwards task; ST, Simon task; GNGT, go-no-go task; NBT, N-back test; TOLT, tower of london test; TMT, trail making test; MI, Moderate intensity; MVI, moderate to vigorous intensities; SAE, single aerobic exercise; CAE, combination aerobic exercise; RT, response time; RS, raw score.

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TABLE 2 EF test characterization chart.

EF tests used	Main test indicators	Study	Adverse event
Stroop task	Inhibitory control	Pan et al. (2016), Benzing and Schmidt (2019), Memarmoghaddam et al. (2016), Pan et al. (2015), Chang et al. (2022), and Chang et al. (2012)	No
Flanker task	Inhibitory control cognitive flexibility	Benzing et al. (2018), Benzing and Schmidt (2019) and Liang et al. (2022)	No
Go-no-go task	Inhibitory control	Memarmoghaddam et al. (2016) and Nejati and Derakhshan (2021)	No
Wisconsin card sorting test	Cognitive flexibility	Pan et al. (2015), Chang et al. (2022), Nejati and Derakhshan (2021), and Chang et al. (2012)	No
Tower of London Test	Working memory	Liang et al. (2022)	No
N-Back test	Working memory	Nejati and Derakhshan (2021)	No
Color span backwards task	Working memory	Benzing et al. (2018), Benzing and Schmidt (2019)	No

TABLE 3 Analysis of the methodological quality of the studies (PEDro scores).

Author (reference)	Item 1	Item 2	Item 3	Item 4	Item 5	Item 6	Item 7	Item 8	Item 9	Item 10	Item 11	Score
Pan et al., 2016	Y	Y	N	Y	Y	N	N	Y	Y	Y	Y	8
Benzing et al. (2018)	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	9
Benzing and Schmidt (2019)	Y	Y	Y	Y	Y	N	N	Y	Y	Y	Y	9
Memarmoghaddam et al. (2016)	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	7
Pan et al. (2015)	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	7
Chang et al. (2022)	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	7
Nejati and Derakhshan (2021)	Y	Y	N	Y	N	N	N	Y	Y	Y	Y	7
Liang et al. (2022)	Y	Y	Y	Y	N	N	N	Y	Y	Y	Y	8
Chang et al. (2012)	Y	Y	Y	Y	N	N	N	Y	Y	Y	Y	8

Range:0–11. Item 1: setting of appropriateness criteria; item 2: random assignment of participants; item 3: assignment concealment; item 4: similarity of groups at baseline; item 5: blinding of participants; item 6: blinding of therapists; item 7: blinding of evaluators; item 8: follow-up rate over 85%; item 9: use of intention-to-treat analyses; item 10: statistical comparisons between groups; and item 11: reporting of data points and indicators of variability.

3.3 Quality assessment

Table 3 presents the PEDro scoring details for the selected literature. For the nine randomized controlled trials (RCTs) involving aerobic exercise interventions, the average PEDro score was 7.78, indicating a high level of credibility. All nine studies were conducted as randomized controlled trials and were assessed for bias risk using the PEDro scoring system, resulting in respective PEDro scores. Among these nine studies, two were rated as having excellent methodological quality, while the remaining seven were assessed to have good evidence levels. It is noted that blinding of therapists and assessors was not reported in any of the nine studies, and only three studies reported blinding of participants (Pan et al., 2016; Benzing et al., 2018; Benzing and Schmidt, 2019). Overall, the literature included in this study demonstrated generally good methodological quality (Yao et al., 2021; Yong et al., 2021).

3.4 Characteristics of executive functions task testing

The Stroop Test in this study primarily assessed IC by asking participants to name colors while ignoring the meanings of color words. In particular, in the Stroop Color-Word condition, participants were required to demonstrate strong inhibition when confronted with conflicting color words and colors (Pan et al., 2015).

The Simon Task assessed IC by asking participants to respond quickly to the color of the star on the screen. This task emphasized the ability to inhibit symmetrical side responses; in other words, participants needed to provide intuitive responses when the response buttons were not aligned with the stimulus location (Benzing and Schmidt, 2019).

The Go-No-Go Task was used to assess IC by asking participants to respond when confronted with certain stimuli (Go stimuli) and inhibit responses when confronted with other stimuli (No-Go stimuli) (Nejati and Derakhshan, 2021).

The Wisconsin Card Sorting Test (WCST) focuses on assessing transferential cognitive flexibility, which is the individual's ability to adjust thinking strategies and behaviors in response to changes in goals or rules, as well as executive functions such as inhibitory control, and is used to analyze higher-order cognitive functioning in the frontal lobe of the brain. This tool is particularly valuable in assessing ADHD, revealing specific impairments in executive functioning (Chang et al., 2022).

The Trail Making Test (TMT) measures transferential cognitive flexibility and visual attention and is divided into two parts: numbers and numbers and letters. Participants are required to connect numbers or numbers and letters in sequence, and the time and quality of

completing the task can reflect their cognitive flexibility and ability to perform complex tasks (Liang et al., 2022).

The Flanker Task assessed CF and attention allocation by asking participants to make choices based on the direction of the fish in the center of the school. This task measured participants' ability to maintain goal-directed behavior in the face of distracting information and their flexibility to adjust strategies when task rules changed (Benzing et al., 2018).

The Color Span Backwards Task assessed visual WM by asking participants to memorize and repeat the sequence of different colored coins in reverse order (Benzing et al., 2018). It tested their memory capacity and attentional control by progressively increasing the number of items to be memorized.

The Tower of London Test assessed WM and planning skills by requiring participants to move a colored ball through a minimum number of steps to match a target pattern. This task required strategic planning, forward thinking, and problem-solving skills (Liang et al., 2022).

The N-Back Test assessed WM. In this task, participants were required to compare the consistency of the currently presented stimulus with the previously presented stimulus. As the number of backtracking steps increased, the difficulty of the task increased accordingly, allowing us to measure an individual's ability to maintain and process past information (Nejati and Derakhshan, 2021).

3.5 Outcome measure of executive functions

IC in EF was reported in 9 RCT studies using EF as an outcome indicator. After AE intervention in trials using Stroop Task, Flanker Task, and Go-No-Go Task before and after the intervention in the control and experimental groups of eight studies showed improvement in raw score or response time for IC (Chang et al., 2012, 2022; Pan et al., 2015, 2016; Memarmoghaddam et al., 2016; Benzing et al., 2018; Benzing and Schmidt, 2019; Liang et al., 2022); however, an improvement in raw score for IC was shown in the study by Nejati and Derakhshan (2021), but no significant difference was found in RT (Nejati and Derakhshan, 2021).

For CF in EF, seven studies performed Flanker Task, Wisconsin Card Sorting Test, and Trail Making Test. After comparing the differences between the experimental and control groups before and after showed a significant improvement in raw score or response time (Chang et al., 2012; Pan et al., 2015; Benzing et al., 2018; Benzing and Schmidt, 2019; Nejati and Derakhshan, 2021; Chang et al., 2022). In the trial of Liang et al. (2022), response time improved, but raw score had no significant effect.

Four studies on WM used the Color Span Backwards Task, N-Back Test, and Tower of London Test for pre- and post-experimental testing of experimental and control groups (Benzing et al., 2018; Benzing and Schmidt, 2019; Nejati and Derakhshan, 2021; Liang et al., 2022). Improvements in both raw score and response time for WM were shown in Liang et al. (2022) and Nejati and Derakhshan (2021), but in Liang et al.'s (2022) study, raw score improvement was slight. However, in two other studies, Benzing et al. (2018) showed no improvement in raw score in a study that performed a single 15-min training session. Benzing and Schmidt (2019) subsequently showed no significant difference in raw score before or after different groups after an 18-week trial.

3.6 Meta-analysis of the effect of exercise intervention

A meta-analysis of seven RCT studies was performed and the outcomes were tested using the Accuracy-incongruent of Flanker Task, Color-word of Simon Task, and Go-True number raw score of Go-No-Go Task as outcome indicators (Chang et al., 2012; Pan et al., 2015; Memarmoghaddam et al., 2016; Pan et al., 2016; Nejati and Derakhshan, 2021; Chang et al., 2022; Liang et al., 2022). The effect of an AE intervention on IC in EF was analyzed in 140 children with ADHD. As shown in Figure 2, with I^2 = 69% after inclusion and analyzed using a random effects model, The results of meta-analysis showed that the IC function in the EF in question showed significant improvement from before the start of the experiment to the end. Specifically, the improvement in inhibitory control functioning was significantly confirmed by statistical analysis [SMD = 0.83,95% CI (0.37–1.29), Z = 3.51, p = 0.0005]. These results suggest that the children with ADHD who participated in the study experienced significant improvements in inhibitory control.

Five studies tested CF in EF using the Wisconsin Card Sorting Test and Trail Making Test with an experimental group involving 105 children with ADHD (Chang et al., 2012; Pan et al., 2015; Nejati and Derakhshan, 2021; Chang et al., 2022; Liang et al., 2022). Total correct or non-perseverative errors and Part A or B errors raw scores were included in the meta-analysis as outcome indicators. As shown in Figure 3, the combined statistic corresponded to I^2 = 0% and thus was analyzed using a random-effects model. The results showed statistically significant differences between the two groups before and

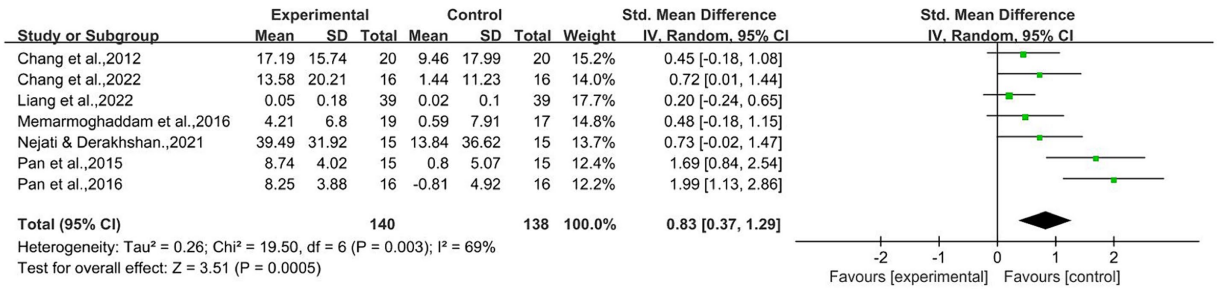


FIGURE 2
Inhibition control raw score.

after the intervention [SMD = 0.65,95% CI (0.37–0.93), $Z = 4.58$, $p < 0.00001$], and AE had a positive improvement effect on shifting CF.

Four studies administered AE interventions to an experimental group of 106 children with ADHD and assessed the effect of AE interventions on WM in the EF of children with ADHD using Color Span Backwards Task, N-Back Test, and Tower of London Test (Benzing et al., 2018; Benzing and Schmidt, 2019; Nejati and Derakhshan, 2021; Liang et al., 2022). Two studies demonstrated a positive effect of AE on WM (Nejati and Derakhshan, 2021; Liang et al., 2022), but two studies showed no significant difference ($p > 0.05$) in the improvement of WM with AE (Benzing et al., 2018; Benzing and Schmidt, 2019). Updating, accuracy, and total move scores raw scores from N-Back Test and Tower of London Test used in the four studies were included in the meta-analysis, showing $I^2 = 62\%$, using a random effects model. As shown in Figure 4, the results showed statistically significant ($p = 0.04$), indicating that AE improved WM in children with ADHD with EF [SMD = 0.48, 95% CI (0.02–0.95), $Z = 2.03$, $p = 0.04$].

3.7 GRADE quality evaluation

Following the GRADE criteria, we conducted an evidence-based assessment of aerobic exercise interventions on three aspects of core functioning (inhibitory control, working memory, and cognitive flexibility) in executive functioning in children with ADHD. As shown in Table 4, aerobic exercise demonstrated moderate-quality evidence support for improving inhibitory control, cognitive flexibility, and working memory in 6- to 12-year-old children with ADHD. Although "Risk of bias" was rated as "yes," performance on the other ratings was "no," supporting the effectiveness of the intervention.

With regard to the "Risk of bias" rating of "Yes," the "Risk of bias" rating of "Yes" was mainly due to the fact that the interventions involved were not evaluated. ", mainly because the studies involved had deficiencies in the randomization process and in the implementation of blinding. This included a lack of transparency in the method of concealment of randomization in some studies and the fact that knowledge of the grouping by the evaluator or participants may have affected the objectivity of the study; "No" for "Inconsistency," although there was some variability among the individual studies. In the case of Inconsistency, although there was some variability between individual studies, the overall trend was consistent, suggesting that aerobic exercise has a positive impact on improving executive function in children with ADHD. The results of heterogeneity tests (e.g., I^2 statistic) support the consistency of the findings; for "Indirectness," our analyses directly addressed the target population and intervention of the study, i.e., children aged 6–12 years with ADHD. Our analysis directly addressed the target population and intervention of the study, i.e., children aged 6–12 years with ADHD, so there was no question of indirectness; for "Imprecision," we rated "No" because, although some of the study samples were small, the overall sample size was sufficient to ensure that the results were representative and accurate; "For "Publication bias," we conducted an Egger's test, which showed that the p-value was greater than 0.05, indicating that no significant publication bias was detected in the existing studies. This result reduces the concern about possible bias in the results of the studies and strengthens the credibility of the evidence.

3.8 Moderator analysis

As shown in Table 5, to analyze the potential role of other moderating variables, subgroup analyses based on Intervention

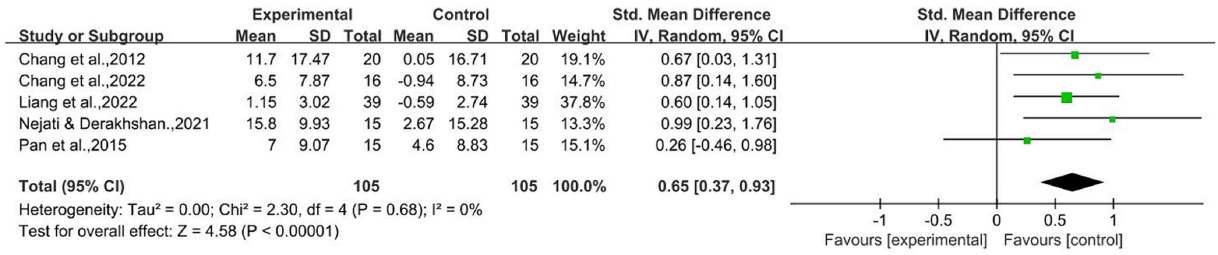


FIGURE 3
Cognitive flexibility raw score.

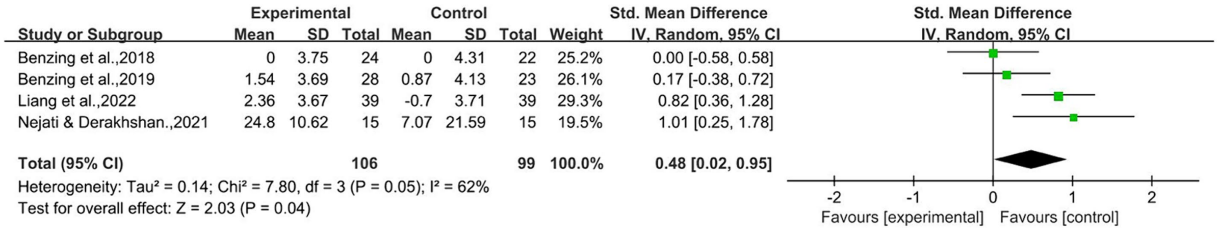


FIGURE 4
Working memory raw score.

TABLE 4 GRADE evidence summary results.

Outcomes	Presence of downgrading item of GRADE					Quality of evidence
	Risk of bias	Inconsistency	Indirectness	Imprecision	Publication bias	
Inhibitory control	Yes	No	No	No	No	Moderate
Working memory	Yes	No	No	No	No	Moderate
Cognitive flexibility	Yes	No	No	No	No	Moderate

Risk of bias: in the RCTs assessed, there were problems with the randomization process and opaque information about allocation concealment and assessor/subject blinding, resulting in potentially biased results; inconsistency: there were slight differences in point estimates among the studies, but 95% confidence intervals overlapped across all the studies and tests for heterogeneity (e.g., I^2 statistic) results were not significant, indicating good agreement between results; indirectness: aerobic exercise assessed directly targeted core executive functions in children with ADHD, directly correlating with the study results, and did not show indirectness with the study results; imprecision: overall sample size was over 300, and there were no wide 95% confidence intervals for effect sizes, ensuring the statistical precision and reliability of the results; publication bias: Egger's test showed a p-value greater than 0.05 and the study involved a comprehensive search of several international databases with no unpublished studies.

TABLE 5 Result of subgroup analysis.

Sub-group classification	Level	IC					CF				
		N	SMD	95%CI	*Z*	*P*	*N*	SMD	95%CI	*Z*	*P*
Intervention type	SAE	134	1.17	[0.44,1.90]	3.15	0.002	102	0.60	[0.20,1.00]	2.96	0.003
	CAE	144	0.38	[0.05,0.71]	2.23	0.03	108	0.70	[0.31,1.09]	3.51	0.0004
Intervention intensity	MI	134	1.17	[0.44,1.90]	3.15	0.002	102	0.60	[0.20,1.00]	2.96	0.003
	MVI	114	0.29	[−0.08,0.66]	1.54	0.12	78	0.60	[0.14,1.05]	3.93	0.010
Intervention cycle	<6wk	70	0.56	[0.08,1.04]	2.31	0.02	70	0.80	[0.31,1.29]	3.20	0.001
	6-12wk	208	0.96	[0.29,1.62]	2.82	0.005	140	0.58	[0.24,0.92]	3.36	0.0008
Intervention time	15-50 min	70	0.56	[0.08,1.04]	2.31	0.02	70	0.80	[0.31,1.29]	3.20	0.001
	60-90 min	208	0.96	[0.29,1.86]	2.82	0.0005	140	0.74	[0.40,1.09]	4.23	0.0001
Use of medication	YES	134	1.17	[0.44,1.90]	3.15	0.002	–	–	–	–	–
	NO	114	0.29	[−0.08,0.66]	1.54	0.12	–	–	–	–	–

N, number; SAE, single aerobic exercise; CAE, combination aerobic exercise; MI, moderate intensity; MVI, moderate to vigorous intensities; WK, week; MIN, minutes.

type (SAE or CAE), Intervention intensity (MI, MVI), Intervention cycle (WK), Intervention time (MIN) and Use of medication were performed using Revman 5.4. to explore whether there was an interaction between IC and CF subgroups and effect sizes with subgrouped variables, respectively. Subgroup analyses were performed on the categories of variables based on Intervention type (SAE or CAE), Intervention intensity (MI, MVI), Intervention cycle (WK), Intervention time (MIN) and Use of medication.

AE treatment modality was influenced by the type of intervention. Among them, single aerobic exercise (single aerobic exercise) had the best effect on the improvement of IC in EF in children with ADHD SMD = 1.17, 95% CI (0.44–1.90), $Z = 3.15$, $p = 0.002$; the effect of single aerobic exercise and combination aerobic exercise on the improvement of shifting CF in participants did not differ significantly, the effect size of improvement in the single aerobic exercise group was SMD = 0.60,95% CI (0.20–1.00), $Z = 2.96$, $p = 0.003$; the effect size of improvement in the combination aerobic exercise group was SMD = 0.70,95% CI (0.31–1.09), $Z = 3.51$, $p = 0.0004$.

In the subgroup analysis of intervention intensity, inhibition control was influenced by moderate intensity and moderate to vigorous intensities, moderate intensity showed the best improvement SMD = 1.17, 95% CI (0.44–1.90). In addition, the effects of moderate intensity and moderate to vigorous intensities on shifting CF were the same: the effect size of moderate intensity group SMD = 0.60,95% CI (0.20–1.60), and the effect size of moderate to vigorous intensities group SMD = 0.60,95% CI (0.20–1.60), (0.20–1.00), $Z = 2.96$, $p = 0.003$; the effect size SMD = 0.60,95% CI (0.14–1.05), $Z = 3.93$, $p = 0.010$ in the moderate to vigorous intensities group.

IC was influenced by the intervention cycle, and AE interventions of 6–12 weeks performed better than those of less than six weeks SMD = 0.96,95%CI (0.29–1.60), $Z = 2.82$, $p = 0.005$. In contrast, for shifting CF improvement, AE interventions of less than six weeks performed better SMD = 0.80,95% CI (0.31–1.29), $Z = 3.20$, $p = 0.001$. The effect of aerobic exercise intervention was influenced by the intervention time, with 60–90 min being more effective in improving EF function. Specifically, the 60-90 min clock improved IC better than the 15-50 min intervention time, SMD = 0.96,95%CI (0.29–1.86), $Z = 2.82$, $p = 0.0005$. Meanwhile, shifting CF was influenced by intervention time, with an intervention time of 15-50 min SMD = 0.80,95%CI (0.31–1.29), $Z = 3.20$, $p = 0.001$ was similar to the improvement of aerobic exercise with 50-90 min SMD = 0.74,95%CI (0.40–1.09), $Z = 4.23$, $p = 0.0001$.

In a subgroup analysis of an AE intervention, significant improvement was observed in the IC of children with ADHD taking medication by AE SMD = 1.17,95%CI (0.44–1.90), $Z = 3.15$, $p = 0.002$, whereas there was no statistically significant improvement in the IC of children with ADHD not taking medication by AE SMD = 0.29, 95%CI (−0.08–0.66), $Z = 1.54$, $p = 0.12$.

TABLE 6 Results of subgroup analysis after EF merger.

Model	Covariate	β	Lower 95%CI	Upper 95%CI	P	R^2 analog	Tau^2
1	Intervention type					−0.007	0.121
	SAE	0.867	0.494	1.240	<0.001		
	CAE	0.521	0.478	1.031	0.004		
2	Intervention intensity					0.208	0.133
	MI	0.928	0.481	1.375	<0.001		
	MVI	0.418	0.131	0.705	0.004		
3	Intervention cycle					−0.260	0.151
	<6wk	0.697	0.354	1.039	<0.001		
	6-12wk	0.804	0.398	1.21.	<0.001		
4	Intervention time					−0.235	0.140
	15-50 min	0.697	0.354	1.039	<0.001		
	60-90 min	0.894	0.492	1.297	<0.001		
5	Use of medication					0.300	0.282
	YES	1.202	0.455	1.950	0.002		
	NO	0.881	−0.075	0.665	0.118		

SAE, single aerobic exercise; CAE, combination aerobic exercise; MI, moderate intensity; MVI, moderate to vigorous intensities.

TABLE 7 ES meta-regression analysis results.

ES	No. of studies/ comparisons	Coef. (β)	Std. err.	95% conf. interval		Test for between-groupheterogeneity		
						Q-value	df (Q)	p-value
Intervention type	12	−0.294	0.314	−0.994	0.406	−0.94	1	0.372
Intervention intensity	10	−0.485	0.350	−1.294	0.323	−1.38	1	0.203
Intervention cycle	12	0.075	0.335	−0.672	0.819	0.22	1	0.831
Intervention time	12	0.159	0.320	−0.553	0.872	0.50	1	0.629
Use of medication	6	−0.850	0.549	−2.374	0.673	−1.55	1	0.196

3.9 Meta-regression analysis

In order to examine the effect of aerobic exercise intervention on executive function in children with ADHD, after combining statistics regarding core functions IC and CF in EF, we performed subgroup analysis and meta-regression analysis on intervention duration, intensity, cycle, time, and use of medication variables. As shown in the Table 6, the results showed that SAE ($\beta = 0.867$, $p < 0.001$), CAE ($\beta = 0.521$, $p = 0.021$), MI ($\beta = 0.928$, $p < 0.001$), MVI ($\beta = 0.418$, $p = 0.021$), less than 6 weeks ($\beta = 0.697$, $p < 0.001$), 6–12 weeks ($\beta = 0.804$, $p < 0.001$), 15–50 min ($\beta = 0.697$, $p < 0.001$), 60–90 min ($\beta = 0.894$, $p < 0.001$) and the use of medication ($\beta = 0.41$, $p = 0.002$) were significantly associated with EF. While no medication use ($\beta = 0.881$, $p = 118$) was not significantly associated with EF. In addition, meta-regression analyses were performed to determine whether the intervention duration, intensity, cycle, time, and use of medication variables had an effect on the various categories of indicators in the Table 7. The regression results showed that type of intervention ($\beta = -0.294$, Q = -0.94, df = 1, $p = 0.372$), intervention intensity ($\beta = -0.485$, Q = −1.38, df = 1, $p = 0.203$), intervention cycle ($\beta = 0.075$, Q = 0.22, df = 1, $p = 0.831$), intervention time ($\beta = 0.159$, Q = 0.50, df = 1, $p = 0.629$), and use of medication ($\beta = -0.850$, Q = −1.55, df = 1, $p = 0.196$) did not have a significant relationship on the effect of EF.

4 Discussion

This review examined the effects of AE on executive function in children with ADHD aged 6–12 years. After analyzing the outcome data from nine RCT trials, the findings showed statistically significant differences in IC, CF, and WM between the experimental and control groups before and after the experiment, indicating a positive effect of an AE intervention on the improvement of EF in ADHD patients. In addition, this study found that the effects of IC and CF were influenced to some extent by the variables of intervention type, intervention intensity, intervention cycle, intervention time, and use of medication.

Several previous meta-analyses have reported positive improvements from EF-focused exercise interventions in patients with ADHD (Tan et al., 2016; Liang et al., 2021); in a review by Liang et al. (2021), children and adolescents with ADHD were studied and evidence was found for improvements in IC and CF with AE intervention in a subgroup (Tan et al., 2016; Liang et al., 2021) patients aged 3–25 years, exercise was found to improve IC and WM. However, because of differences in

exercise type and age characteristics, the effect of AE on the improvement of EF in children with ADHD cannot be accounted for. We included only relevant studies of children aged 6–12. In the meta-analysis, seven studies testing IC using the Flanker Task, Stroop Task, and Go-No-Go Task showed significant improvements in EF after combining the effect sizes. In the tests of CF, five studies using the Wisconsin Card Sorting Test and Trail Making Test task on shifting CF showed a positive effect on EF improvement after combining effect sizes. Further, in the four studies using the Color Span Backwards Task, N-Back Test, and Tower of London Test on WM, AE was also shown to improve WM in children with ADHD after combining effect sizes. Hence, AE resulted in an improvement in overall EF in children with ADHD.

Of the nine included studies, no adverse events were reported in the experimental group participating in AE. This finding has important implications for clinical practice, suggesting that AE may not only be beneficial for improving EF in children with ADHD, but also have a favorable safety profile, possibly making AE a valuable and safe intervention. Our effect sizes for IC, CF, and WM were statistically significant after combining the statistics. However, some studies still provided non-significant improvements or negative results. For example, Liang et al. (2022) showed no significant improvement in accuracy-incongruent before and after the experiment after testing IC using the Flanker Task in their study; Benzing et al.'s study in WM for two consecutive years with 1-week and 8-week interventions on color span showed no significant improvement. Analyses of the sum of correct responses in the regression task showed no significant difference and the study results were negative (Benzing et al., 2018; Benzing and Schmidt, 2019). Notably, all nine studies showed that AE was effective in improving IC.

In addition, in the subgroup analysis it was found that variables such as different types of exercise, intensity of intervention influenced the effect of inhibition and cognitive flexibility improvement. Also we found in the subgroup analysis after combining IC, CF that the intervention type, intensity, duration, period, and the use of medication showed to be significant in the variables, and the effect size of a single exercise program, moderate intensity, 60–90 min, 6–12 weeks, and the use of medication was greater than the effect size of the other subgroups, but no between-group differences were observed in their meta-regression analyses, which may be related to the sample size, study design heterogeneity, different implementation methods, or measurement error. Therefore, the results may be biased and this relative advantage should be interpreted with caution.

In terms of exercise type improvement, in terms of motor type improvement, overall SAE improved a greater effect size than CAE. Neudecker et al. (2019) used a systematic review of research methods to conclude that CAE had the greatest effect on ADHD children's cognitive, behavioral, Improvements in ADHD symptom presentation and fine motor accuracy were mainly evident in male and female participants (Choi et al., 2014; Pan et al., 2014), but the study lacked data support in this regard. However, in our data-supported analysis, the opposite conclusion was reached, finding that SAE was superior to CAE in improving inhibitory control, and that SAE was more effective in improving executive functioning in children with ADHD; in addition to this, it is interesting to note that out of the nine studies included, both the experimental and the control groups in the study by Nejati and Derakhshan (2021) used an aerobic exercise intervention. The difference was that the experimental group used Exercise for cognitive improvement and rehabilitation (EXCIR) cognitive integrated category of aerobic exercise, which consisted of 12 exercises such as color jumping, arrow jumping, number jumping, pattern walking, slow walking, and limb movement, while the control group had a single event category of Aerobic exercise running, both groups showed improvement in executive function, but the combined aerobic exercise with cognitive category was better than the running program improvement. This result may be due to the fact that the EXCIR cognitive category of aerobic exercise is designed with the idea of combining physical activity with cognitive challenges, which not only promotes physical fitness but also enhances executive functioning through an exercise component with progressive cognitive demands (Nejati and Derakhshan, 2021). This leads us to subsequently place more emphasis on exploring the effects of combining physical activity and cognitive challenge in an integrated class of aerobic exercise to improve executive function when evaluating interventions for children with ADHD.

A single session of moderate to vigorous physical activity (MVPA) was found to be more effective for EF enhancement in children with ADHD in a review by Chueh et al. (2022), who also concluded that age was unlikely to be a factor influencing the results, and which included three studies of 11–16 year old adolescents among them. However, in our review only children aged 6–12 years were included and intervention intensity was found to influence the improvement in inhibitory control, as evidenced by a better improvement in overall executive functioning gains with moderate intensity than with moderate to vigorous intensity. We emphasized the importance of matching children's developmental stage and individual differences, and that for children aged 6–12 years, moderate-intensity physical activity provides a more optimal balance of stimulating cognitive and physical development while maintaining children's engagement and interest, ultimately leading to better improvement in inhibitory control.

Aerobic exercise was shown to improve EF effect sizes more significantly over the intervention period of 6–12 weeks, with better inhibitory control improvements than less than 6 weeks; however, improvements in switching cognitive flexibility were shown to be better at less than 6 weeks. The better improvement in inhibitory control may be due to the fact that long-term exercise promotes functional connectivity and the overall efficiency of neural networks in regions of the brain associated with executive function, especially in areas such as the anterior cingulate gyrus, occipital lobe, and frontal lobe. Long-term exercise also increases the nutrient supply to neurons in the hippocampal gyrus, which enhances memory and cognitive function (Song et al., 2023; Wang et al., 2023). For the enhancement of cognitive flexibility, especially over a period of less than 6 weeks, it may be attributed to a rise in physiological activation levels triggered by aerobic exercise. This rise is primarily characterized by an increase in key neurotransmitters such as dopamine and norepinephrine in the body, which play a positive and direct role in improving executive function (Cantelon and Giles, 2021). Additionally, this result may be due to the fact that in trials of less than 6 weeks, Chang et al.'s study was only tested after running on a treadmill for One session of 30 min, which may have had an impact on the overall amount of effect.

Finally, the effect size of 60–90 min aerobic exercise to improve EF was more significant among the different intervention durations, and the improvement of inhibitory control showed the best effect of 60–90 min, probably due to the fact that sustained aerobic exercise can increase the level of cortisol, which is important for inhibiting the

over-activation of the submandibular body and contributes to the improvement of inhibitory control (Heijnen et al., 2016). Improvements in shifting cognitive flexibility showed little difference between 15–50 min and 60–90 min improvements. The good effects of 15–50 min and 60–90 min exercise on shifting cognitive flexibility improvements may be related to the pattern of activity in which the brain makes adjustments, enhancing bilateral superior frontal, middle frontal, and superior lobular activity in the performance of cognitive flexibility tasks that typically trigger activity in prefrontal and parietal regions (Jamadar et al., 2010; Boucard et al., 2012).

It was concluded that with medication in children with ADHD, the medication acts directly on the organs for metabolism and reduces the duration of treatment, whereas AE regulates the metabolic level of the body and provides a physiological basis for the efficient transmission of neural signals (Li et al., 2016), thus making AE more effective in children with ADHD taking medication. However, this result may be biased due to differences in the number of studies included in this meta-analysis, and more studies will be included subsequently to support this conclusion.

For clinicians, AE—as a non-pharmacologic adjunctive therapy—can improve EF in children with ADHD, particularly in the areas of IC and CF. This provides a new clinical intervention that can be combined with 15–50 min of moderate-intensity AE in a treatment program to supplement medication and perhaps improve treatment outcomes. For researchers, the positive effect of AE in improving EF in children with ADHD suggests that more rigorous and standardized RCTs are needed to validate these findings and further determine how the optimal duration, intensity, and frequency of intervention; intervention period; and medication use affect AE to provide more precise theoretical guidance for clinical practice.

5 Strengths and limitations

The strengths of this study lie in the construction of our conceptual model, the selection of the study population, and the experimental design. First, the conceptual model was methodologically oriented toward AE, for which a "conceptual model of AE intervention for children with ADHD in executive function" was proposed. The concept of AE was defined, AE studies of single and combined exercise types were included, and AE studies of moderate intensity or moderate to vigorous intensity were included. Second, the study population was selected from children aged 6–12 years with a diagnosis of ADHD, and the mean age of children with ADHD in the nine included studies was 9.31 ± 1.33 years. Finally, for the choice of experimental design, we included only RCT experimental studies to ensure the quality level of the included studies.

It is understood that relative to other studies of exercise interventions for EF in children with ADHD. This study is the first systematic evaluation and meta-analysis of the effects of AE interventions on EF in children with ADHD aged 6–12 years, but there are still several limitations in the study. First, the included studies needed to comply with the RCT study design, while the selection in age made the number of compliant studies limited, which may lead to insufficient evidence for the results of the analysis. Second, boy participants accounted for 80% of the total participants in the analyzed studies, which prevented us from developing an exploration of the effect of gender differences on the improvement of EF. In addition, the lack of girls in five studies may have also biased our findings (Pan et al., 2015, 2016; Memarmoghaddam et al., 2016; Nejati and Derakhshan, 2021). Finally, studies have focused primarily on the analysis of reactive cognitive flexibility rather than spontaneous cognitive flexibility, and this selective focus has its limitations, one of the included studies did not report medication use (Nejati and Derakhshan, 2021), and the remaining studies did not have an unmedicated control group and also lacked studies that controlled for the type and dose of medication used in children with ADHD (Pan et al., 2015). The difference in the number of studies makes it difficult to analyze the effect of improvement in CF, and WM in children with ADHD with or without medication.

6 Conclusion

Aerobic exercise intervention modality can effectively improve executive function in children with ADHD. In the improvement of executive function, a single aerobic exercise class is more conducive to the improvement of executive function in children with ADHD; the intervention period is 6–12 weeks, the intervention time is 50-90 min, moderate intensity aerobic exercise intervention is more conducive to the improvement of executive function, and the improvement effect is obvious in children with ADHD who are taking medication. It was particularly valuable in improving inhibitory control and cognitive flexibility. However, considering the differences in the included studies, methodological quality, intervention period, and medication use, additional, rigorous, and standardized RCTs are needed to define specific intervention protocols further.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

GY: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation. QL: Writing – review & editing, Validation, Supervision, Resources, Methodology, Formal analysis, Data curation, Conceptualization. WW: Writing – review & editing. WL: Writing – review & editing. JL: Writing – review & editing, Validation, Supervision, Resources, Project administration, Formal analysis, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Does a single session of transcranial direct current stimulation enhance both physical and psychological performance in national- or international-level athletes? A systematic review

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Some studies showed that a single session of transcranial direct current stimulation (tDCS) has the potential of modulating motor performance in healthy and athletes. To our knowledge, previously published systematic reviews have neither comprehensively investigated the effects of tDCS on athletic performance in both physical and psychological parameters nor investigated the effects of tDCS on high-level athletes. We examined all available research testing a single session of tDCS on strength, endurance, sport-specific performance, emotional states and cognitive performance for better application in competition and pre-competition trainings of national- or international-level athletes. A systematic search was conducted in PubMed, Web of Science, EBSCO, Embase, and Scopus up until to June 2023. Studies were eligible when participants had sports experience at a minimum of state and national level competitions, underwent a single session of tDCS without additional interventions, and received either sham tDCS or no interventions in the control groups. A total of 20 experimental studies (224 participants) were included from 18 articles. The results showed that a single tDCS session improved both physical and psychological parameters in 12 out of the 18 studies. Of these, six refer to the application of tDCS on the motor system (motor cortex, premotor cortex, cerebellum), five on dorsolateral prefrontal cortex and two on temporal cortex. The most sensitive to tDCS are strength, endurance, and emotional states, improved in 67%, 75%, and 75% of studies, respectively. Less than half of the studies showed improvement in sport-specific tasks (40%) and cognitive performance (33%). We suggest that tDCS is an effective tool that can be applied to competition and pre-competition training to improve athletic performance in national- or international-level athletes. Further research

would explore various parameters (type of sports, brain regions, stimulation protocol, athlete level, and test tasks) and neural mechanistic studies in improving efficacy of tDCS interventions.

Systematic Review Registration: https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42022326989, identifier CRD42022326989.

KEYWORDS

high-level athletes, physical performance, psychological performance, noninvasive brain stimulation, efficacy

1 Introduction

Athletes undergo systematic training over a long time to improve their athletic performance and achieve superior athletic results in competition. Athletic performance is multifactorial, including both physical and psychological aspects. It requires the development of not only muscular endurance, explosive power, motor coordination and quick and accurate strategic thinking (Colzato et al., 2016), but also stable emotional states and cognitive performance (Hagan et al., 2017). Athletes are often willing to apply top-tier training techniques to enhance athletic performance. Numerous studies have revealed that the brain is crucial for improving athletic performance beyond muscles, heart and lung (Noakes, 2011).

Transcranial direct current stimulation (tDCS) is a non-invasive brain stimulation technique that applies a constant weak direct electrical current using two or more electrodes placed on the scalp to facilitate or inhibit neural activity and/or excitability (Nitsche et al., 2003b). Classically, the effects of tDCS are polarity-dependent in that anodal tDCS (a-tDCS) enhances cortical excitability by subthreshold depolarization of the neural resting membrane potential, and cathodal tDCS (c-tDCS) reduces cortical excitability through hyperpolarization of the neural resting membrane potential (Nitsche and Paulus, 2000; Liebetanz et al., 2002; Stagg and Nitsche, 2011). The after-effects of tDCS last for up to 120 min, or longer, and have been linked to long-term potentiation or long-term depression (Nitsche and Paulus, 2001; Polania et al., 2012; Jamil et al., 2017). Besides, some studies showed that tDCS is an effective method for inducing sustained and widespread changes in regional neural activity and functional connectivity (Lang et al., 2005; Polania et al., 2012). tDCS is widely used in basic research, neuropsychiatric and neurological disorders to modulate cortical excitability, reorganize neuroplasticity, and improve motor performance (Fregni et al., 2006; Angius et al., 2017; Gold and Ciorciari, 2021; Yang et al., 2021; Hou et al., 2022). Therefore, it has attracted the attention of sports scientists. There have been substantial studies showing that tDCS applied over the primary motor cortex (M1), temporal cortex (TC), cerebellum (CB), premotor cortex (PMC) and dorsolateral prefrontal cortex (DLPFC) enhances crucial aspects of motor performance, including muscular strength (Maezawa et al., 2020; Vieira et al., 2020), endurance (Lattari et al., 2016; Ciccone et al., 2019), cognitive control (Wiegand et al., 2019), dynamic balance (Kaminski et al., 2016; Yosephi et al., 2018), and reaction speed (Denis et al., 2019) in healthy people and lower-level athletes.

The effects of tDCS on strength and endurance are more researched, but the results are mixed. The review of Holgado et al. (2019) reported a-tDCS had a small but positive effect on exercise performance, but the effects were not significantly moderated by type of outcome, electrode placement, muscles involved, number of sessions, or intensity and duration of the stimulation. A previous systematic review and meta-analysis reported a-tDCS leads to small and moderate effects on strength (maximal voluntary contraction) and endurance (time to task failure) in healthy young and old adults (Alix-Fages et al., 2019). The review of Machado et al. (2019) reported that a-tDCS but not c-tDCS over M1 improved exercise performance in cycling only in healthy adults. The review of Shyamali Kaushalya et al. (2021) reported that a-tDCS enhance running and cycling time in time to exhaustion tasks but no improved in endurance time trial or sprint tasks in healthy people. The review of Chinzara et al. (2022) reported that tDCS has the potential to be used as an ergogenic aid in physical endurance, muscular strength, and visuomotor skills in healthy adults. This controversy in reviews might be attributed to different brain region targets, stimulation protocols, test tasks, and motor abilities in participants.

Some studies showed that tDCS effectively improves sport-specific performance, such as golf putting (Zhu et al., 2015) and basketball performance (shooting precision, specific dribbling, and agility) in healthy people (Veldema et al., 2021). A recent systematic review and meta-analysis reported that a single anodal tDCS session can enhance sport-specific motor performance in healthy adult athletes who have been regularly participating in organized sports for at least 2 years (Maudrich et al., 2022). However, some studies yielded inconsistent results (Valenzuela et al., 2019; Penna et al., 2021; Moreira et al., 2022). Achieving high-level of athletic performance is often believed to demand a minimum of a decade or 10,000 h of practice, based on the time dedicated to practicing a task (Ericsson KA and Tesch-Römer, 1993). According to McKay et al. (McKay et al., 2022) 's classification of sports levels, athletes above tier 3 (Highly Trained/National Level, Elite/International Level and World Class) in studies could provide reliable performance outcomes and suited to both laboratory- and field-based research. The brains of high-level athletes have different characteristics compared with the general population and lower-level athletes (Nakata et al., 2010), such as higher neural excitability (Wright et al., 2010; Callan and Naito, 2014; Monda et al., 2017) and specific neural responses during exercise (Del Percio et al., 2010; Casanova et al., 2013; Ermutlu et al., 2015). Whether a single session of tDCS can apply to competition and pre-competition training in national- or international-level athletes remains uncertain. More importantly, psychological parameters such as emotional state and cognitive performance are important for athletic performance under intense conditions (Hagan et al., 2017; Valenzuela et al., 2019; Fortes et al., 2022). Emotional state had proven a relationship with athletic performance and change of sporting success (Zandi and Rad, 2013; Brandt et al., 2017). Cognitive performance such as inhibitory control, visual search and decision-making are crucial for accuracy and

consistency of movements, as well as efficiently processing the surrounding information to adopt the correct action in a given situation (Chiu et al., 2017). Yet previous review studies focused only on the effects of tDCS on motor and sport-specific performance in healthy people and athletes of all levels, with less attention paid to cognitive performance and emotional states. Whether a single session of tDCS improved athletic performance in high-level athletes and in what aspects it is effective is still inconclusive. Therefore, we carried out a systematic review to comprehensively analyze the effects of a single session of tDCS on athletic performance in strength, endurance, sport-specific performance, emotional states and cognitive performance in national- or international-level athletes, in order to improve the efficacy of tDCS on high-level athletes.

2 Methods

A systematic literature review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Liberati et al., 2009). Details of the review protocol were registered on PROSPERO on April 2022 (CRD42022326989). A meta-analysis was not conducted due to high measurement and methodological heterogeneity in the selected studies.

2.1 Literature search

The literature search was performed until June 2023 by two independent researchers (Y.Y., Z.X.B.) using the PubMed, Web of Science, EBSCO, Embase, and Scopus databases, and the keywords ("tDCS" OR "transcranial Direct Current Stimulation") AND ("athlete" OR "player" OR "sport" OR "athletic performance" OR "psychological performance" OR "physical performance" OR "cognitive performance" OR "cognitive function"). Additional relevant studies were also scanned in the references of the retrieved literature to broaden the search.

2.2 Study inclusion and exclusion criteria

Studies were included according to the "participants, intervention, comparator, outcomes, study design" inclusion criteria: 1) healthy athletes in highly trained/national level and elite/international level (McKay et al., 2022); 2) intervention consisting of a single tDCS session; 3) sham tDCS or no interventions as control groups; 4) inclusion of all detailed test results; and 5) randomized controlled trials with crossover or parallel group designs.

The exclusion criteria were: 1) no specification of the level of athletes; 2) other interventions during the experiment; and 3) non-English language, review papers, conference abstracts, study protocols, and papers without relevant experimental data.

2.3 Study selection and risk-of-bias assessment

The literature screening was conducted independently by two researchers based on the inclusion and exclusion criteria. A third researcher was consulted in case of disagreement. The Cochrane Risk of Bias assessment tool assessed bias in the included studies (Habay et al., 2021). Quality assessment included random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, incomplete outcome data bias, selective reporting, and other biases. Each component was rated as having a "high", "low", or "unclear" risk of bias. The Review Manager 5.4.1 software (Cochrane Collaboration, Oxford, UK) was used.

3 Results

3.1 Search results

A total of 589 articles (PubMed, 208; Web of Science, 92; EBSCO, 87; Embase, 70; Scopus, 130; other sources, 2) were found in the systematic literature search. After the removal of duplicate articles, 330 articles were screened based on their title and abstract, of which 266 articles were excluded. After full-text assessment, 47 records were excluded. Finally, 18 articles were eligible for the systematic review. The literature search process is shown in Figure 1.

3.2 Quality and risk-of-bias assessment

The overall quality of the included studies was high, with all studies using a randomized controlled experimental design. However, 12 of the included studies showed an unclear risk of selection bias, due to unclear random sequence generation in 10 articles and unclear allocation concealment in six articles. One study showed an unclear risk with respect to blinding of outcome assessment. Four studies showed an unclear risk of other biases. The risk-of-bias graphs and a summary are presented in Figure 2.

3.3 Study characteristics and result synthesis

An overview of literature characteristics is given in Table 1. All studies used crossover designs with a sham condition as a comparator. In total, 224 athletes were included in 18 studies, with 156 men (69.64%) and 68 women (30.36%). The mean age of the participants ranged from 16.10 ± 0.90 years (Vargas et al., 2018) to 33.00 ± 9.00 years (Okano et al., 2015). The average age of the subjects in one study conducted by Liang et al. (2022) was unknown. All studies used sham tDCS as a control condition. The studies covered handball, soccer, shooting, swimming, basketball, gymnastic, volleyball, triathlon, rowing, taekwondo, archery, and cycling. All subjects had sports experience at least state- and national-level competitions. All experimental groups used a-tDCS, while two studies used both, anodal/cathodal stimulation (Mehrsafar et al., 2020; Salehi et al., 2022). With the exception of eight studies applying a cephalic montage of the return electrode, all examined studies applied an extracephalic montage of the return electrode. Regarding the tDCS application protocol, all studies opted for the offline modality (testing after stimulation), with five studies including also the online stimulation modality (testing during

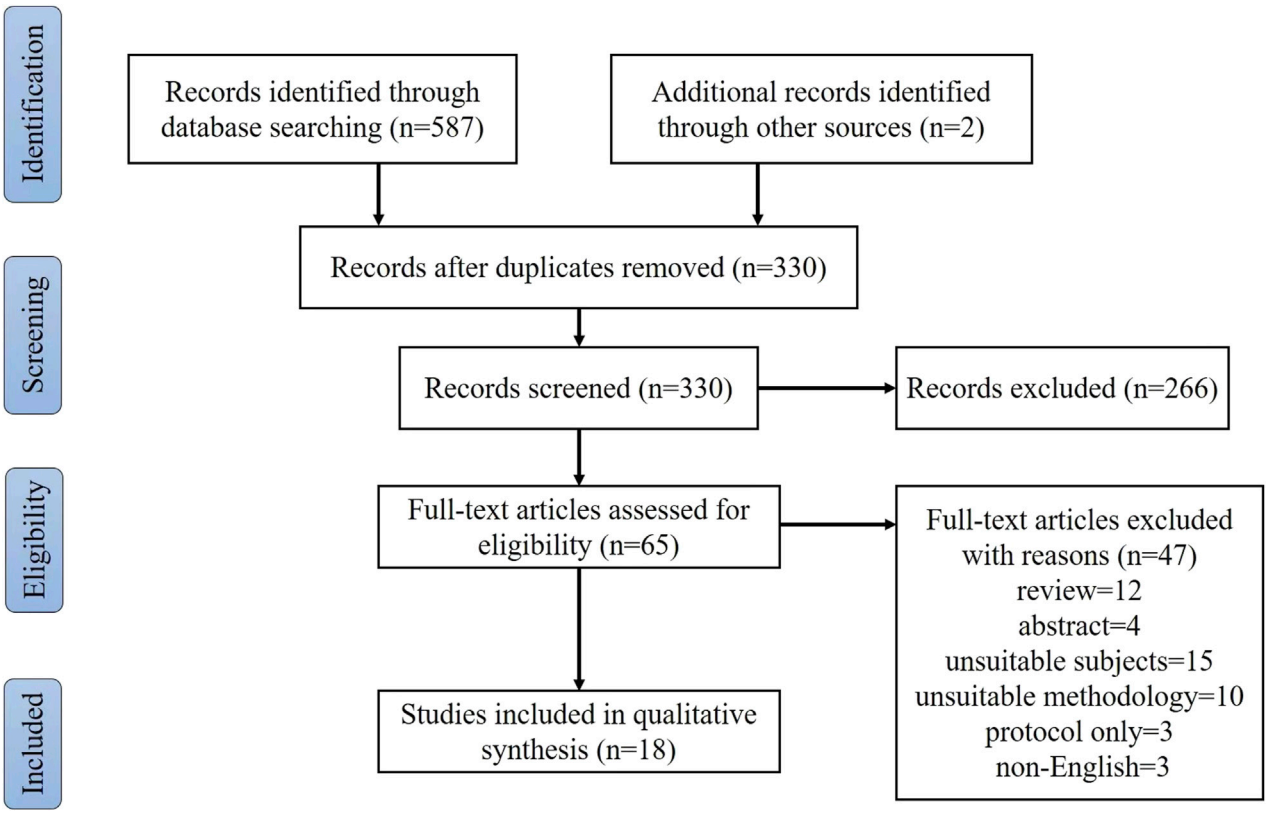


FIGURE 1
Selection of studies.

stimulation) (Hazime et al., 2017; Vargas et al., 2018; Fortes et al., 2022; Moreira et al., 2022; Anoushiravani et al., 2023). Three studies out of 18 studies did not measure side effects of the tDCS intervention. None of the studies reported any adverse effects or injuries after the intervention and the common sensations were itching and tingling. The basic characteristics of the literature are shown in Tables 1, 2.

These studies contained five stimulation regions: M1 (44.44%), DLPFC (33.33%), PMC (5.5%), CB (5.5%), and TC (16.67%). Five studies used bilateral anodal stimulation protocols (Mesquita et al., 2019b; Mesquita et al., 2020; Pollastri et al., 2021; Gallo et al., 2022; Anoushiravani et al., 2023), and the remaining studies used unilateral stimulation. Three studies used high-definition tDCS (HD-tDCS), and the other studies used a conventional tDCS setup using two electrodes (anode and cathode). Regarding the HD-tDCS setups, two used two sets of 3 × 1 electrodes (i.e., one anode and three cathodes) with 3.14-cm2 circular electrodes (Pollastri et al., 2021; Gallo et al., 2022), and Machado et al. (Machado et al., 2021) adopted a 6 × 3 (i.e., three anodes and six cathodes) ring configuration. Studies used stimulation durations of 15–30 min. The current intensity was 1.5 mA (Pollastri et al., 2021), 2.0 mA (Okano et al., 2015; Hazime et al., 2017; Vargas et al., 2018; Valenzuela et al., 2019; Mesquita et al., 2020; Machado et al., 2021; Penna et al., 2021; Moreira et al., 2022; Park et al., 2022; Salehi et al., 2022; Anoushiravani et al., 2023), 2.2 mA (Liang et al., 2022), and 2.4 mA (Machado et al., 2021). The electrode size varied between 3.14 cm2 and 36 cm2. The electrode size for HD-tDCS in the study by Machado et al. (2021) was not reported. The stimulation times, sites, and current intensities are shown in Figure 3.

The effects of tDCS on improving athletic performance were categorized into the following domains: strength (5 studies), endurance (4 studies), sport-specific performance (9 studies), emotional states (4 studies), and cognitive performance (3 studies).

Regarding muscle strength measurements, five studies used maximal voluntary isometric contraction (MVIC), the countermovement jump test (CMJ), broad jump test (BJT), and one-repetition maximum loads to measure the effects of tDCS in soccer, handball, taekwondo, gymnastic, and volleyball athletes (Hazime et al., 2017; Vargas et al., 2018; Mesquita et al., 2019a; Park et al., 2022; Anoushiravani et al., 2023). Among them, three studies (60%) found improvements. Vargas et al. (2018) and Hazime et al. (2017) found that 2-mA a-tDCS (0.0571 mA/cm2) over M1 (electrodes C3 or C4; International 10–20 System) for 20 min improved the MVIC of knee extensors in soccer players and external and internal shoulder rotators in handball players during stimulation, these effects lasted for 60 min. Anoushiravani et al. (2023) reported that 2-mA a-tDCS (0.0571 mA/cm2) improved BJT performance and MVIC of all tested upper body muscles when applied over the PMC for 20 min, and MVIC of the right deltoid and trapezius, and left biceps and pectoralis muscles when applied over the CB for 20 min. Park et al. (2022) reported no significant improvements of CMJ performance, bench press performance, and back squat one-repetition maximum loads in volleyball players by 2-mA a-tDCS (0.0714 mA/cm2) over M1 (Cz) for

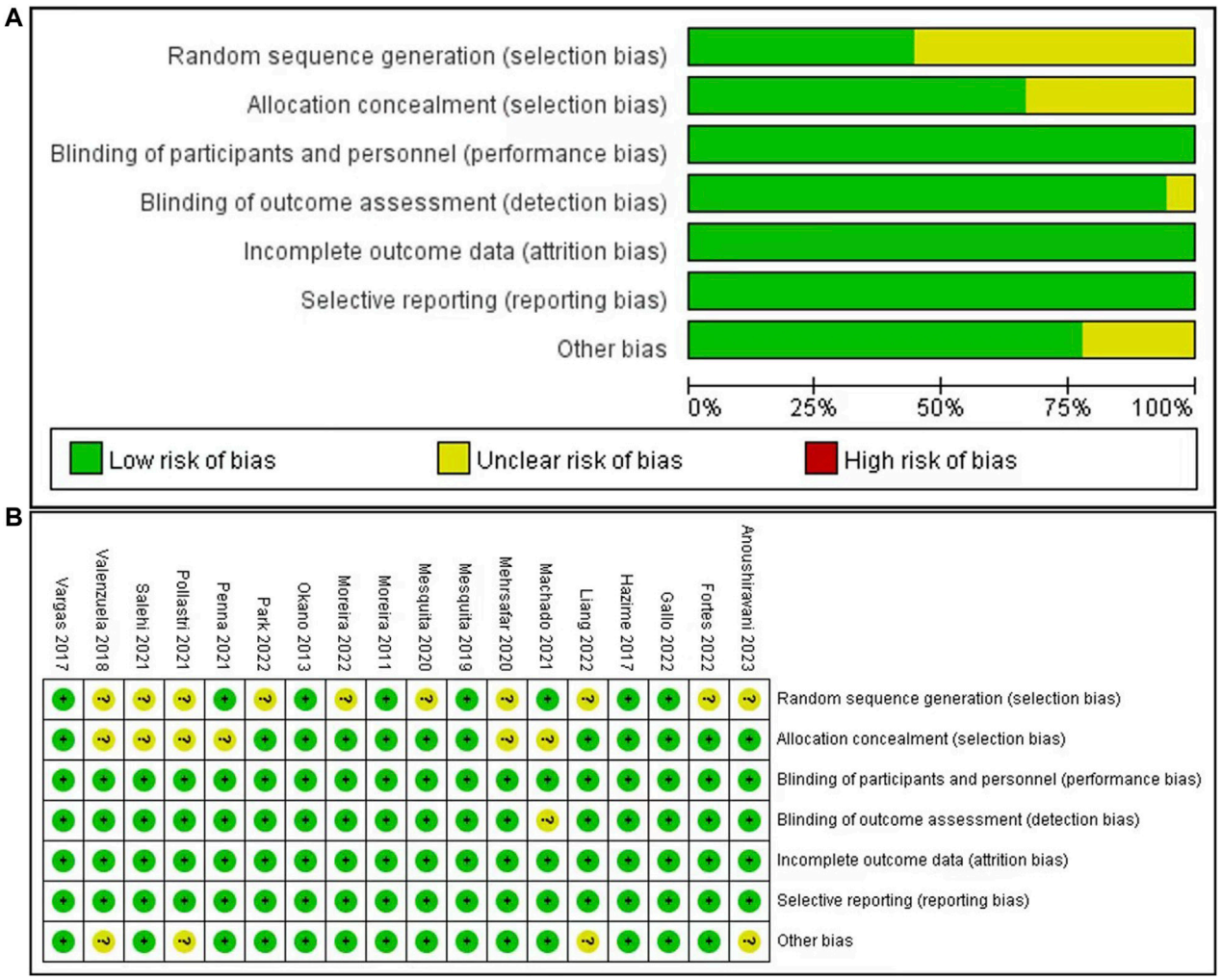


FIGURE 2
Quality and risk-of-bias assessment. Risk of bias graph **(A)**: review authors' judgments about each risk of bias item presented as percentages across all included studies; and risk of bias summary **(B)**: review authors' judgments about each risk of bias item for each included study.

20 min. Mesquita et al. (2019a) found that 1.5-mA a-tDCS (0.0428 mA/cm2) for 15 min applied over M1 bilaterally (C3 and C4) did not have significant improving effects on CMJ performance in taekwondo athletes.

Regarding endurance performance, four studies used peak power output (PPO) and the time in time-to-exhaustion test (TTE), time trial test (TT), or maximal incremental test (MIT) to assess the effects of tDCS in cyclists and rowers (Okano et al., 2015; Machado et al., 2021; Pollastri et al., 2021; Gallo et al., 2022). Among these studies, three (75%) reported positive influences. Okano et al. (Okano et al., 2015) showed that 2-mA a-tDCS (0.0571 mA/cm2) applied over the left TC (T3) for 20 min increased PPO in the MIT in cyclists. Gallo et al. and Pollastri et al. applied 1.5-mA HD-tDCS (0.238 mA/cm2) over the bilateral DLPFC (F3 and F4) for 20 min, and this stimulation protocol improved total time in 2-km TT, PPO and total time in 15-km PPO in cyclists compared with sham stimulation (Pollastri et al., 2021; Gallo et al., 2022). Machado et al. (2021) however report that neither 2.4-mA HD-tDCS over the M1 (Cz, C1, and C2) for 20 min nor 2-mA conventional a-tDCS over M1 (Cz) for 20 min affected total time in TTE at 80% PPO in cyclists and rowers compared with sham stimulation. The authors did not report the electrode sizes used for HD-tDCS, and the stimulus and reference electrode current densities were 0.055 mA/cm2 and 0.0571 mA/cm2, respectively, for conventional tDCS.

Regarding sport-specific performance, the test parameters in the nine studies included swimming speed (50 m and 800 m), 5 km rowing, basketball shooting accuracy, volleyball spike performance, gymnastic performance, the Progressive Specific Taekwondo Test, and the Taekwondo frequency speed of kick test (Mesquita et al., 2019b; Valenzuela et al., 2019; Mesquita et al., 2020; Penna et al., 2021; Liang et al., 2022; Moreira et al., 2022; Park et al., 2022; Salehi et al., 2022). Among them, only three studies reported positive effects of tDCS. Salehi et al. (2022) reported that 2-mA a-tDCS (0.0571 mA/cm2) applied over the left DLPFC (F3) for 20 min improved 50-m swimming speed in professional swimmers. Moreira et al. (2022) used identical tDCS parameters and found however no effects on shooting accuracy in basketball players. Moreover, neither Valenzuela et al.nor Penna et al. found improvements in the 800-m swimming test using 2-mA a-tDCS over M1 (C3) for 20 min and left

TABLE 1 Characteristics of the studies.

References	Sports	Gender	Age	Sports experience	Timing	Model	Design
Okano et al. (2015)	Cycling	10M	33.00 ± 9.00	Nation level	Offline	a-tDCS	Crossover
Hazime et al. (2017)	Handball	8F	19.65 ± 2.55	State and national competitions	Online/Offline	a-tDCS	Crossover
Mesquita et al. (2019a)	Taekwondo	12M7F	19.00 ± 3.00	Nation level	Offline	a-tDCS	Crossover
Vargas et al. (2018)	Soccer	20F	16.10 ± 0.90	State and national competitions	Online/Offline	a-tDCS	Crossover
Valenzuela et al. (2019)	Triathlon	8M	22.00 ± 2.00	International competitions	Offline	a-tDCS	Crossover
Mesquita et al. (2020)	Taekwondo	8M4F	19.00	National or international tournaments	Offline	a-tDCS	Crossover
Mehrsafar et al. (2020)	Archery	12M	26.51 ± 2.31	National level	Offline	a/c-tDCS	Crossover
Moreira et al. (2021)	Soccer	12M	19.00 ± 1.00	Professional Football Club Players	Offline	a-tDCS	Crossover
Pollastri et al. (2021)	Cycling	8M	20.00 ± 1.50	International competitions	Offline	a-tDCS	Crossover
Machado et al. (2021)	Cycling, Rowing	12M	29.40 ± 7.30	State, national or world-class competitions	Offline	a-tDCS	Crossover
Salehi et al. (2022)	Swimming	15M	23.00 ± 1.00	State and national competitions	Offline	a/c-tDCS	Crossover
Penna et al. (2021)	Swimming	10M	30.00 ± 6.00	National level	Offline	a-tDCS	Crossover
Liang et al. (2022)	Rowing	8F	NR	National level	Offline	a-tDCS	Crossover
Park et al. (2022)	Volleyball	13F	21.92 ± 2.81	Professional Volleyball Club Players	Offline	a-tDCS	Crossover
Moreira et al. (2022)	Basketball	8F	25.00 ± 8.00	Professional Basketball Players	Online/Offline	a-tDCS	Crossover
Gallo et al. (2022)	Cycling	12M	21.3 ± 4.30	Nation level	Offline	a-tDCS	Crossover
Fortes et al. (2022a)	Basketball	20M	24.77 ± 4.2	National level	Online/Offline	a-tDCS	Crossover
Anoushiravani et al. (2023)	Gymnastic	17M	21.05 ± 2.04	National competitions	Online/Offline	a-tDCS	Crossover

Abbreviations: M = male; F = female; NR, not reported; a-tDCS, anodal tDCS; c-tDCS, cathodal tDCS.

TC (T3) for 30 min (Valenzuela et al., 2019; Penna et al., 2021). Park et al. (2022) showed that 2-mA a-tDCS (0.0714 mA/cm2) over M1 (Cz) for 20 min improved volleyball spike speed and consistency compared with sham stimulation. Mesquita et al. (2019b; 2020) reported that 1.5-mA a-tDCS over the bilateral M1 (C3 and C4) for 15 min did not improve performance of the Progressive Specific Taekwondo Test and worsened performance on the frequency speed of kick test in taekwondo athletes. Similarly, Liang et al. (2022) showed that 2.2-mA a-tDCS over M1 (Cz) for 20 min did not increase 5-km rowing speed. Anoushiravani et al. (2023) reported that 2-mA a-tDCS over the PMC for 20 min improved performance on the straddle lift to handstand test, back hang scale test, and dips on parallel bars test and that 2-mA a-tDCS over the CB for 20 min improved straddle lift to handstand test performance in gymnastic athletes.

Four studies investigated the effects of tDCS on emotional states, with testing parameters including the Brunel Mood Scale, Competitive State Anxiety Inventory Second Edition, and Well-Being Questionnaire in archers, soccer players, triathletes, cyclists, and rowers (Valenzuela et al., 2019; Mehrsafar et al., 2020; Machado et al., 2021; Moreira et al., 2021). Among these studies, three reported positive results. Mehrsafar et al. found that 2-mA (0.08 mA/cm2) a-tDCS over the left DLPFC (F3) for 20 min improved vigor and reduced tension and anxiety in archers (Mehrsafar et al., 2020). Moreira et al. (2021) used the same tDCS parameters and found that a-tDCS (0.0571 mA/cm2) improved wellbeing in soccer players after a match. Still, there were inconsistent results regarding the effects of tDCS applied over the M1 on emotional states. Valenzuela et al. (2019) showed that 2-mA a-tDCS over the M1 (C3) for 20 min improved the vigor of triathletes compared with sham stimulation. Machado et al. (2021) found that neither HD-tDCS nor conventional a-tDCS over M1 improved Brunel Mood Scale scores in cyclists and rowers.

Three studies investigated the effects of tDCS on cognitive performance using reaction time (RT) and accuracy in the Stroop task (Okano et al., 2015; Penna et al., 2021), visuomotor skill and decision-making task (Fortes et al., 2022) in basketball players and cyclists. Among them, one study reported positive results. Fortes et al. (2022) found that 2 mA a-tDCS (0.08 mA/cm2) over the middle TC (CP5) for 30 min improved RT and accuracy in visuomotor skills as well as RT in decision-making in basketball players. Moreira et al. (2022) did not find improvements in Stroop task RT and accuracy in basketball players using 2-mA a-tDCS over the left DLPFC (F3) for 20 min. Moreover, Gallo et al. (2022) showed that 1.5-mA HD-tDCS over the bilateral DLPFC (F3 and F4) for 20 min did not improve Stroop task RT and accuracy in cyclists.

4 Discussion

In the present study, we performed a systematic review of the literature on the effects of a single session of tDCS in national- or international-level athletes. Numerous studies and reviews have investigated the effects of tDCS on exercise performance such as strength and endurance in individuals with motor impairments and

TABLE 2 Overview of studies investigating a single session of transcranial direct current stimulation for improving athletic performance in elite athletes.

References	Stimulus(S) Reference(R)	Electrode size [cm^2]	Intensity [mA]	Duration [mins]	Indicators	Main outcomes
Strength						
Hazime et al.	S:M1 (C3 or C4) R:IOC	S = R = 35	2.0	20	MVIC	a-tDCS improved MVIC of shoulder rotator
Vargas et al.	S:M1 (C3 or C4) R:COC	S = R = 35	2.0	20	MVIC	a-tDCS improved MVIC of external and internal knee extensor
Mesquita et al.	S:Bilateral M1 (C3, C4) R:IS	S = 35 R = 25	1.5	15	CMJ	No significant difference in CMJ
Park et al.	S:M1 (Cz) R:M1 (C5, C6)	S = R = 28	2.0	20	1RM, CMJ	No significant difference in CMJ, bench-press and back-squat 1 RM
Anoushiravani et al.	S: Bilateral PMC R: COC	S = R = 35	2.0	20	BJT, MVIC	a-tDCS improved BJT, MVIC of all upper body muscles
	S: Bilateral CB R: COC	S = R = 35	2.0	20		a-tDCS improved MVIC of right deltoid and trapezius, left biceps and pectoralis muscle
Endurance						
Okano et al.	S:Left TC (T3) R:COC	S = R = 35	2.0	20	MIT	a-tDCS improved PPO
Pollastri et al.	S:Bilateral DLPFC (F3, F4) R:Fp1, F7, C3, Fp2, F8, C4	S = R = 3.14	1.5	20	15 km TT	a-tDCS improved PPO and total time
Machado et al.	S:M1 (Cz, C1, C2) R:C3, C4, FC1, FC2, P1, P2	NR	2.4	20	TTE at 80% PPO	No significant difference
	S:M1 (Cz) R: Occipital protuberance	S = 36 R = 35	2.0	20		
Gallo et al.	S:Bilateral DLPFC (F3, F4) R:Fp1, F7, C3, Fp2, F8, C4	S = R = 3.14	1.5	20	2 km TT	a-tDCS improved total time
Sport-specific performance						
Salehi et al.	S:Left DLPFC (F3) R: COC (Fp2)	S = R = 35	2.0	20	50-m swimming test	a-tDCS improved total time
Valenzuela et al.	S:M1 (C3) R:COC (Fp2)	S = R = 25	2.0	20	800-m swimming test	No significant difference
Penna et al.	S:Left TC (T3) R:IS	S = R = 35	2.0	30	800-m swimming test	No significant difference
Moreira et al.	S:Left DLPFC (F3) R:Right DLPFC (F4)	S = R = 35	2.0	20	Shooting task	No significant difference
Liang et al.	S:M1 (Cz) R:C5, C6	S = R = 24	2.2	20	5 km rowing	No significant difference in speed and power
Mesquita et al.	S:Bilateral M1 (C3, C4) R:IS	S = 35 R = 25	1.5	15	FSKT	a-tDCS worsens the total number of kicks
Park et al.	S:M1 (Cz) R:C5, C6	S = R = 28	2.0	20	Spike task	a-tDCS improved spike speed
Mesquita et al.	S:Bilateral M1 (C3, C4) R:IS	S = 35 R = 25	1.5	15	PSTT	No significant difference in kicking frequency
Anoushiravani et al.	S: Bilateral PMC R: COC	S = R = 35	2.0	20	BHST, SLHT,DLCT, ASFT,SRT,DPBT	a-tDCS improved SLHT, BHST, DPBT
	S: Bilateral CB R: COC	S = R = 35	2.0	20		a-tDCS improved SLHT
Emotional state						
Valenzuela et al.	S:M1 (C3) R:COC (Fp2)	S = R = 25	2.0	20	BMS	a-tDCS improved vigor
Mehrsafar et al.	S:Left DLPFC (F3) R:Right DLPFC (F4)	S = R = 25	2.0	20	BMS, CSAI-2	a-tDCS improved vigor, decreased tension, fatigue and anxiety

(Continued on following page)

TABLE 2 (*Continued*) Overview of studies investigating a single session of transcranial direct current stimulation for improving athletic performance in elite athletes.

References	Stimulus(S) Reference(R)	Electrode size [cm^2]	Intensity [mA]	Duration [mins]	Indicators	Main outcomes
Moreira et al.	S:Left DLPFC (F3) R:Right DLPFC (F4)	S = R = 35	2.0	20	WBQ	a-tDCS improved total score
Machado et al.	S:M1 (Cz, C1, C2) R:C3, C4, FC1, FC2, P1, P2	NR	2.4	20	BMS	No significant difference in total score
	S:M1 (Cz) R: Occipital protuberance	S = 36 R = 35	2.0	20		
Cognitive performance						
Moreira et al.	S:Left DLPFC (F3) R:Right DLPFC (F4)	S = R = 35	2.0	20	Stroop task	No significant difference in RT and accuracy
Gallo et al.	S:Bilateral DLPFC (F3, F4) R: Fp1, F7, C3, Fp2, F8, C4	S = R = 3.14	1.5	20	Stroop task	No significant difference in RT and accuracy
Fortes et al.	S:Middle TC (CP5) R:Visual cortex (Oz)	S = R = 25	2.0	30	Visuomotor task Decision-making	a-tDCS improved RT and accuracy in decision-making, and RT in visuomotor task

The effects of tDCS on improving athletic performance were categorized into strength, endurance, sport-specific performance, emotional states, and cognitive performance. Abbreviations: a-tDCS, anodal tDCS; FSKT, frequency speed of kick test; PSTT, progressive specific taekwondo test; MVIC, maximal voluntary isometric contraction; CMJ, countermovement jump; TTE, time to exhausted test; MIT, maximal incremental test; TT, time trail; PPO, peak power output; 1RM, 1 repetition maximum; BJT, broad jump test; SLHT, straddle lift to handstand test; DLCT, double legs circle test; BHST, back hang scale test; ASFT, active shoulder flexibility test; SRT, sit and reach test; DPBT, dips on parallel bars test; WBQ, Wellbeing Questionnaire; BMS, brunel mood scale; CSAI-2, competitive state anxiety inventory second edition; RT, reaction time; cm^2 = square centimeter; mA = milliamps; mins, minutes; M1 = primary motor cortex; DLPFC, dorsolateral prefrontal cortex; TC, temporal cortex; PMC, premotor cortex; CB, cerebellum; COC, contralateral orbitofrontal cortex; IOC, ipsilateral orbitofrontal cortex; IS, ipsilateral shoulder; S = stimulating electrode; R = reference electrode; NR, not reported; F = female; M = male.

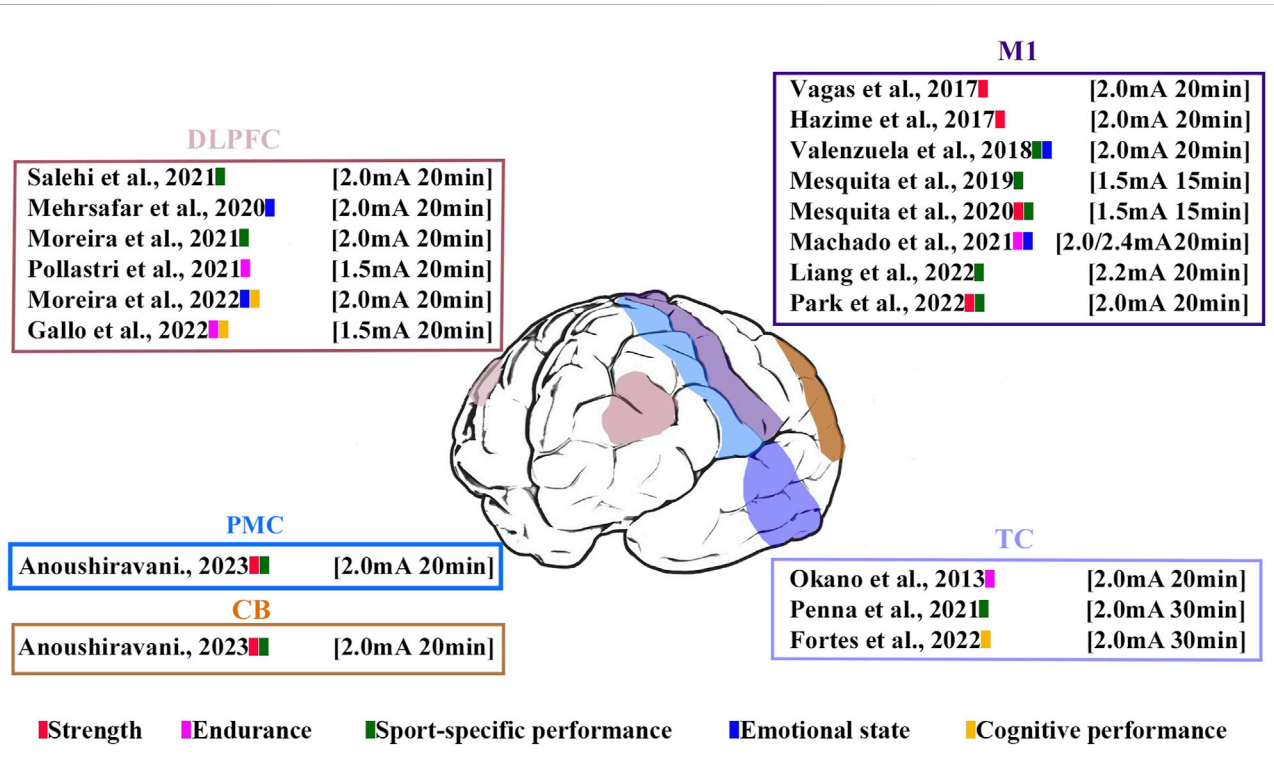


FIGURE 3
Visualization of stimulated time, site, current intensity and performance in the analyzed studies. The color bars represent athletic performance involved in analyzed studies.

in healthy individuals (Alix-Fages et al., 2019; Holgado et al., 2019; Morya et al., 2019; Patel et al., 2019; Chinzara et al., 2022; Marinus et al., 2022), but the number of studies on athletes, particularly national- or international-level athletes, is limited. A recent systematic review and meta-analysis investigated a single anodal tDCS session on sport-specific motor performance in athletes

participating regularly for at least 2 years (Maudrich et al., 2022). As far as we know, no reviews study has comprehensively investigated the effects of tDCS on athletic performance in both physical and psychological parameters in high-level athletes. Our studies included high-level athletes at tiers 3 (highly trained/national level) and four (international level), based on a recently proposed participant classification framework (McKay et al., 2022). Therefore, we examined 18 studies, involving 224 subjects in 12 sports disciplines. Our analysis showed that a single session of 1.5–2.4-mA tDCS with a duration of 15–30 min resulted in heterogeneous outcomes. The most sensitive to tDCS are strength (improvement in 67% of studies), endurance (improvement in 75% of studies), and emotional states (improvement in 75% of studies). It is interesting to note that the positive effects of tDCS on performance are significantly reduced in the case of sport-specific tasks (40% of studies) and cognitive performance (33% of studies). This suggests that tDCS is a promising tool to improve sportive performance but that it is more effective in no task specific aspects of athletic performance. More importantly, this is the first systematic review to analyze the effects of tDCS on emotional states and cognitive performance in high-level athletes. Emotional state and cognitive performance are crucial for athletic performance under intense conditions. Our analysis showed that tDCS can modulate emotional states, such as improving vigor and decreasing tension, fatigue, and anxiety, as well as cognitive performance, such as improving reaction time and accuracy in decision-making. However, research on the effects of tDCS on emotional states and cognitive performance is relatively sparse. Both of these are key focus points for future research.

tDCS applied to specific brain regions can induce particular neuromodulatory processes (Machado et al., 2021). Through complex networks and systems, several brain areas regulate or promote athletic performance, including the M1, PMC, CB, DLPFC and TC. M1 plays a crucial role in athletic performance, however results with tDCS applied over M1 were inconsistent (Edwards et al., 2017; Machado et al., 2019; Shyamali Kaushalya et al., 2021). Machado et al. (2019) reported that a-tDCS over M1 improved exercise performance in cycling only in healthy adults. Among the seven studies applying tDCS over M1, four showed improvements in muscle strength, sport-specific performance, and emotional states. Regarding muscle strength performance, two studies showed that a-tDCS (2 mA, 20 min) over M1 (C3 or C4) increased the MVIC in handball and football athletes (Hazime et al., 2017; Vargas et al., 2018). tDCS over M1 can enhance corticospinal excitability to alter motor unit firing and muscle recruitment strategies (Krishnan et al., 2014; Dutta et al., 2015; Polania et al., 2018). Regarding sport-specific performance, Park et al. (2022) showed improved volleyball spike speed and consistency using a-tDCS (2 mA, 20 min) over M1. Spike performance is closely related to coordination patterns and muscle synergies of the entire body (Wagner et al., 2014). Veldema et al. (2021) reported that 1-mA a-tDCS over M1 for 20 min improved basketball shooting performance in healthy sports students. This implies that tDCS may have positive effects on specific motor coordination in high-level athletes. In addition, tDCS over M1 may potentially increase explosive force (Lu et al., 2021), as shown for volleyball spike speed. Regarding emotional states, Valenzuela et al. (2019) used 2-mA a-tDCS for 20 min over the M1 and improved vigor in triathletes. A previous study found that tDCS over M1 (C3) improved mood in patients with fibromyalgia, which may be related to elevated serum beta-endorphin levels (Khedr et al., 2017). tDCS has been observed to alter activation and functional connectivity of the region under the anode. Additionally, the conventional method using two large sponge pad electrodes was found to affect the functional connectivity of other cortical and deep brain regions, particularly in the DLPFC (van den Heuvel and Sporns, 2013; To et al., 2018; Piretti et al., 2022). The activation of the DLPFC has been linked to improvements in mood states (Ligeza et al., 2021). Hence, tDCS applied over the M1 likely alter activation and functional connectivity of the DLPFC, potentially causing the observed augmentations in mood after tDCS.

Some studies however report no difference in neuromuscular or sport-specific performance between M1-tDCS and sham stimulation (Mesquita et al., 2019b; Valenzuela et al., 2019; Machado et al., 2021; Liang et al., 2022; Park et al., 2022), suggesting that tDCS over the M1 may not affect sport-specific movement patterns in high-level athletes in each case, and that facilitation of cortical excitability does not always induce improvements in athletic performance in high-level athletes. The brains of high-level athletes show specific neural responses during exercise compared to the general population and non-elite athletes (Del Percio et al., 2010; Nakata et al., 2010; Wright et al., 2010; Casanova et al., 2013; Callan and Naito, 2014; Ermutlu et al., 2015; Monda et al., 2017). Long-term training may develop specialized neural networks that implement the automatic execution of movements and reduce neural activity in high-level athletes (Xu et al., 2016; Guo et al., 2017). These findings are in line with the "neural efficiency" hypothesis, which suggests more efficient cortical functions in more skilled individuals, requiring less cortical activation (Del Percio et al., 2008; Babiloni et al., 2010; Dunst et al., 2014). On the other hand, high-level athletes showed higher baseline levels of neural excitability and brain-derived neurotrophic factor concentration compared to healthy non-athletes (Al-Khelaifi et al., 2018; Donati et al., 2021). Although the exact mechanisms underlying these effects have not been clarified in detail, some studies have shown that tDCS can affect neural excitability and neural plasticity through reducing gamma-aminobutyric acid inhibition and increasing brain-derived neurotrophic factor levels (Liebetanz et al., 2002; Nitsche et al., 2003a; Frazer et al., 2016). Thus, tDCS may not affect on neural excitability and plasticity in high-level athletes. Mesquita et al. (2019b) reported that 1.5-mA a-tDCS over the bilateral M1 for 15 min did not enhance kick frequency in 19 black-belt taekwondo athletes and reduced the total number of kicks compared to a control group. This implied that bilateral M1 stimulation worse performance than unilateral stimulation. This discrepancy may be explained by current flow direction. A recent study reported that corticospinal excitability was decreased after a-tDCS over bilateral M1 in healthy adults (Behrangrad et al., 2022). Studies investigating the effects of tDCS on neural excitability in athletes are scarce. Future research should focus on neural mechanistic studies to elucidate the impact of various protocols and target brain areas of tDCS on high-level athletes.

The PMC forms an important node in frontoparietal networks and contributes to specification of movement parameters (Kantak et al., 2012). One study found that 2-mA a-tDCS over the PMC for

20 min improved MVIC of all upper body muscles and gymnastic performance in gymnastic athletes (Anoushiravani et al., 2023). A recent study showed that a-tDCS over PMC improved functional connectivity within PMC and between PMC and M1, and enhanced motor performance after stroke (Unger et al., 2023). This implies that PMC activation via tDCS could enhance motor network activity and premotor-motor functional connectivity, and result in performance improvements. Further, the CB is an important node in motor control and coordination of complex movements (Jacobs and Horak, 2007). One study found that 2-mA a-tDCS over the CB for 20 min improved MVIC of the right deltoid and trapezius and left biceps and pectoralis muscles and straddle lift to handstand test in gymnastic athletes (Anoushiravani et al., 2023). Kenville et al. (2020) showed that 2-mA tDCS over CB for 20 min improved MVIC during isometric barbell squats in healthy individuals. Studies showed enhanced connectivity in fronto-parietal-cerebellar networks and motor cortex-cerebellar networks following motor adaptation in healthy subjects (Sami and Miall, 2013; Vahdat et al., 2014). tDCS over CB has potential benefits for motor tasks and improves locomotor performance, and tDCS can increase postural control by affecting connections between the CB and M1 and influencing the function of the vermis (Celnik, 2015). There are inhibitory interactions between the CB and M1, which may have limited the effects of tDCS over CB. According to the latest finding, a-tDCS over right CB increased cerebellar brain inhibition and reduced M1 excitability (Galea et al., 2009). Behrangrad et al. found that bilateral a-tDCS over the M1 + CB and bilateral a-tDCS over the CB significantly increased corticospinal excitability (Behrangrad et al., 2022). It seems that the stimulation protocol affects the effects of tDCS over CB on neural excitability and muscle strength enhancement and this should be investigated in future studies.

Five studies included in this review investigated the effects of tDCS applied over the DLPFC on endurance, emotional states, and cognitive performance. Regarding endurance, two studies reported that 1.5-mA HD-tDCS over the bilateral DLPFC (F3 andF4) for 20 min improved total time required for in 2-km TT, PPO and total time required for 15 km distance in cyclists compared with sham stimulation (Pollastri et al., 2021; Gallo et al., 2022). It was reported that 1.5-mA HD-tDCS over the bilateral DLPFC (F3 and F4) for 20 min delayed the increase in ratings of perceived exertion (RPE) during TT and lead to higher power output at the same RPE compared with sham stimulation (Pollastri et al., 2021). The main function of the DLPFC is executive control of behavior (Miller and Cohen, 2001), a-tDCS over DLPFC demonstrated an increase in resting functional connectivity within networks including the DLPFC (Keeser et al., 2011) and increased coupling between the left and right DLPFC and the left sensorimotor cortex (Stagg et al., 2013). A recent study showed that 2-mA a-tDCS over the left DLPFC for 30 min delayed TTE, reduced the heart rate and RPE, and improved Stroop task performance in healthy individuals (Angius et al., 2019). tDCS over the left DLPFC enhances endurance performance, improves inhibitory control, and reduces the perception of effort by enhancing neural activity (Maeoka et al., 2012). Regarding emotional states, Moreira et al. (2021) reported that 2-mA a-tDCS over the left DLPFC for 20 min improved wellbeing scores in soccer players in real competition. Mehrsafar et al. (2020) found that a-tDCS enhanced vigor and reduced tension and pre-competition anxiety in archers. The activation of the prefrontal cortex has been associated with improvements in mood states (Ligeza et al., 2021; Park et al., 2021). It reported that tDCS over left DLPFC promote the descending pain inhibitory system by enhancing neural activity (Maeoka et al., 2012). However, two studies found that tDCS over DLPFC did not improve Stroop task performance in basketball players and cyclists (Gallo et al., 2022; Moreira et al., 2022). The Stroop paradigm is a valid indicator of inhibitory function. Inhibitory control is associated with the exclusion of irrelevant information or behavioral distractions and avoiding errors (Engle, 2016), affecting anticipation and decision-making during competition (Wood et al., 2016). Athletes demonstrate significantly higher cognitive performance than the general population (Nakamoto and Mori, 2008; Post et al., 2009; Irwin et al., 2011; Smith et al., 2016; Andrade et al., 2020). The "neural efficiency" hypothesis proposes that high-level athletes have lower brain activation during simple tasks and only show higher brain activation when performing difficult tasks (Del Percio et al., 2010). Simple cognitive tasks (e.g., Stroop task) may have a "ceiling effect" that does not effectively reflect the effects of tDCS. Besides, laboratory tests lack high levels of ecological validity, which may complicate detection of the effects of tDCS in high-level athletes (Machado et al., 2021). Efficacy of stimulation may also depend on number of sessions. A previous study reported that a-tDCS (2 mA, 20 min) over the left DLPFC over ten consecutive days improved attention and memory in professional athletes (Borducchi et al., 2016). This implies that a single tDCS session may be insufficient to enhance cognitive performance in high-level athletes. Further research should explore the effects of tDCS on cognitive performance in high-level athletes using multi-session and sport-specific cognitive tasks.

Another brain region that plays an essential role in athletic performance regulation is the TC. Two studies included in this review investigated the effects of tDCS applied over the TC on endurance and cognitive function. Regarding endurance, one study found that 2-mA a-tDCS over the left TC for 20 min increased PPO in the MIT in cyclists. The TC is an important part of the central autonomic network, which is involved in higher-order control of autonomic cardiovascular functions (Dono et al., 2020). tDCS over the TC can furthermore increase neural excitability of the insular cortex (Montenegro et al., 2011). The insular cortex is a major contributor to awareness of the body and subjective feelings related to athletes' perceptions of physical exertion during exercise and is responsible for cardiac autonomic control (Okano et al., 2015; Penna et al., 2021). It has been speculated that a-tDCS over the TC may increase parasympathetic modulation or decrease sympathetic modulation of the autonomic nervous system thereby improving endurance performance (Okano et al., 2015). Regarding cognitive function, one study reported that 2-mA a-tDCS over the middle TC for 20 min improved visuomotor and basketball decision-making skills in basketball players under mental fatigue (Fortes et al., 2022). Previous studies have also demonstrated an association of the TC with perception (e.g., visual search) in exercise (Brascamp et al., 2010; Qiu et al., 2019; Jedidi et al., 2021). Makris and Urgesi. (2015) showed that repetitive transcranial magnetic stimulation over the superior temporal sulcus decreased action anticipation in soccer players. The TC is a node in the action–observation network (Avenanti et al., 2013). tDCS over the TC may activate action-

observation network and improve perceptual-cognitive skills in high-level athletes.

The presently reviewed studies contained 14 different electrode placement protocols with eight different reference electrode positions. Holgado et al. (2019) reported the effects of tDCS on exercise performance were not significantly moderated by type of outcome, electrode placement, muscles involved, number of sessions, or intensity and duration of the stimulation. Differences in electrode placement and stimulation protocols also contributed to mixed results. Anoushiravani et al. reported that tDCS over PMC have better effects in improving strength and sport-specific performance of gymnastic athletes in comparison with tDCS over CB (Anoushiravani et al., 2023). Some studies showed that tDCS over DLPFC and M1 yielded inconsistent results in the same swimming test (Valenzuela et al., 2019; Salehi et al., 2022). Athletic performance is influenced by a variety of abilities modulated by different brain regions, and few studies have examined the effects of stimulating different brain regions on identical athletic performance. Kamali et al. (2019) use a two channel a-tDCS, one anode electrode over M1 (Cz, C1 and C2) and one over TC (T3) for 13 min, and found improvements in one-repetition maximum loads in experienced bodybuilders. A recent study reported that corticospinal excitability was significantly higher following tDCS over M1 and DLPFC than M1 (Vaseghi et al., 2015). This implied that dual-site stimulation may have better effects. The effects of different stimulation protocols and dual-site stimulation on high-level athletes should be investigated in future studies.

5 Conclusion

A single session of 1.5–2.4-mA tDCS with a duration of 15–30 min improved strength, endurance, sport-specific performance, emotional states, and cognitive performance in national- or international-level athletes in 12 out of the 18 studies. Of these, six refer to the application of tDCS on the motor system (M1, PMC, CB), five on DLPFC and two on TC. Of all the variables examined in our review, the most sensitive to tDCS are strength (improvement in 67% of studies), endurance (improvement in 75% of studies), and emotional states (improvement in 75% of studies). It is interesting to note that the positive effects of tDCS on performance are significantly reduced in the case of sport-specific tasks (40% of studies) and cognitive performance (33% of studies). This suggests that tDCS is a promising tool to improve sportive performance but that it is more effective in no task specific aspects of athletic performance.

In conclusion, our work suggests that a single tDCS session can apply to competition and pre-competition training to improve athletic performance including both physical and psychological aspects of national- or international-level athletes. Given the relevance of tDCS as a tool to improve athletic performance, further studies focusing on various parameters (type of sports, brain regions, stimulation protocol, athlete level and test tasks) and neural mechanistic studies are needed to improve efficacy of tDCS interventions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

YY: Investigation, Software, Visualization, Writing–original draft. XZ: Resources, Software, Writing–original draft. MN: Writing–review and editing. CV: Writing–review and editing. FQ: Conceptualization, Funding acquisition, Resources, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Balance performance of healthy young individuals in real versus matched virtual environments: a systematic scoping review

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Background: Due to technological advancements and the development of consumer-oriented head mounted displays (HMDs), virtual reality (VR) is used in studies on balance performance and balance trainability more and more frequently. Yet, it may be assumed that balance performance is affected by the physical characteristics of the HMD (e.g., weight) as well as by the virtual visual environment. Moreover, it has been shown that balance is age-dependent with children and adolescents showing worse performances compared to young adults, which may also affect their balance performance in virtual environments.

Objectives: The present systematic scoping review aims to provide an overview on the current evidence regarding balance performance of healthy, young individuals (6–30 years) in real and matched virtual environments.

Methods: A systematic literature search in the electronic databases PubMed, Web of Science, and SPORTDiscus (from their inception date to February 2024) resulted in 9,554 studies potentially eligible for inclusion. Eligibility criteria were: (i) investigation of healthy, young individuals (6–30 years), (ii) balance assessment in the real and a matched virtual environment, (iii) use of a fully immersive HMD, (iv) reporting of at least one balance parameter. A total of 10 studies met the predefined inclusion criteria and were thus included in this review. All studies were conducted with healthy, young adults (19–30 years).

Results: Five studies assessed static balance, four studies quantified dynamic balance, and one study measured static as well as dynamic balance performance. In healthy young adults, static balance performance was similar with and without VR during simple standing tasks (e.g., two-legged stance), but worse in VR during more challenging tasks (e.g., one-legged stance). Concerning dynamic balance, four out of five studies reported worse performance in VR, while one study did not find differences between visual environments. Most importantly, none of the studies investigating healthy children (6–12 years) and/or adolescents (13–18 years) met the predefined inclusion criteria.

Conclusion: In healthy young adults, balance performance seems to be affected by VR only during challenging static (e.g., one-legged stance) as well as during dynamic balance tasks. The underlying causes remain unclear, but factors such as perceived presence in VR, a shift in sensory organization and/or perceptual distortion may play a role. Of particular importance is the finding that there is a void in the literature on the influence of VR on balance performance of healthy children and adolescents.

KEYWORDS

postural control, balance performance, virtual reality, head-mounted display, healthy youth, healthy young adults

Introduction

In recent years, the use of immersive virtual reality (VR) has become increasingly popular in sciences due to advancements in the underlying technology, reduced acquisition costs, and a constantly growing spectrum of applications. A literature search in the online database PubMed using the term "virtual reality" revealed that over the last two decades the number of available peer-reviewed publications relating to this topic has increased from 1,188 in 2003 to 21,978 in 2023. An important step in the technological progress of VR-systems was the development of modern high-resolution head mounted displays (HMDs) over the last decade. Previously used equipment often included (multiple) large, stationary screens to apply a visual stimulus to a subject, thus limiting the possibility to synchronize visual input with the subject's head movements and leaving them unable to move freely in the virtual environment. For instance, in a study by Hollman et al. (2006) participants had to walk on a treadmill while looking at a moving, continuous virtual corridor projected onto a curved screen placed in front of the treadmill. On the one hand, such an approach limits immersion (i.e., the devices' technological capability to deliver lifelike experiences) as for example physical reality was not completely shut out (Slater and Wilbur, 1997). On the other hand, participants' perceived presence (i.e., the sense of really being in the virtual environment) may be restricted as they could not move freely in VR (Slater and Wilbur, 1997). In contrast, modern HMDs are relatively lightweight devices which provide subjects with an almost lifelike field of view and visual as well as auditory stimuli which are constantly aligned with the individual's (head) movements (Garner, 2018) and it has indeed been shown that they provide greater immersion (Rose et al., 2018) and higher presence (Shu et al., 2019) than less sophisticated VR-tools.

Exposing individuals to VR using modern HMDs thereby enables researchers to investigate an individual's behavior under almost real life (visual and auditory) conditions, such as walking across a crowded pedestrian crossing or standing in an open-air elevator while physically remaining in the laboratory and applying appropriate test equipment (e.g., motion capturing, force plate; Koilias et al., 2020; Bzduskova et al., 2022). Thus, VR may help to overcome the everlasting challenge of weighing up the pros and cons when deciding whether to conduct a lab- or a field-based test. Consequently, it is not surprising that VR is also used in postural control research more and more frequently as indicated by an almost threefold increase of yearly publications indexed in PubMed from 2013 ($N = 34$ studies) to 2023 ($N = 92$ studies) when searching for "virtual reality postural control."

In this regard, studies using HMD-driven VR have focused on balance assessments (Rosiak et al., 2024) as well as on balance training (Lubetzky et al., 2022). During several balance assessments [e.g., Sensory Organization Test (Nashner and Peters, 1990)] for example, researchers apply test conditions where visual input is manipulated (e.g., by a moving visual stimulus) to assess the contribution of different afferents (i.e., visual, vestibular, somatosensory) for the control of balance. However, these tests usually require sophisticated equipment which is costly and stationary. To address this problem, researchers have successfully adapted the test conditions using HMDs (Wittstein et al., 2020; Moon et al., 2021). Additionally, HMDs allow researchers to use an almost infinite number of configurations regarding the design of a visual perturbation (e.g., amplitude, direction, frequency) and/or the visual environment and thereby may help in identifying individuals with balance deficits and/or at risk of falls (Soltani and Andrade, 2020).

Concerning balance, one group of scientific interest are children and adolescents. More specifically, it has been shown that, compared to adults, they show poorer balance performance, even if they are generally healthy (Balogun et al., 1994; Granacher et al., 2011; Schedler et al., 2021). The poorer balance performance can most likely be attributed to the immaturity of their postural control system (e.g., vestibular function, cerebellar function), which does not develop until early adulthood (Gouleme et al., 2014, 2018). Similarly to older individuals, lower balance performance in youth is accompanied with an increased risk of falls (Tang et al., 2021) and/or sustaining sports-related injuries (Emery, 2003). Consequently, balance assessments as well as balance training are particularly important in the healthy youth. Besides the aforementioned potential benefits of VR for postural control research, using virtual environments may have additional advantages such as higher motivation and entertainment for the younger populations. Moreover, children are known to rely more on vision than young or older adults as their vestibular system is still developing (Hirabayashi and Iwasaki, 1995; Steindl et al., 2006). Therefore, one could assume that the effects of the virtual environment on balance performance could vary depending on age.

Despite the aforementioned potential benefits of VR for postural control research, it has to be considered that balance performance might be affected when applying VR using HMDs. More precisely, one could argue that balance performance when viewing a virtual environment may not reflect an individual's capability to balance in the real environment. In fact, some studies have addressed this question resulting in equivocal findings. For young adults, Asslander and Streuber (2020) showed a comparable body sway during two legged-stance on a fixed as well as on a moving platform while viewing the real or a virtual replica of the laboratory. In contrast, Peterson et al. (2018) observed significantly worse performances (i.e., more failures, lesser beam passes, slower gait speed) when young adults balanced on a virtual compared to a real balance beam. Further and with respect to the aforementioned age-related differences in balance performance in youth, it may be supposed that VR may have different effects on healthy children's, adolescents', and/or young adults' balance performance. Such age-related differences of the influence of VR on balance would however be of major importance for researchers as well as for practitioners (e.g., physical therapists, coaches) to be able to design appropriate test and training conditions for different age groups when VR is used to assess and/or train balance. For instance, if VR has age-dependent effects on balance

performance in healthy children, adolescents and young adults, test conditions (i.e., during balance assessment) and balance exercises (i.e., during balance training) may have to be adapted when VR is used.

Therefore, the aim of the present systematic scoping review was to aggregate findings on balance performance in healthy children, adolescents, and young adults when assessed in real and matched virtual environments.

Methods

The present systematic scoping review was conducted according to the PRISMA Extension for Scoping Reviews (PRISMA-ScR; Tricco et al., 2018). The procedure followed a preassigned protocol, which was however neither registered nor published. The protocol can be provided by the corresponding author if requested.

Search strategy

To identify relevant research articles, a systematic literature search in the electronic databases PubMed, Web of Science, and SPORTDiscus was performed using the following Boolean search term: ("virtual reality" OR "VR" OR "virtual" OR "augmented reality" OR "AR" OR" virtual environment" OR "head mounted display" OR" HMD" OR "immersive") AND ("balance" OR "postural control" OR" postural stability" OR" posturography" OR "equilibrium" OR "posture" OR "beam") NOT ("patients" OR "rehabilitation" OR "syndrome" OR "cerebral palsy" OR "stroke" OR "disorder" OR "injury" OR "disease" OR "elderly" OR "seniors"). The search was limited to English full texts investigating the human species published from the inception date of the respective database to March 2024. After duplicates were removed, two authors (SS, TM) independently screened the titles of potentially eligible studies sequentially according to the predefined inclusion and exclusion criteria. Subsequently, the abstracts and full-texts of the remaining articles were read and assessed for eligibility by both authors. Disagreements were solved through discussion and consensus. No screening software was used during the whole inquiry.

Study selection criteria

Study selection was conducted according to several predefined inclusion and exclusion criteria (Table 1). Eligible for inclusion were English full-texts investigating healthy young individuals (6–30 years), which assessed balance performance in the real and a matched virtual environment provided through a fully immersive HMD. Additionally, only cross-sectional studies and intervention studies providing baseline data were considered for inclusion. With respect to balance performance, studies were selected if they reported at least one parameter of either static or dynamic balance based on the definitions provided by Shumway-Cook and Woollacott (2007). Concerning static balance, the preferred outcome was postural sway velocity, while regarding dynamic balance it was gait velocity. An overview on the preferred and alternative outcomes is provided in Table 2.

TABLE 1 Inclusion and exclusion criteria applied during the literature search.

	Inclusion criteria	Exclusion criteria
Document	English full-text	Abstracts, Conference Papers, non-English full-text
Study group	Healthy individuals	Athletes, patients (e.g., morbus parkinson, cerebral palsy)
Age	6–30 years	>30 years
Study design	Cross-sectional, Intervention	Case report, Observational, Intervention without reporting baseline data, Systematic Review
Hardware used for virtual, visual stimulus	Fully immersive, stereoscopic head-mounted-display (e.g., HTC Vive)	Screen-based devices (e.g., CAVE system), smartphone-based devices (e.g., Google cardboard)
Virtual visual environment	Resemblance of real visual environment (e.g., laboratory)	Fictional visual environment (e.g., city, forest, transformer station)
Outcome	At least one parameter of balance performance (e.g., sway velocity)	Brain activity, psychometric measures

TABLE 2 Overview of the preferred and alternative outcomes for static and dynamic balance.

	Preferred outcome	Alternative outcomes
Static balance performance	• Postural sway velocity	• Postural sway velocity in medio-lateral direction • Postural sway velocity in anterio-posterior direction • Postural sway path • Root-mean-square error of postural sway
Dynamic balance performance	• Gait velocity	• Failures • Number of steps

Data extraction

Data of included studies was extracted and specified according to author(s), year of publication, number, age, and sex of participants, balance assessment and outcomes, VR hardware (i.e., HMD used), and results. Relating to participants' age, studies were categorized as investigating children (<12 years), adolescents (12–18 years), and/or young adults (18–30 years). Further, depending on the respective balance assessment(s), studies were categorized as investigating static (i.e., maintain balance while body is stationary) and/or dynamic (i.e., maintain balance while body is moving) balance performance.

Results

Study selection

A complete overview of the selection process following the literature search is provided in the Flow chart depicted in Figure 1. Initially, the systematic literature search revealed 9,554 studies potentially eligible for inclusion in this review. After removing duplicates ($n = 376$), 9,057 studies were excluded based on their title. Of the remaining 121 records, 118 were retrieved and assessed for eligibility. The majority of these studies was excluded, for the following reasons: (i) the virtual environment was not matched to the real environment ($n = 29$), (ii) the age of included participants ($n = 19$), (iii) balance performance was not compared between real and matched virtual conditions ($n = 41$), (iv) no balance assessment ($n = 5$), (v) no HMD was used ($n = 14$). Consequently, the systematic literature search resulted in a total of 10 studies (Kelly et al., 2008, 2019; Cleworth et al., 2012; Ida et al., 2017; Peterson et al., 2018; Asslander and Streuber, 2020; Pastel et al., 2020; Liang et al., 2021; Ketterer et al., 2022) which were included in this systematic scoping review.

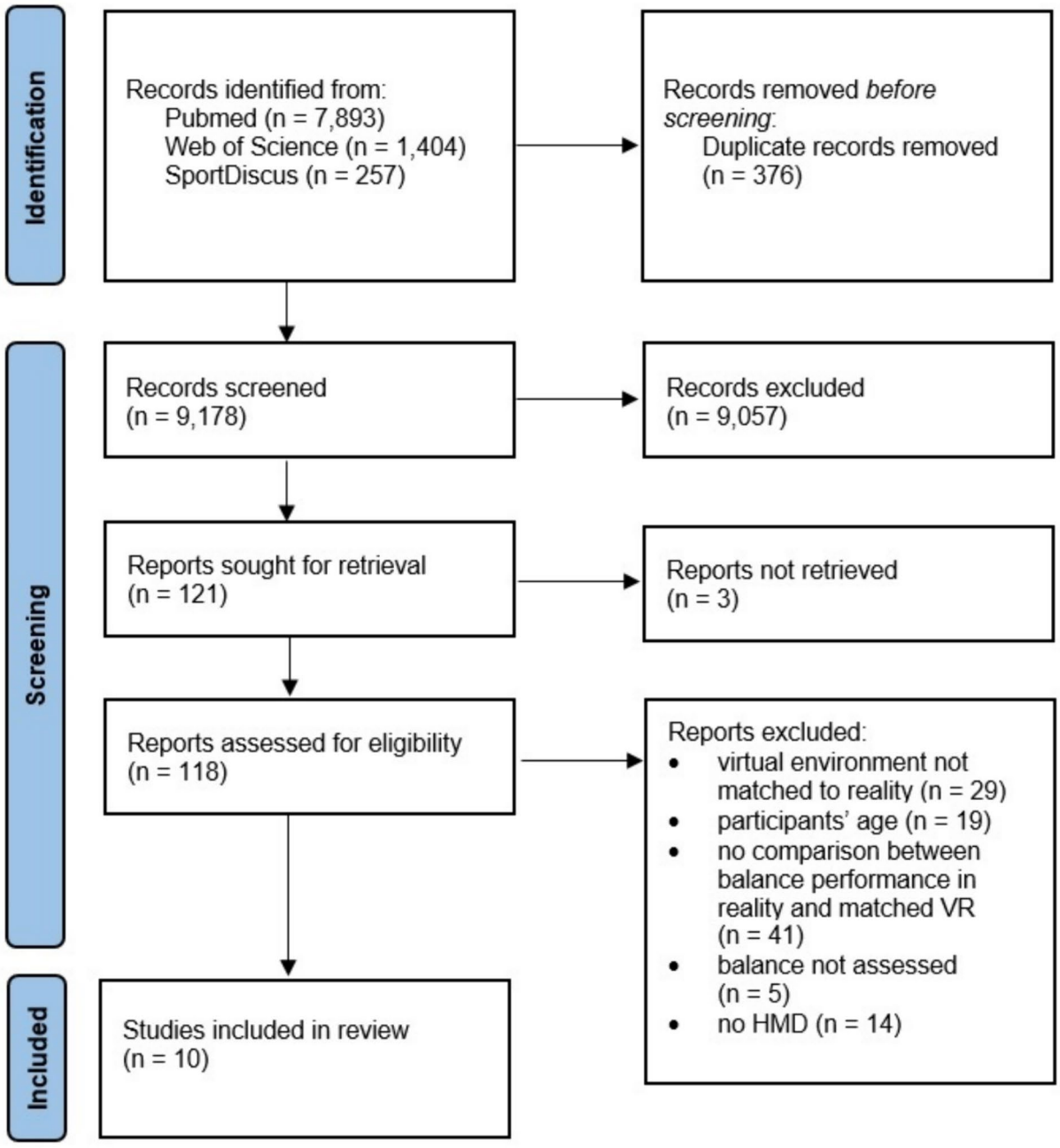


FIGURE 1
PRISMA flow chart showing the different stages of the literature search.

Study characteristics

The main characteristics of the included studies are presented in Table 3. None of the included studies investigated balance performance in a real and a matched virtual environment in healthy youth; neither in children nor in adolescents. Thus, all of the included studies were conducted with healthy young adults. Altogether, 193 (93 females, 100 males) healthy young adults (18–30 years) were investigated. Five studies (Kelly et al., 2008, 2019; Cleworth et al., 2012; Liang et al., 2021; Ketterer et al., 2022) assessed static balance performance, four studies (Ida et al., 2017; Peterson et al., 2018; Boroomand-Tehrani et al., 2020; Pastel et al., 2020) measured dynamic balance performance, and one study (Asslander and Streuber, 2020) recorded static as well as dynamic balance performance. Eight different HMDs were used in the included studies with the HTC Vive Pro ($n = 2$; Asslander and Streuber, 2020; Liang et al., 2021) and the HTC Vive Pro Eye ($n = 2$; Pastel et al., 2020; Ketterer et al., 2022) being the ones used most frequently. The other employed HMDs were Virtual Research V8 ($n = 1$; Kelly et al., 2008), Vuzix iWear ($n = 1$; Ida et al., 2017), Sensics piSight ($n = 1$; Cleworth et al., 2012), Oculus Rift DK1 ($n = 1$; Boroomand-Tehrani et al., 2020), Oculus Rift DK2 ($n = 1$; Peterson et al., 2018), and HTC Vive ($n = 1$; Kelly et al., 2019). All of these HMDs are PC-powered and thus cable-bound. In accordance with the predefined inclusion criteria, participants viewed a virtual resemblance of the real surrounding (e.g., laboratory) during balance assessment under VR conditions.

Two of the included studies assessed virtual reality sickness using either the "Motion Sickness Assessment Questionnaire (MSAQ)" (Peterson et al., 2018), or the "Simulator Sickness Questionnaire (SSQ)" (Asslander and Streuber, 2020). Further, one study (Asslander and Streuber, 2020) used the "iGroup Presence Questionnaire (IPQ)" and one study (Boroomand-Tehrani et al., 2020) used the" Presence Questionnaire" to measure the degree of perceived presence in the virtual reality scenario.

Static balance performance under real versus matched virtual conditions

Three studies (Cleworth et al., 2012; Asslander and Streuber, 2020; Ketterer et al., 2022) did not find significant differences between static balance performance under real when compared to matched virtual conditions. Another three studies (Kelly et al., 2008, 2019; Liang et al., 2021) observed worse performances in VR compared to the real condition, but only when balance task difficulty was increased (e.g., by reducing the base of support). No study detected worse static balance performance in the real compared to the virtual environment.

Dynamic balance performance under real versus matched virtual conditions

Comparing participants' dynamic balance performance under real versus matched virtual conditions, four studies (Ida et al., 2017; Peterson et al., 2018; Boroomand-Tehrani et al., 2020; Pastel et al., 2020) observed worse performances in the virtual compared to the real environment. In contrast, one study (Asslander and Streuber, 2020) did not find significant differences in dynamic balance performances between real and VR conditions. There was no study which found worse dynamic balance performance in the real compared to the virtual environment.

Discussion

The results of the present systematic scoping review can be summarized as follows: (i) in the majority of the included studies (i.e., seven out of ten) balance performance was at least to some extent worse when assessed under virtual compared to real conditions, (ii) detrimental effects of virtual reality were evident during demanding static (e.g., one-legged stance) and dynamic balance tasks, (iii) no study investigating children and/or adolescents met the inclusion criteria.

The influence of VR on static balance performance

At first glance, the results of the influence of VR on static balance performance in healthy young individuals seem to be inconsistent as three studies (Cleworth et al., 2012; Asslander and Streuber, 2020; Ketterer et al., 2022) did not find differences between balance performance in VR compared to the real environment, whereas three studies (Kelly et al., 2008, 2019; Liang et al., 2021) reported worse performance when individuals balanced while being exposed to VR. With respect to the latter studies, Kelly et al. (2008) assessed balance performance during three stance conditions (i.e., side-by-side, heel-to-toe, one-legged stance) while viewing a real room as well as a virtual replica in eight undergraduate students (six males, two females). Significantly increased sway in the virtual compared to the real visual environment was only observed during the heel-to-toe and the one-legged stance, but not during the easier side-by-side stance. Similarly, Liang et al. (2021) reported significantly larger body sway in VR compared to the real visual environment during tandem- and one-legged-stance, but not during a standardized two-legged-stance and side-by-side standing in 34 young adults (11 males, 23 females; mean age: 26.5 years). Lastly, in the study by Kelly et al. (2019), who also detected worse performances in 32 young adults (16 males, 16 females, mean age: 19.78 years) in the virtual compared to the real environment, participant's balance was only assessed during the more difficult one-legged stance. In contrast, the authors of the studies which reported similar balance performances in the real and a matched virtual environment assessed balance during two-legged standing (Cleworth et al., 2012; Asslander and Streuber, 2020; Ketterer et al., 2022), which is relatively easy to perform, especially for healthy young individuals. Actually, these findings agree with those of Kelly et al. (2008) and by Liang et al. (2021) and overall the present analysis indicates that there is a task-specific effect of VR on static balance performance in healthy young adults in the age range between 19 and 30 years.

Based on these results, one could argue that the type of visual input (i.e., real vs. virtual) has little relevance during simple balance tasks (e.g., two-legged stance), which can also easily be performed when visual input is removed. Yet, during more challenging conditions (e.g., one-legged stance) studies have found that visual input becomes more important (Hazime et al., 2012; Tomomitsu et al., 2013). The results of the included studies however indicate that balance performance decreases in the virtual condition during challenging tasks even though visual input is available. Thus, despite the high fidelity of modern HMDs, visual input may still be perceived as being inappropriate or unreliable when viewing a virtual replica of the real

TABLE 3 Characteristics of the included studies examining balance performance of healthy, young individuals in real and matched virtual environments.

Reference	Study group (age, sex)	Balance test(s) (type of balance)	HMD	VR-scenario	Balance outcomes	Results
Kelly et al. (2008)	8 young adults (N/A; 2 *f*, 6 *m*)	• Side-by-side, heel-to-toe, and one-legged stance (static)	Virtual Research V8	Virtual Laboratory	• Body sway (analyzed via head movements)	Balance performance in VR significantly worse compared to REAL, but only in more demanding tasks (i.e., heel-to-toe, one-legged stance)
Cleworth et al. (2012)	18 young adults (19–28 years old; 11 *f*, 7 *m*)	• Two-legged stance on a force platform at 0.8 m and 3.2 m (static)	Sensics piSight	Virtual Laboratory	• RMS of CoP in A/P and M/L directions • MPF of CoP in A/P and M/L directions • Mean position of CoP in A/P direction	No significant differences between balance performances in VR and REAL
Ida et al. (2017)	10 young adults (27.3 ± 4.7 years; 5 *f*, 5 *m*)	• Leg lifting to avoid an approaching obstacle while standing on a force platform (dynamic)	Vuzix iWear VR920	Virtual Laboratory	• CoP sway path in M/L direction • sEMG • Accelerometry	Balance performance in VR significantly worse compared to REAL
Peterson et al. (2018)	19 young adults (23 ± 4 years; 9 *f*, 10 *m*)	• Heel-to-toe beam walking on a balance beam (305 × 3.8 × 2.5 cm) (dynamic)	Oculus Rift Development Kit 2	Virtual Laboratory (participants also walked over the physical beam in the VR conditions)	• Failures (i.e., stepping off the beam) • Beam passes • Gait speed	Balance performance in VR significantly worse compared to REAL
Kelly et al. (2019)	32 young adults (19.78 ± 1.93 years; 16 *f*, 16 *m*)	• One-legged stance facing a door from close (0.85 m) and far (3 m) distance (static)	HTC Vive	Virtual laboratory	• RMS of body sway • Sway velocity • Romberg quotients (all analyzed via head movements)	Balance performance in VR significantly worse compared to REAL
Asslander and Streuber (2020)	10 young adults (25.4 ± 4.7 years; 5 *f*, 5 *m*)	• Two-legged stance on custom built platform (static) • Two-legged stance on custom built moving platform (dynamic)	HTC Vive Pro	Virtual Laboratory	• Sway velocity	No significant differences between balance performances in VR and REAL
Boroomand-Tehrani et al. (2020)	22 young adults (22.8 ± 1.8 years; 12 f, 12 m)	• Beam walking on a balance beam (300 × 3.8 × 10 cm) (dynamic)	Oculus Rift Development Kit 1	Virtual Laboratory	• Step success • Steps before first fail • Time to first fail	Balance performance in VR significantly worse compared to REAL
Pastel et al. (2020)	20 young adults (21.6 ± 1.6 years; 7 *f*, 13 *m*)	• Beam walking on a balance beam (400 × 10 × 4 cm) (dynamic)	HTC Vive Pro Eye	Virtual Laboratory with different grades of body representation (i.e., whole body, whole body except feet, whole body except feet and legs, no body); (participants also walked over the physical beam in the VR conditions)	• Time to completion • Failures (i.e., stepping off the beam) • No. of steps	Balance performance in VR significantly worse compared to REAL

(Continued)

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TABLE 3 (Continued)

Reference	Study group (age, sex)	Balance test(s) (type of balance)	HMD	VR-scenario	Balance outcomes	Results
Liang et al. (2021)	34 young adults (26.5 ± 6.3 years; 23 *f*, 11 *m*)	• Two-legged (i.e., standard, narrow, tandem) and one-legged stance wearing a tracker (static)	HTC Vive Pro	Virtual Laboratory	• CoP sway path in A/P and M/L directions • CoP velocity in A/P and M/L directions	Balance performance in VR significantly worse compared to REAL, but only in more demanding tasks (i.e., narrow tandem, one-legged stance)
Ketterer et al. (2022)	18 young adults (24.1 ± 2.0 years; 10 *f*, 8 *m*)	• Two-legged stance (static)	HTC Vive Pro Eye	Virtual Laboratory	• CoM sway assessed via 3D movement analysis	No significant differences between balance performances in VR and REAL

A/P, anterior–posterior; CoM, Centre of mass; CoP, Centre of pressure; EC, eyes closed; EO, eyes opened; f, female; HMD, Head-Mounted-Display; m, male; M/L, medial-lateral; MPF, mean power frequency; N/A, not applicable; No., Number; RMS, root mean square; sEMG, surface electromyography; VR, virtual reality.

environment. This could be related to altered depth perception in VR which, although it has significantly improved in modern HMDs, does still not match the distance estimates made in the real environment (Kelly, 2023). As a result, individuals may rely more strongly on somatosensory and/or vestibular input to keep their balance. Nonetheless, it has to be mentioned that participants in the included studies were still able to successfully perform the requested, more challenging balance tasks in the virtual environment.

Further, performance decreases were only observed in some of the included studies (Kelly et al., 2008, 2019; Liang et al., 2021) and even within some of these studies (Kelly et al., 2008; Liang et al., 2021) they were limited to certain test conditions. This indicates that balance performance is not affected by the physical characteristics of the HMD (e.g., mass), which corresponds to the findings of Mihalik et al. (2008) who could not find differences when participants performed different stance variations with eyes closed while wearing or not wearing a HMD.

The influence of VR on dynamic balance performance

Four of the included studies (Peterson et al., 2018; Boroomand-Tehrani et al., 2020; Pastel et al., 2020; Ida et al., 2022) reported decreased dynamic balance performance when healthy, young adults viewed a virtual replica of the real surrounding indicating a detrimental effect of VR on dynamic balance performance. This is in contrast to the findings of Asslander and Streuber (2020) who could not find differences in body sway of 10 young adults (5 males, 5 females; mean age: 25.4 years) following pseudo-randomized perturbations while standing on a tilting-platform and viewing the real or a virtual replica of the laboratory. One possible explanation could relate to methodological differences between these studies as participants actively moved in the virtual environment in three studies (Peterson et al., 2018; Boroomand-Tehrani et al., 2020; Pastel et al., 2020) or at least reacted (i.e., leg-lifting) to a moving visual stimulus (i.e., approaching obstacle; Ida et al., 2017), while visual environment stayed relatively stable in the other study (Asslander and Streuber, 2020), in which participants responded to a perturbation of the support surface.

Peterson et al. (2018), Boroomand-Tehrani et al. (2020), and Pastel et al. (2020) compared beam walking performance on a physical balance beam while viewing the real environment or a virtual replica of it and observed worse performances (e.g., slower gait velocity) in the VR condition in 19 (10 males, 9 females; mean age: 23 years), 20 (13 males, 7 females; mean age: 23.6 years), and 24 young adults (12 males, 12 females; mean age: 22.8 years), respectively. Previous studies (Horsak et al., 2021, 2023) have already shown that healthy adults adopt a more cautious gait strategy (e.g., slower gait velocity, longer time in double support) when walking in a virtual environment, perhaps as a consequence of a sensory conflict induced by the virtual visual condition even when it resembles the real environment. This effect may have been amplified by the increased task difficulty (i.e., beam walking) in the included studies (Peterson et al., 2018; Boroomand-Tehrani et al., 2020; Pastel et al., 2020). In fact, participants in the study of Pastel et al. (2020) perceived beam walking in the virtual environment as being more difficult than in the real environment.

Concerning the effects of moving in VR, an interesting finding has been reported by Ketterer et al. (2022). These authors found no differences between static balance performance when viewing the real

environment or a virtual replica in 18 young adults (8 males, 10 females; mean age: 24.1 years). However, after participants were allowed to move freely in VR for 3 min to accustom themselves with this visual condition, performance significantly decreased. This finding may either indicate that moving in VR indeed causes a shift in sensory organization and/or movement strategy or that factors such as the time spent in VR also affect postural control, for instance due to eye strain.

Further, body representation may be an important aspect to successfully perform a rather challenging balance task like beam-walking in VR. However, in two of the studies (Peterson et al., 2018; Pastel et al., 2020) participants were provided with an avatar in the virtual environment. Even more important, Pastel et al. (2020) compared individuals' performances not only between the real and the virtual environment, but also between different levels of body representation in VR (i.e., whole body, whole body except of feet, whole body except of feet and legs, no body), that were synchronized to participants' movements. Although the best balance performance in VR was achieved with whole body representation, it was still worse compared to the real condition. Thus, although the level of body representation seems to affect balance performance in VR, it cannot fully explain decreased performance in VR. However, it has to be mentioned that the avatars used were not entirely matched to participants regarding for instance stature, clothes, or shoes worn.

Future directions

The present systematic scoping review revealed several issues that should be addressed in future studies. First and most importantly there is an urgent need for studies on the influence of HMD-driven VR on balance performance in healthy children and adolescents. Previous studies (Balogun et al., 1994; Gouleme et al., 2014, 2018) on the development of postural control have shown age-related differences between children's, adolescents' and young adults' balance performances. Children, for example rely more heavily on visual input to control their posture and thus maintain their balance (Hirabayashi and Iwasaki, 1995; Steindl et al., 2006). Therefore, the effects of VR on balance performance may be stronger in children than young adults.

Two parameters potentially affecting balance performance in VR are an individuals' perceived presence when immersed in the virtual environment (Asslander and Streuber, 2020) as well as virtual reality sickness (e.g., dizziness, nausea; Chang et al., 2020). However, presence was only assessed in two (Asslander and Streuber, 2020; Boroomand-Tehrani et al., 2020) of the included studies. Similarly, only two studies (Peterson et al., 2018; Asslander and Streuber, 2020) recorded proxies of virtual reality sickness. Future studies should analyze how these psycho-physical variables are associated with balance performance in healthy young individuals when viewing a virtual environment through a HMD.

The findings presented in this review are limited to immediate effects of VR matched to the real environment on balance performance. However, there is evidence that the time spent in VR affects balance performance in VR (Ketterer et al., 2022) as well as in the real environment once the HMD is taken off (Akizuki et al., 2005). This relationship should be investigated in future studies as it is particularly important with respect to VR-assisted balance training. Additionally, it might also be interesting to investigate long-term (training/de-training) effects of VR on balance performance as well as the effects different virtual environments. In this regard, one could suppose that balance may be affected more strongly when the virtual environment does not correspond to the real environment.

All of the HMDs used in the included studies were cable-bound and connected to a PC. This may have affected balance performance as well as perceived presence as the cords would probably move, especially in dynamic conditions, which participants presumably sensed. The latest generation of consumer-oriented HMDs (e.g., Meta Quest 3, HTC VIVE Focus 3) are standalone devices, which should provide users with an even more realistic experience when immersed in virtual reality. Consequently, future studies should investigate their effects on balance performance in healthy young populations.

Lastly, previous research (Esteves et al., 2022; Deodato et al., 2023) has also shown that unilateral injuries may not only affect balance performance of the injured but also of the actually healthy limb, perhaps due to a general reorganization of balance control. Future studies could investigate whether VR provides benefits for research within this topic, as it could for instance be used as a training tool.

Limitations

There are a few limitations which have to be addressed. First, reporting biases cannot be assessed as the present protocol has not been registered or published in advance. Second, the presented findings only apply to healthy young individuals, who balanced under real and matched virtual conditions using modern fully immersive HMDs. Consequently, it remains unclear how different virtual environments affect balance performance.

Conclusion

The present systematic scoping review revealed that healthy, young adults' balance performance is affected by VR using modern, fully immersive HMDs during demanding static as well as during dynamic balance tasks, even when the virtual scene resembles the respective real visual environment. Currently, the underlying mechanisms remain unclear and should therefore be investigated in future studies. Factors such as perceived presence in VR as well as a shift in sensory organization due to the virtual visual environment could potentially play a role. More importantly, concerning balance there is a serious lack of studies on the use and effects of HMD-driven VR in healthy children and adolescents, which are a group of special interest due to their maturing postural control system.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

SS: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. KG: Methodology, Writing – original draft, Writing – review & editing. MH: Methodology, Writing – original draft, Writing – review

& editing. TM: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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The effect of contextual interference on transfer in motor learning - a systematic review and meta-analysis

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Since the initial study on contextual interference (CI) in 1966, research has explored how practice schedules impact retention and transfer. Apart from support from scientists and practitioners, the CI effect has also faced skepticism. Therefore, we aimed to review the existing literature on the CI effect and determine how it affects transfer in laboratory and applied settings and in different age groups. We found 1,287 articles in the following databases: Scopus, EBSCO, Web of Science, ScienceDirect, supplemented by the Google Scholar search engine and manual search. Of 300 fully screened articles, 42 studies were included in the systematic review and 34 in the quantitative analysis (meta-analysis). The overall CI effect on transfer in motor learning was medium (SMD = 0.55), favoring random practice. Random practice was favored in the laboratory and applied settings. However, in laboratory studies, the medium effect size was statistically significant (SMD = 0.75), whereas, in applied studies, the effect size was small and statistically non-significant (SMD = 0.34). Age group analysis turned out to be significant only in adults and older adults. In both, the random practice was favored. In adults, the effect was medium (SMD = 0.54), whereas in older adults was large (SMD = 1.28). In young participants, the effect size was negligible (SMD = 0.12).

Systematic review registration: https://clinicaltrials.gov/, identifier CRD42021228267.

KEYWORDS

contextual interference, practice schedule, random practice, blocked practice, transfer, motor learning

Introduction

The very first meta-analysis on contextual interference (CI) in motor learning was published in 2004 by Brady (2004). Brady asked how CI affects retention and transfer, i.e., two processes which, according to Battig (1966, 1972), are altered by CI level. Battig noted that high CI level originating from "random order," i.e., an order (or schedule) consisting of the trials arranged randomly and rapidly changing, hindered performance and facilitated retention and transfer. On the other hand, the so-called "blocked order," i.e., an order in which one skill

variation trials were completed before introducing the next skill, resulted in a low CI level. Low CI, unlike high CI, facilitated performance and hindered retention and transfer.

This rather unexpected finding was soon tested in motor learning, originally by Shea and Morgan (1979) and later by many others. In Brady (2004) meta-analytically studied CI effect in motor learning concluding that the general (on retention and transfer) effect size (ES) in laboratory research was medium (Cohen's $d = 0.57$) and in applied research was negligible (Cohen's $d = 0.19$). On the other hand, the ES in studies on transfer in adults was small, i.e., $d = 0.47$ for laboratory research and $d = 0.43$ for applied research. In children, the ES in applied research was negligible ($d = 0.10$).

Retention and transfer, though both equally important in motor learning measure assess different constructs. Retention is a good indicator of learning, whereas transfer is a good indicator of adaptability (Magill and Anderson, 2021). One could argue that the ultimate goal of practice is to transfer skills from one context to another, i.e., generalize practiced skill to a non-practice one (Raviv et al., 2022). Consequently, transfer could be considered more reliable measure of CI effect (Shewokis, 1997; Brady, 2004). It is hence crucial to analyze and discuss CI effect on transfer exclusively.

Almost 20 years have passed since Brady performed his meta-analysis. Given that the meta-analysis should be updated within 2 years (Cumpston and Chandler, 2019) and the median time for the update in Cochrane Collaboration is about 5.5 (Shojania et al., 2007), the meta-analysis on the CI effect should have been updated much earlier. Some other analyses were performed in the meantime. However, most of them focused on very specific questions, e.g., CI effect in random vs. serial practice (Lage et al., 2021), CI effect in children with cerebral palsy (Graser et al., 2019), or CI effect in students in medical and physiotherapy education (Sattelmayer et al., 2016).

Recently, in 2023, Ammar and colleagues published a meta-analysis (Ammar et al., 2023) on the CI effect on retention and transfer in sport settings. They referred to the CI effects as "a myth" because they found statistically non-significant and small effect sizes favoring random practice in transfer and retention tests (in analyses on the whole population). Unfortunately, they did not report how they treated outcomes retrieved from one sample (multiple dependent effect sizes), i.e., how they dealt with the dependency problem. Additionally, they did not screen the EBSCO databases, which include key resources like APA PsycArticles, APA PsychInfo, SPORTDiscus with Full Text, Medline, and Academic Search Complete. Furthermore, they did not preregister their study, a now common practice in research that reduces publication bias and selective reporting of outcome-related bias.

Given all of the above, we decided to perform a systematic review, and we formulated our objectives based on the ones advanced by Brady (2004). However, we exclusively focused on transfer due to the number of conducted analyses and included studies. The study's primary objective is to determine the overall effect size of CI on transfer in motor learning. Our secondary objectives, based on Brady (2004) inclusion criteria, are:

1) To estimate the CI effect in laboratory vs. field-based studies
2) To estimate the CI effect in young vs. adults vs. elderly adults
3) To estimate the CI effect in novice vs. experienced participants

Methods

The study was registered in PROSPERO under the number CRD42021228267. Given the number of conducted analyses and included studies as well as the page/word limit for an article, the registered review has been split into two consecutive papers: retention (Czyż et al., 2023) and transfer meta-analyses. Transfer performance was analyzed in the present study. Each consecutive step of the study was performed in accordance with the PICO guidelines (Methley et al., 2014), the PRISMA statement (Moher et al., 2009, 2015; Page and Moher, 2017; see Supplementary Appendix 1), and, successively *Quality Assessment Tool for Quantitative Studies* (Thomas, 2003; Thomas et al., 2004).

Inclusion and exclusion criteria

The inclusion criteria were defined in accordance with PICO (*Population*, *Intervention*, *Control*, *Outcome*) and included:

Population: adult, young, novice, experienced. In line with Brady's inclusion criteria (Brady, 2004), only healthy participants were considered, and two variables (age and experience) were incorporated. Participants under 18 years old were labeled as *Young*. Participants aged 60 years old and more were classified as *Older Adults*, and those between 18 and 60 years old were ranked as *Adults*.

Intervention: field setting, high CI volume (random/interleaved schedule);

Control: laboratory settings, low CI volume (blocked schedule/repetitive practice);

A wide variety of motor tasks and experimental procedures were utilized in reviewed studies potentially considered for inclusion; however, it is worth mentioning that only the studies using single-task procedures were relevant for the current review.

The main classification considered for analysis was based on contextual interference volume: studies including groups with different practice schedules: blocked order (low CI), and random order (high CI) were compared.

The subgroup analysis was performed based on the age of participants: young (<18 years old), adults, and older adults (>60 years old). The subsequent subgroup analysis was the nature of the research: studies carried out in a controlled laboratory environment were matched up with studies conducted in a field setting using typical sports skills (applied research). The subsequent subgroup analysis was the experience—experienced participants vs. novices.

Outcome: transfer test results. The primary outcomes were the standardized effect sizes of CI in transfer in motor learning. The outcomes evaluating the transfer of the learned motor skill were considered selectable. Taking into account the effect of *sleep-induced consolidation of trained skills* (Diekelmann and Born, 2010; Yang et al., 2014) current meta-analysis consisted of delayed-transfer results. Studies covering immediate-transfer testing were discussed in the systematic review. This approach is similar to Brady (2004) since he used only delayed outcomes, assuming that learning effects may be obscured in the more immediate measures.

Search methods and selection procedure

AW performed the search on the following databases: EBSCO ("contextual interference" in Title OR Abstract—no Keywords option),

Scopus ("contextual interference" in Title OR Abstract OR Keywords), ScienceDirect ("contextual interference" in Title OR Abstract OR Keywords), Web of Science ("contextual interference" in Topic), in September 2021 (2020 to 2021), and updated March 2022 (period 2021–2022) and November 2022. Relevant studies were scrutinized using the Google Scholar search engine ("contextual interference" in Title OR Abstract OR Keywords). SC searched the PsycINFO database ("contextual interference" in Title OR Abstract OR Keywords).

Studies in languages other than English and the "gray literature" (e.g., master and Ph.D. dissertations and theses, conference proceedings, non-reviewed articles, etc.) available online in the searched databases were excluded to facilitate the reliable risk-of-bias assessment. Exclusion of non-English literature does not cause systematic bias (Morrison et al., 2012) and the proper and reliable translation from other languages into English may be problematic (Jackson and Kuriyama, 2019). Moreover, Jackson and Kuriyama noticed that only 2% of the articles included in the systematic reviews were published in languages other than English (Jackson and Kuriyama, 2019). On the other hand, there was no reason to include gray literature, since the topic (CI) is not novel (Gunnell et al., 2020) and gray literature inclusion would cause unnecessary burden on the reviewers (Mahood et al., 2014). Some of the non-peer-reviewed documents have different structure, different length, some of them are not peer-reviewed at all, some only partially.

Due to a large number of retrieved studies, a method proposed by Dundar and Fleeman (2017) was applied, i.e., AW evaluated the titles, abstract, and keywords for inclusion criteria, and a random sample was cross-checked by the senior researcher (SC). Inadequate articles were excluded, and duplicates of identified studies were removed. Subsequently, the full text of each study was read by the two co-authors (AW and PS), who independently assessed the papers for final eligibility. In case of a disagreement, a senior researcher (SC) was consulted, and a consensus was reached.

Data collection and analysis

During the screening process, all relevant data were summarized by AW and PS in developed MS Excel data extraction forms. Each entry consisted of study specifications, such as the authors' names, the study title, the year of publishing, and the journal title, in case of multiple experiments in the same study—number of experiments. The following details were based on PICO criteria:

- *Population* (age, gender, number of participants, expertise level).
- *Intervention* (testing procedure, dependent variable, nature of research, practice schedule, type of motor task).
- *Objectives/Outcomes* (immediate transfer results and delayed transfer results: extracted means and standard deviations for all groups and all measures). Consistently with our meta-analysis on retention (2023?), the results of the first block only from the transfer testing procedures were considered for the extraction. We assumed that the following blocks might enhance further learning. If the standard error of the mean (SEM) was available, we converted it into standard deviation (SD). If quartiles were available, we used the Mean Variance calculator (Luo et al., 2018; Shi et al., 2020a,b) to convert these into SD. Furthermore, study quality indicators were included, covering the following sections: selection bias, study design, confounders, blinding, data collection methods, withdrawals and dropouts, and global rating, based on *Quality Assessment tool for Quantitative studies* (Thomas, 2003; Thomas et al., 2004).

Since included studies utilized different motor skills (tasks) and the transfer was measured with different units (meters, seconds, number of cycles etc.) and scores (percentages, numbers), we used standardized mean differences (SMDs) effect sizes, i.e., Hedges' (adjusted) g, very similar to Cohen's d, but it includes an adjustment for small sample bias. The I^2 statistic was used to evaluate the heterogeneity among the studies. The interpretation of I^2 is as follows: 30–60% represent moderate heterogeneity; 50–90%—substantial heterogeneity; and 75–100%—considerable heterogeneity (Higgins et al., 2021). Nevertheless, interpretation thresholds can be misleading (Deeks et al., 2019).

In line with the Cohen's recommendation of interpreting the magnitude of SMD in the social sciences (Cohen, 1988), we applied the following guidelines: small (SMD = 0.2); medium (SMD = 0.5); and large (SMD = 0.8).

We computed a 3-level mixed model which uses (restricted) maximum likelihood procedures (Cheung, 2014; Assink and Wibbelink, 2016). The advantage of that model is that it takes into account the potential dependence among the effect sizes, i.e., when there are multiple outcomes (effect sizes) from a single study. The model assumes that the random effects at different levels and the sampling error are independent. Three levels of the model refer to variance between effects sizes among participants (level 1), outcomes, i.e., effect sizes extracted from the same study (level 2; within-cluster variance), and studies (level 3; between-clusters variance) (Assink and Wibbelink, 2016). There is no need to know the correlations between outcomes extracted from one study for estimating the covariance matrix of the effect sizes since the second level in the model accounts for sampling covariation (Assink and Wibbelink, 2016).

Sensitivity analysis was performed using Cook's D distances. Outcomes further than 4/n (where n was the number of outcomes) were removed to assess how these outliers influence the pooled effect.

Meta-analyses were performed with RStudio (version 2023.06.0) and the following packages "metaphor," "dmetar," "tidyverse," "readxl," and "ggplot."

Assessment of risk of bias/quality assessment of included studies

We followed the guidelines of the Effective Public Health Practice Project (EPHPP) *Quality Assessment Tool for Quantitative Studies* (Thomas, 2003) while assessing the risk of bias in included studies. The checklist elements (sample selection, study design, identification of confounders, blinding, reliability and validity of data collection methods, withdrawals, and dropouts) could be rated strong, moderate, or weak. According to a standardized guide and dictionary, the comprehensive evaluation is determined by assessing six rating aspects. Studies with two or more weak ratings are considered weak, those with less than four strong ratings and one weak rating are considered moderate, and, subsequently, studies with no weak ratings and at least four strong ratings are regarded as strong (Thomas et al., 2004). AW and PS independently assessed the level of evidence and

methodological quality of the eligible studies. In case of discrepancy, the authors discussed until a consensus was reached. Any issues regarding the quality of the study was discussed with the senior researcher (SC).

Results

Results of the search

The primary search in the databases identified 2,161 potential records. After removing duplicates, the titles and abstracts of 1,287 articles were screened according to PICO criteria, including 8 records identified manually (see Supplementary Appendix 2 for more details). Nine hundred eighty-seven articles (987) were excluded due to study design issues, not relevant topics, and population. The detailed evaluation process is highlighted in the PRISMA Flow Diagram (Moher et al., 2009; Figure 1).

The remaining 300 studies were evaluated, and 258 were excluded (comprehensive reasons for exclusion are listed in Supplementary Appendix 3). In case of missing data, the authors were contacted via e-mail and/or the ResearchGate platform. Finally, 42 articles were included in the present systematic review. The quantitative analysis covered 34 studies. Transfer tests conducted up to 24 h after the acquisition were defined as *immediate transfer testing,* and consequently, testing procedures performed after 24 h were defined as a *delayed transfer*. Eight studies described immediate transfer testing; therefore, the meta-analysis did not include these results. The summary of all included studies is provided in Supplementary Table S1. The summary of studies characteristics is presented in Supplementary Table S2.

Reasons for exclusion of individual experiments or particular groups of participants

Occasionally, more than one experiment was presented in a single paper. There were cases where the authors did not report data on all of them, or, similarly, some studies did not report statistically non-significant data on specific variables. In such situations, we contacted authors; however, the authors did not provide the data in a few cases—the main reported reason was that their studies were performed a long time ago.

An article by Ste-Marie et al. (2010) consisted of three experiments where the authors examined the CI effect on handwriting skills in young participants. Unfortunately, it was not possible to obtain data from the first experiment. In the second experiment, data on the scores measure, and in the third experiment, data on the time variable were unavailable. In the paper by Porter and Magill (2010) covering two experiments, the results of the first one were available. The second experiment was excluded from the analysis due to group characteristics not compliant with PICO: group of ratio-feedback and segment-feedback. In the study by Chua et al. (2019) three experiments were conducted; however, the results of the first one were excluded from our review as these were describing constant practice group instead of blocked practice.

Some of the included studies covered more than two (random and blocked) groups of participants. In line with PICO criteria, in that situation, only the results of groups with blocked and random/interleaved schedules were regarded as appropriate for the analysis. Included primary studies consisting of more than two groups are listed below. In the study by Goodwin and Meeuwsen (1996), participants were randomly assigned to three groups: random, blocked/random, and blocked. Transfer results of blocked and random groups were included in the meta-analysis. Participants of the study by Porter and Beckerman (2016) were randomly allocated to three groups with random, increasing, or blocked schedules. The random and blocked group transfer data were considered applicable for the current analysis. In the study by Beik et al. (2021), participants were randomly assigned into six groups of blocked-similar, algorithm-similar, random-similar, random-dissimilar, blocked-dissimilar, and algorithm-dissimilar. Out of these groups, transfer results of four (blocked-similar, blocked-dissimilar, random-similar, random-dissimilar) were considered appropriate according to PICO. A similar situation occurred in the study by Beik and Fazeli (2021), where participants were randomly allocated to one of six groups of blocked-similar, blocked-dissimilar, learner-adapted-similar, random-similar, random-dissimilar and learner-adapted-dissimilar. Four groups were considered appropriate for analysis (random-similar, random-dissimilar, blocked-similar, blocked-dissimilar).

Results of quality assessment of included studies

The detailed methodological assessment of the included studies is presented in Supplementary Appendix 4. None of the included studies was assessed as strong. Only two articles (Ste-Marie et al., 2010; Johnson et al., 2022) presented moderate methodological quality according to the *Quality Assessment Tool for Quantitative studies* (Thomas, 2003). The primary studies failed mainly on the latter criteria: 26 studies scored weak in Selection Bias, more than 21 articles scored weak in the *Confounders* section, 30 received weak ratings in the *Withdrawals and dropouts* section. The applied assessment tool specification might explain such relatively strict evaluation: two weak ratings were enough to automatically determine a weak classification of a study in its global rating for all six determinants of the checklist.

According to Thomas et al. (2004), only articles rated as moderate or strong should be included in the meta-analysis. Nevertheless, excluding all articles with *weak* global ratings would make the current analysis relatively doubtful (with only two studies included). For this reason, we have decided to include 34 studies in the meta-analysis. The impact of this decision on heterogeneity was taken into account.

Findings

As aforementioned, only delayed transfer results were considered for the current meta-analysis, yielding 86 effect sizes. Outcomes of 34 studies were included, resulting in testing 1,421 participants. A wide range of variables was involved: time (absolute error time, decision time, variable time, response time, reaction time, completion time), the number of performed movements, distance (absolute error

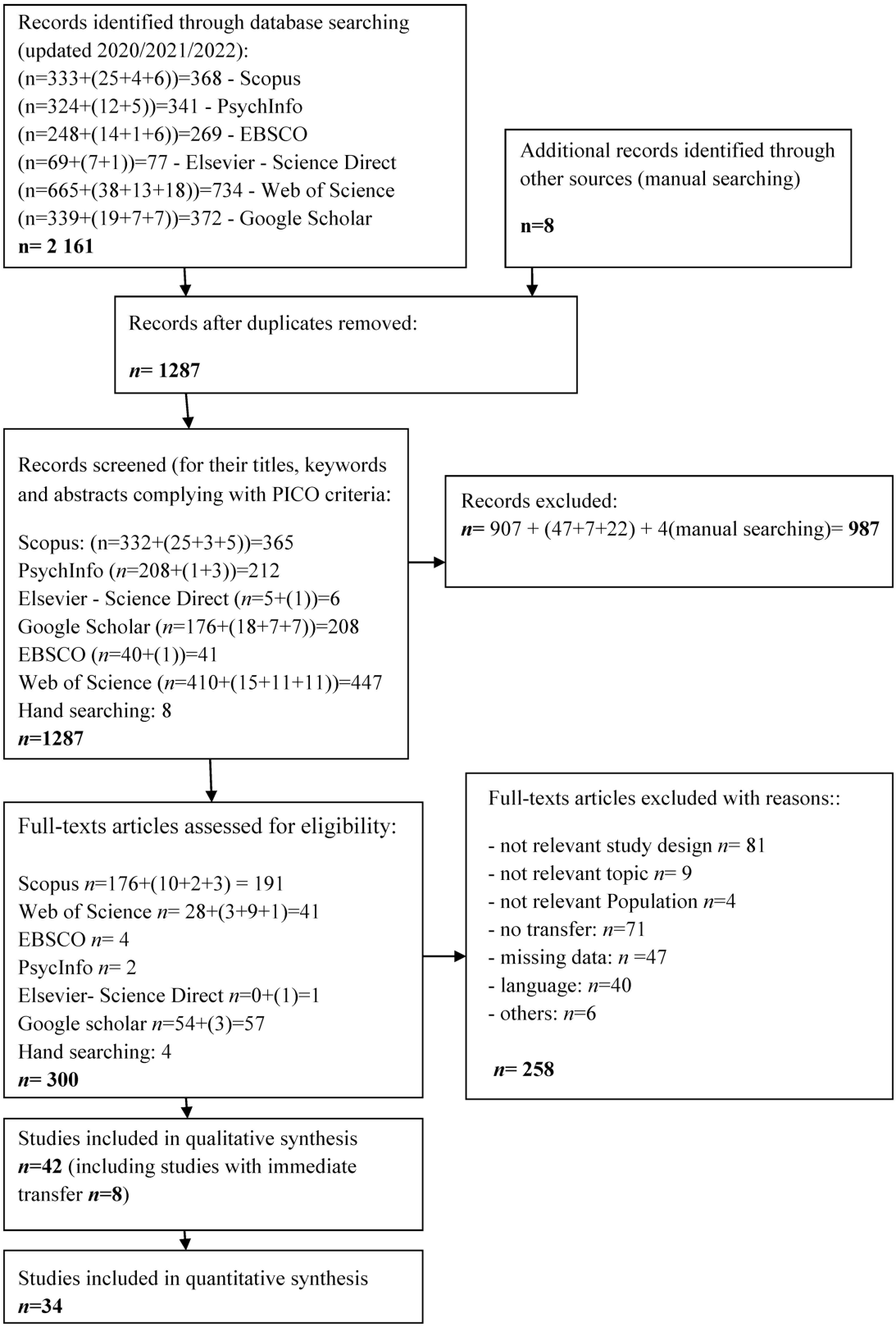


FIGURE 1
PRISMA flow diagram of the search process (Moher et al., 2009). Flowchart of the primary search (1966–2020), updated searches (2020 to 2021 and 2021 to 2023), and the inclusion and exclusion process.

distance, accuracy error distance, median pathway traveled), accuracy (proficiency percentage, accuracy scores). Evaluation of transfer was presented by the mean of various outcome measures' units: meters, seconds, percentages, or scores.

Motor skills utilized in primary studies varied in many ways. They were presented in different arrangements: discrete and continuous motor skills, open and closed motor skills, or fine and gross motor skills. Motor tasks were associated with volleyball (Bortoli et al., 1992; Meira and Tani, 2003; Fialho et al., 2006; Travlos, 2010; Pasand et al., 2016), golf (Goodwin and Meeuwsen, 1996; Porter and Magill, 2010; Chua et al., 2019), tennis (Broadbent et al., 2015), hockey (Cheong et al., 2016), throwing darts (Meira and Tani, 2001; Frömer et al., 2016), hopping (Parab et al., 2018), basketball (Porter et al., 2020), baseball (Hall et al., 1994), throwing (Vera and Montilla, 2003; Chua et al., 2019), learning of the Pawlata roll (Smith and Davies, 2008) and riffle shooting (Moretto et al., 2018). Non-sports skills included laparoscopic skills (Shewokis et al., 2017; Johnson et al., 2022) and handwriting (Ste-Marie et al., 2010), and Wii-Fit dynamic balance task (Jeon et al., 2020).

The other motor tasks applied in the primary studies covered: serial reaction time tasks (Lin et al., 2018), key pressing tasks (Del Rey et al., 1994; Shewokis, 1997; Shea et al., 2001; Meira et al., 2015; Beik et al., 2021), pursuit tracking tasks (Dunham et al., 1991; Porter and Beckerman, 2016), positioning tasks (Perez et al., 2005; Lage et al., 2006) and reversal or rapid movements on manipulandum (Green and Sherwood, 2000; Herzog et al., 2022).

Laboratory versus applied setting—comparison characteristics

Laboratory vs. applied meta-analytic comparison included 34 studies. Seventeen studies, covering 46 effect sizes in total, were describing experiments conducted in laboratory settings. There were 738 participants in laboratory studies, of which 121 were older adults, and 542 were adults. The age of participants in the aforementioned studies ranged from 10 ± 0.6 years (Perez et al., 2005) to 82 years (Jeon et al., 2020). It is worth mentioning that only 75 participants from the laboratory studies were less than 18 years old (Perez et al., 2005; Broadbent et al., 2015). Motor skills utilized in the laboratory setting were: Wii-Fit dynamic balance task (Jeon et al., 2020), rapid movements on manipulandum (Green and Sherwood, 2000; Herzog et al., 2022), pursuit tracking tasks (Dunham et al., 1991; Porter and Beckerman, 2016), key pressing tasks (Shewokis, 1997; Shea et al., 2001; Meira et al., 2015; Beik et al., 2021), serial reaction time task (Lin et al., 2018), positioning tasks (Perez et al., 2005; Lage et al., 2006). In the study of Broadbent (Broadbent et al., 2015), the acquisition of tennis skills was conducted in laboratory settings—similar to the study by Chua et al. (2019), where the acquisition and testing of throwing skills and golf were assessed in the laboratory environment. An article by Frömer et al. (2016) described virtual darts throwing in the laboratory environment.

Applied studies were performed in natural environments (during physical education classes or game-based). Seventeen articles described experiments conducted in an applied setting, covering 40 effect sizes. Six hundred eighty-three (683) participants were included in these studies, of which 393 were under 18 years old, and 290 were adults. An article by De Souza et al. (2015) was the only study describing the transfer of motor skills in applied settings in older adults (65–80 years old). The motor task implemented in the study consisted of throwing a boccia ball to three targets. However, this study was excluded from the meta-analytic analysis due to missing data. The age of participants in the aforementioned studies ranged from 5.5 years (Ste-Marie et al., 2010) to 35 years (Thomas et al., 2021).

The following motor skills were practiced and examined in the included applied studies: golf skills (Goodwin and Meeuwsen, 1996; Porter and Saemi, 2010), volleyball skills (Bortoli et al., 1992; Meira and Tani, 2003; Fialho et al., 2006; Travlos, 2010; Pasand et al., 2016), hockey (Cheong et al., 2016), baseball (Hall et al., 1994), throwing skills (Vera and Montilla, 2003), riffle shooting (Moretto et al., 2018). In the study by Moretto et al. (2018) acquisition and testing of riffle shooting were conducted in indoor laboratories; however, all adjustments, including the position target height, followed the *Olympic and International Shooting Sport Federation* standards; and for this reason results were included in the *applied setting* comparison. Pawlata roll (Smith and Davies, 2008) learning and testing procedures took place in the indoor pool. CI effect on handwriting skills in children was tested by Ste-Marie et al. (2010) in the school setting. Laparoscopic skills in the study by Shewokis et al. (2017) were performed by medical students and post-graduate residents using a virtual reality simulator (LapSim® VR simulator), mimicking the regular laparoscopic tasks. In the study by Johnson and colleagues (Johnson et al., 2022), laparoscopic skills were practiced and tested with the use of *Fundamentals of Laparoscopic Surgery* (FLS) box trainer (VTI Medical, Waltham, MA). The laparoscopic tasks were acquired and tested in both articles according to the FLS program.

The CI effect in youth vs. adults vs. elderly adults—comparison characteristics

The age of participants in the studies included in the present review ranged from 5.5 years (Ste-Marie et al., 2010) to 82 years (Jeon et al., 2020). The age subgroup analyses were classified as follows: young (up to 18 years old), adults (18 years old to 59 years old), and older adults (60 years and older). The eight articles reporting immediate transfer covered the results of 80 children (Del Rey et al., 1983a), 10 adolescents (Fialho et al., 2006), and 318 adults (Del Rey et al., 1983b; Smith and Rudisill, 1993; Del Rey et al., 1994; Meira and Tani, 2001; Lage et al., 2006; Sherwood and Duffel, 2010). In the delayed transfer studies, there were 468 young participants, 812 adults, and 121 older adults. The results of 20 participants aged 17–21 described in the article by Hall and colleagues (Hall et al., 1994) were not classified in any of the age subgroups analysis. According to specific age group criteria applied in the present study: young (up to 18 years old), adults (18 years old to 59 years old), and older adults (60 years and older), the participants from the aforementioned study shall be included in both groups young and adults simultaneously. Therefore, we refrained from including their results.

The CI effect in novice vs. experienced participants—comparison characteristics

In his meta-analytic study on CI, Brady (2004), among the other subgroup analyses, compared the CI effect between novice and skilled participants. While classifying their skill levels, Brady was guided by how the authors labeled the participants' experience. We utilized the same

rule in our review. In the immediate transfer articles, 90 participants were described as skilled (Del Rey et al., 1983a; Fialho et al., 2006). Out of the studies on delayed transfer, we classified 62 participants as experienced (Hall et al., 1994; Broadbent et al., 2015; Porter et al., 2020). Participants of these studies were characterized as follows: "*intermediate-level junior tennis players*" (Broadbent et al., 2015, p. 1245), "*baseball players from a junior college baseball team (…) with an average of 9.5 years of experience in competitive baseball*" (Hall et al., 1994, p. 837–838), participants "*had less than two years' basketball playing experience (1.1 ± 1.3 years) and no representative level basketball playing experience*" (Porter et al., 2020, p. 7).

The primary studies in the current review referred to different inclusion standards for a *skilled* group. Classifying skill (experience) levels correctly could lead our review in a different direction, still not warranting there will be no confusion or doubts. Therefore, we decided not to conduct the subgroup analysis of *skilled* versus *novice*.

Meta-analysis: results

The analysis of the CI effect on delayed transfer (Figure 2) covered 34 studies, yielding 86 effect sizes and resulting in testing 1,421 participants.

The pooled effect size based on the three-level meta-analytic model was medium SMD = 0.55 (95% CI: 0.25, 0.86; $p < 0.001$). The estimated variance components (tau squared) were $\tau_3^2 = 0.488$ and $\tau_2^2 = 0.403$ for the level 3 and level 2 components, respectively. This means that $I^2_3 = 47\%$ of the total variation can be attributed to between-cluster, and $I^2_2 = 39\%$ to within-cluster heterogeneity. Total $I^2 = 86\%$. We found that the three-level model provided a significantly better fit compared to a two-level model with level 3 heterogeneity constrained to zero ($\chi^2 = 9.99$; $p < 0.001$): for three level model (df = 3) AIC = 246 while for the 2-level model AIC = 254. Test of moderators: $F(1, 84) = 1.34$, $p = 0.25$ suggesting the subgroup analyses are not necessary, though, we decided to perform them analogically to Brady (2004).

Sensitivity analysis revealed that there were 5 outcomes which were further than 4/n threshold (Figure 2). These were outcomes from Beik et al. (2021) and Beik and Fazeli (2021)—one outcome, Green and Sherwood (2000) and Parab et al. (2018). After having removed the outliers (Figure 3), the pooled effect size was small SMD = 0.40 (95% CI: 0.18, 0.62; $p < 0.001$). The estimated variance components (tau squared) were $\tau^2_3 = 0.19$ and $\tau^2_2 = 0.23$; $I^2_3 = 34\%$ and $I^2_2 = 41\%$; respectively. The outliers had a substantial effect on pooled effect size, i.e., SMD decreased from 0.55 (with outliers included) to 0.40 (without outliers).

Laboratory vs. field-based (applied) studies

The primary studies were divided into those carried out in a laboratory setting ($n = 17$), including 738 participants (46 effect sizes), and the remaining ($n = 17$) conducted in an applied setting (40 effect sizes), including 683 participants.

A subgroup analysis of the CI effect in laboratory studies was performed (Figure 4). The pooled effect size based on the three-level meta-analytic model was medium SMD = 0.75 (95% CI: 0.26, 1.25; $p = 0.004$). The estimated variance components (tau squared) were $\tau_3^2 = 0.68$ and $\tau_2^2 = 0.52$ for the level 3 and level 2 components, respectively. Heterogeneity was high, $I^2_3 = 50\%$ and $I^2_2 = 39\%$; total $I^2 = 88.96\%$.

Sensitivity analysis revealed that after removing two outcomes, i.e., Green and Sherwood (2000) and Lin et al. (2018), the pooled effect size dropped SMD = 0.62 (95% CI: 0.24, 1.01; $p = 0.002$).

Analogously, a subgroup analysis of the CI effect in applied studies was conducted (Figure 5). The pooled effect size based on the three-level meta-analytic model was small SMD = 0.37 (95% CI: −0.02, 0.69; $p = 0.06$). The estimated variance components (tau squared) were $\tau_3^2 = 0.27$ and $\tau_2^2 = 0.31$ for the level 3 and level 2 components, respectively. Heterogeneity was high, $I^2_3 = 37\%$ and $I^2_2 = 44\%$; total $I^2 = 81.35\%$.

Sensitivity analysis revealed that after removing two outcomes, i.e., Travlos (2010) and Pasand et al. (2016), the pooled effect size decreased to negligible SMD = 0.11 (95% CI: −0.13, 0.34; $p = 0.36$).

The CI effect in young vs. adults vs. elderly adults

Thirty-three articles were included in a meta-analytic comparison of the CI effect in three age groups (Figure 6), resulting in the testing of 468 young participants, 812 adults, and 121 older adults. As aforementioned, the results of 20 participants aged 17–21 from the study by Hall et al. (1994) were not included in the current subgroup analysis. This analysis yielded 2,632 measurements in total and elicited: 21 effect sizes for young participants, 55 effect sizes for adults, and eight effect sizes for the group of older adults.

Firstly, we performed an analysis for the subgroups of young participants. The pooled effect size based on the three-level meta-analytic model was negligible SMD = 0.12 (95% CI: −0.28, 0.53; $p = 0.54$). The estimated variance components (tau squared) were $\tau_3^2 = 0.10$ and $\tau_2^2 = 0.31$ for the level 3 and level 2 components, respectively. Heterogeneity was high, $I^2_3 = 18\%$ and $I^2_2 = 60\%$; total $I^2 = 78.42\%$.

Sensitivity analysis revealed that after removing one outcome, i.e., Travlos (2010), the pooled effect size decreased to SMD = 0.02 (95% CI: −0.36, 0.39; $p = 0.36$).

Secondly, we analyzed the adult's subgroup (Figure 7). The pooled effect size based on the three-level meta-analytic model was medium SMD = 0.54 (95% CI: 0.16, 0.92; $p = 0.54$). The estimated variance components (tau squared) were $\tau_3^2 = 0.42$ and $\tau_2^2 = 0.53$ for the level 3 and level 2 components, respectively. Heterogeneity was high, $I^2_3 = 39\%$ and $I^2_2 = 48\%$; total $I^2 = 86.82\%$.

Sensitivity analysis revealed that after removing five outcomes, i.e., Green and Sherwood (2000), Shea et al. (2001), Travlos (2010), Pasand et al. (2016), and Lin et al. (2018), the pooled effect size decreased to medium SMD = 0.38 (95% CI: 0.13, 0.62; $p = 0.003$).

Thirdly, an analysis for older adults was performed (Figure 8). The pooled effect size based on the three-level meta-analytic model was large SMD = 1.28 (95% CI: −0.34, 2.90; $p = 0.10$). The estimated variance components (tau squared) were $\tau_3^2 = 1.24$ and $\tau_2^2 = 0.15$ for the level 3 and level 2 components, respectively. Heterogeneity was high, $I^2_3 = 77\%$ and $I^2_2 = 10\%$; total $I^2 = 87.05\%$.

There were no outcomes further than 4/n Cook's D distances.

Risk of publication bias assessment

The risk of publication bias was assessed using a funnel plot (Figure 9). Given that substantial heterogeneity was present in each of the analyses we performed, we decided not to apply other statistical methods, i.e., Egger's regression test or rank-correlation test.

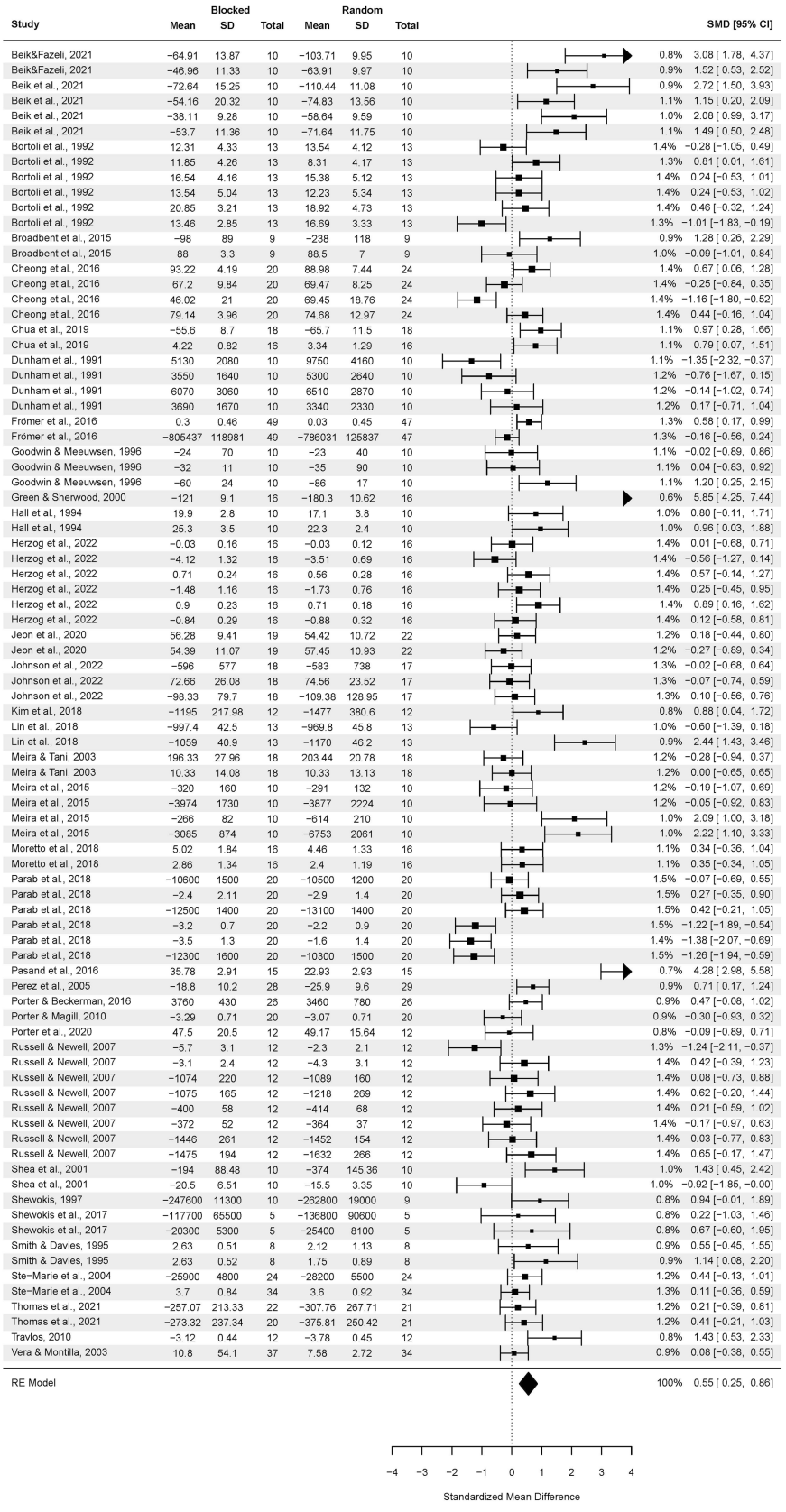


FIGURE 2
Analysis of transfer test results of random practice vs. blocked practice. The forest plot presents the results obtained by participants aged 5.5–82, including various motor tasks and different outcome measures.

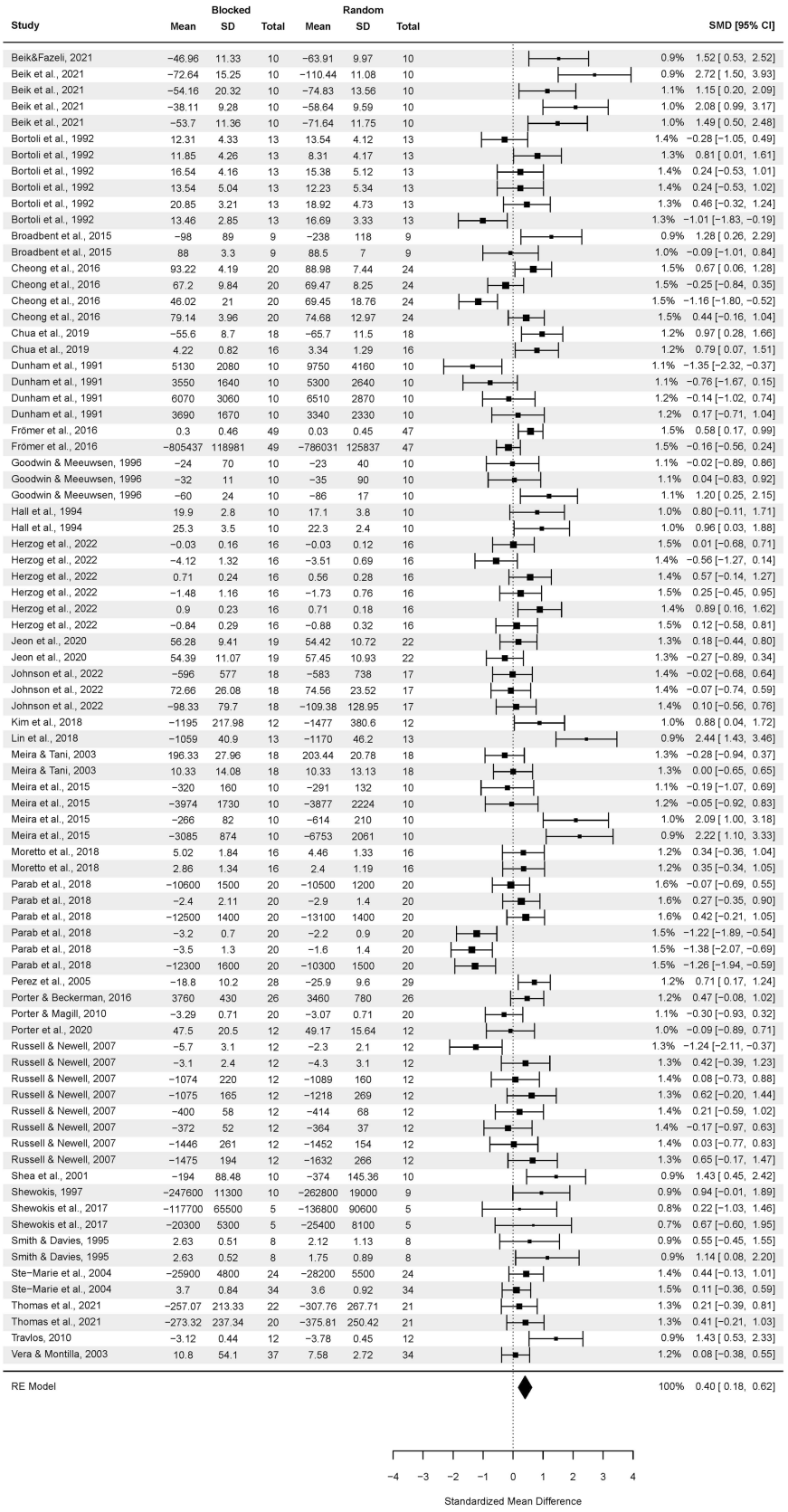


FIGURE 3
Analysis of transfer test results of random practice vs. blocked practice with no outliers (further than 4/n Cook D distances).

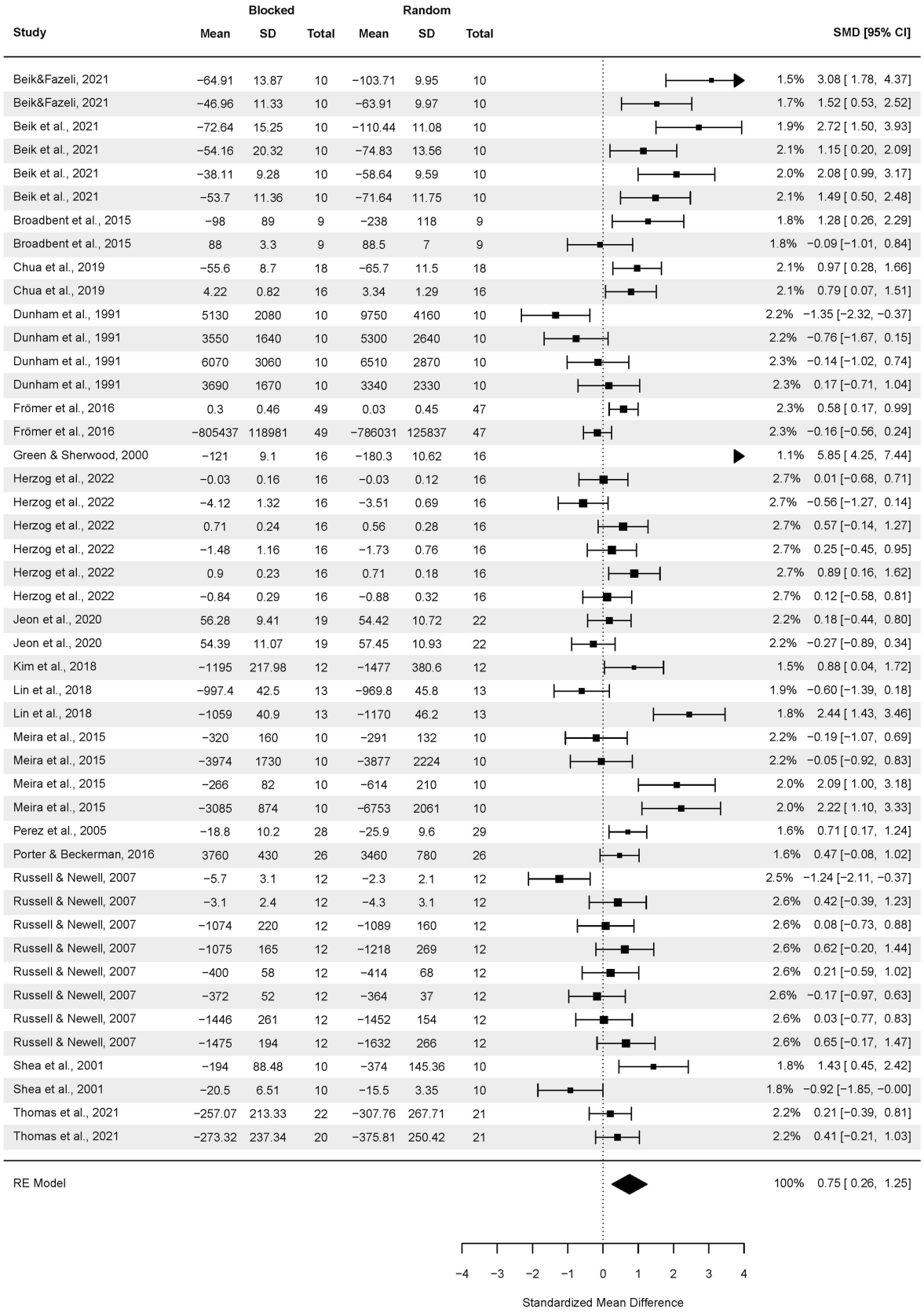


FIGURE 4
Analysis of transfer test results in a random and blocked schedule in a laboratory setting. The forest plot presents the transfer test results obtained by participants practicing in a laboratory setting, including various motor tasks and different outcome measures.

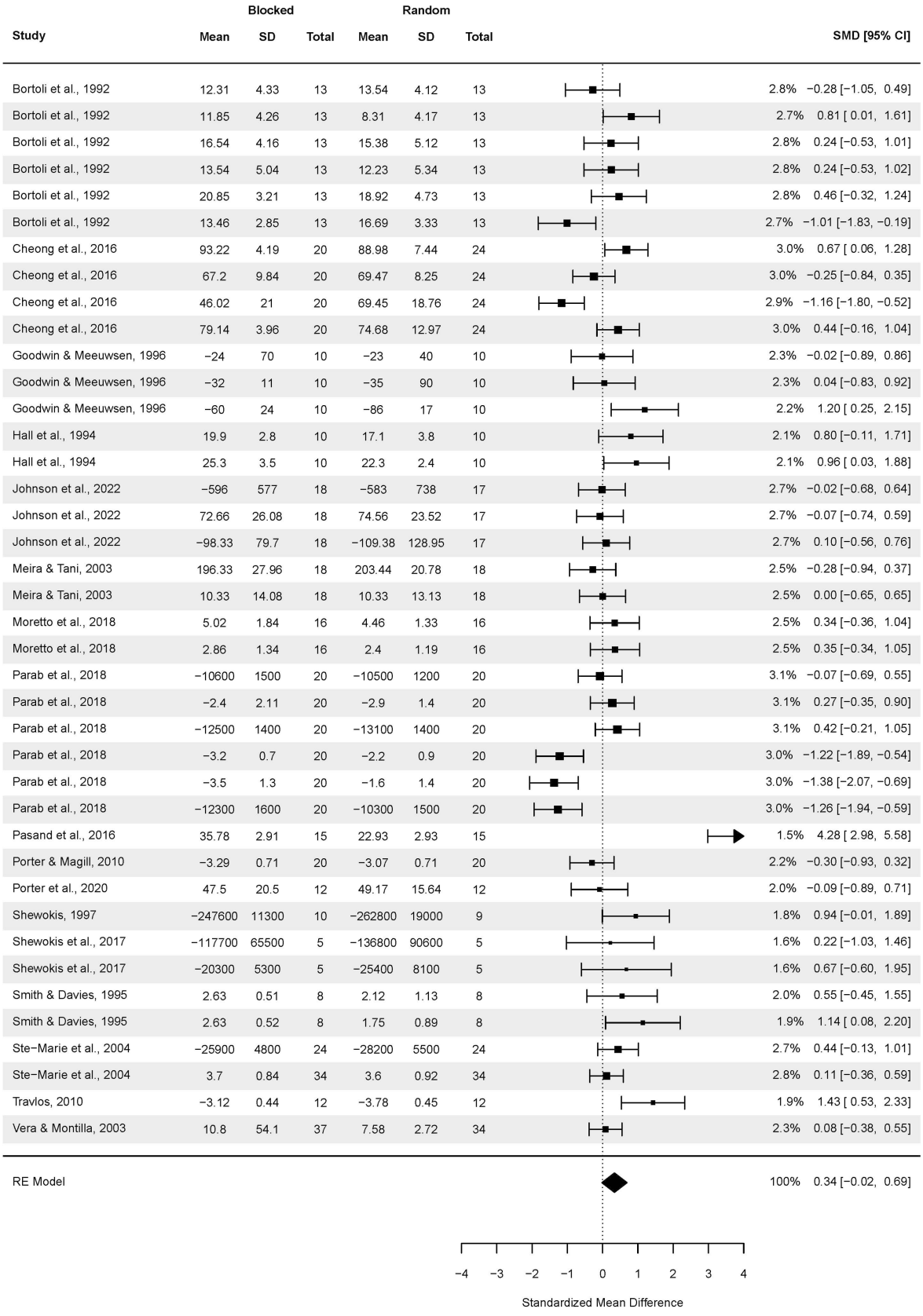


FIGURE 5
Analysis of random and blocked schedule transfer test results in an applied setting. The forest plot presents the transfer test results in an applied setting, including various motor tasks and different outcome measures.

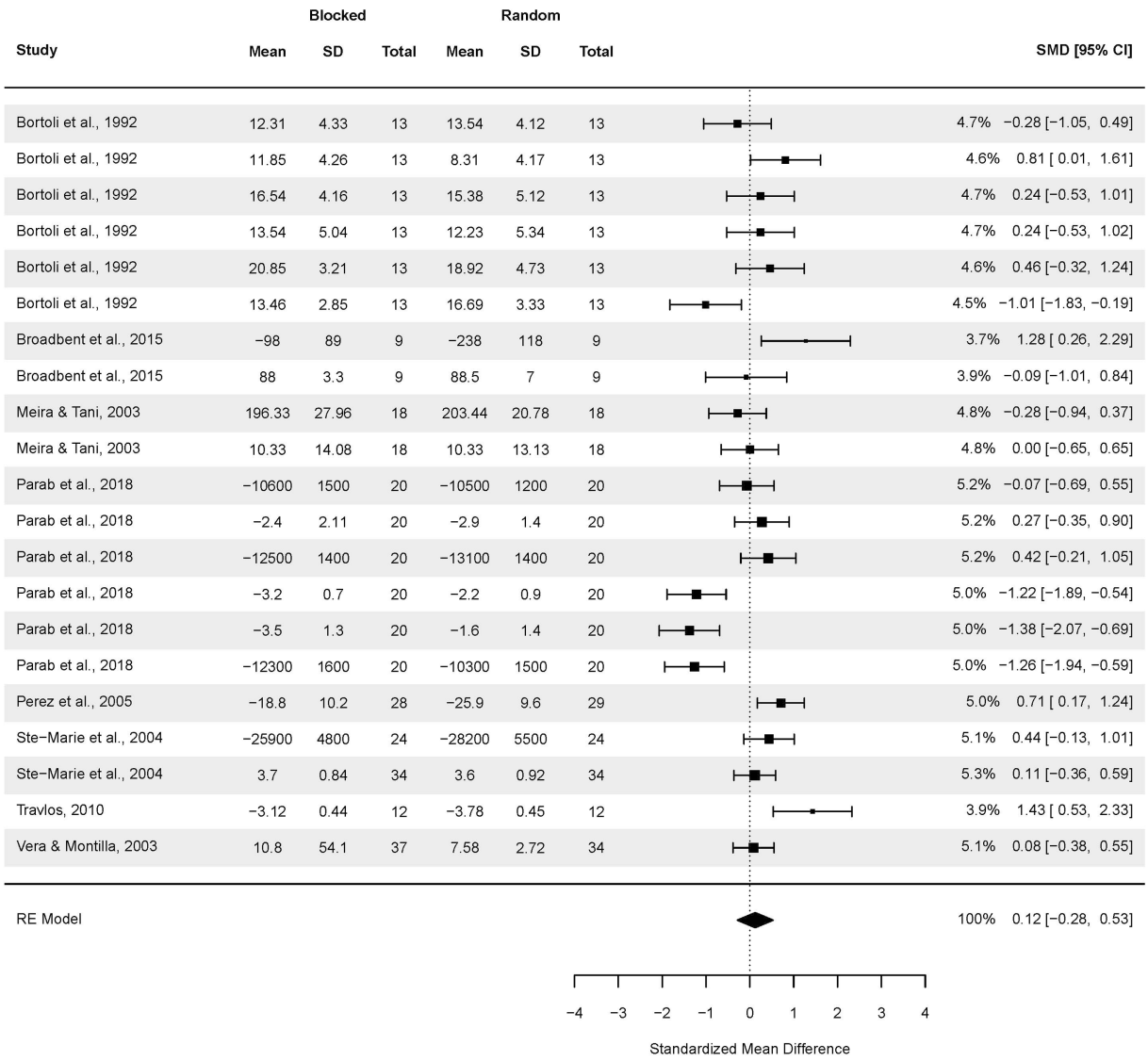


FIGURE 6
Analysis of young participants' transfer test results: random vs. blocked practice. The forest plot presents the transfer test results of participants aged 5.5–18, including various motor tasks and different outcome measures.

Discussion

The study's primary objective was to determine the overall effect size of CI on transfer in motor learning. We found that the statistically significant overall CI effect on transfer was medium (SMD = 0.55) in favor of the random practice.

Our secondary objectives were to estimate the CI effect on transfer in laboratory versus non-laboratory studies and the CI effect in different age groups. Similarly, to the overall effect, the random practice was favored in the laboratory and applied settings. However, in laboratory studies, the medium effect size was statistically significant (SMD = 0.75), whereas, in applied studies, the effect size was small and statistically non-significant (SMD = 0.34). Significant and larger effect sizes in laboratory settings may be due to well-controlled environmental variables and simpler tasks utilized in laboratories (Jeon et al., 2020). Complex tasks used in applied settings may be too challenging for information processing (Hebert et al., 1996) and deleterious for learning as a result (Wulf and Shea, 2002). However, there may be another explanation; as Al-Mustafa stated, CI is a laboratory artifact (Al-Mustafa, 1989; Brady, 2004), i.e., CI effect is conspicuous in labs but not in real life.

Age group analysis turned out to be significant only in adults and older adults. In both age categories, random practice was favored. In adults, the effect was medium (SMD = 0.54), whereas in older adults was large (SMD = 1.28). The results in the adult group align with Brady's (Brady, 2004), who reported small effect sizes in both laboratory and applied settings. However, Brady did not recognize the older adult group; therefore, comparing the results with any previous ones is difficult. On the other hand, nonsignificant effect size in young participants was negligible (SMD = 0.12).

Comparison with Brady's and Ammar's et al. meta-analysis

Only seven studies originally included in Brady's meta-analysis, yielding 17 effect sizes, were included in our analysis.

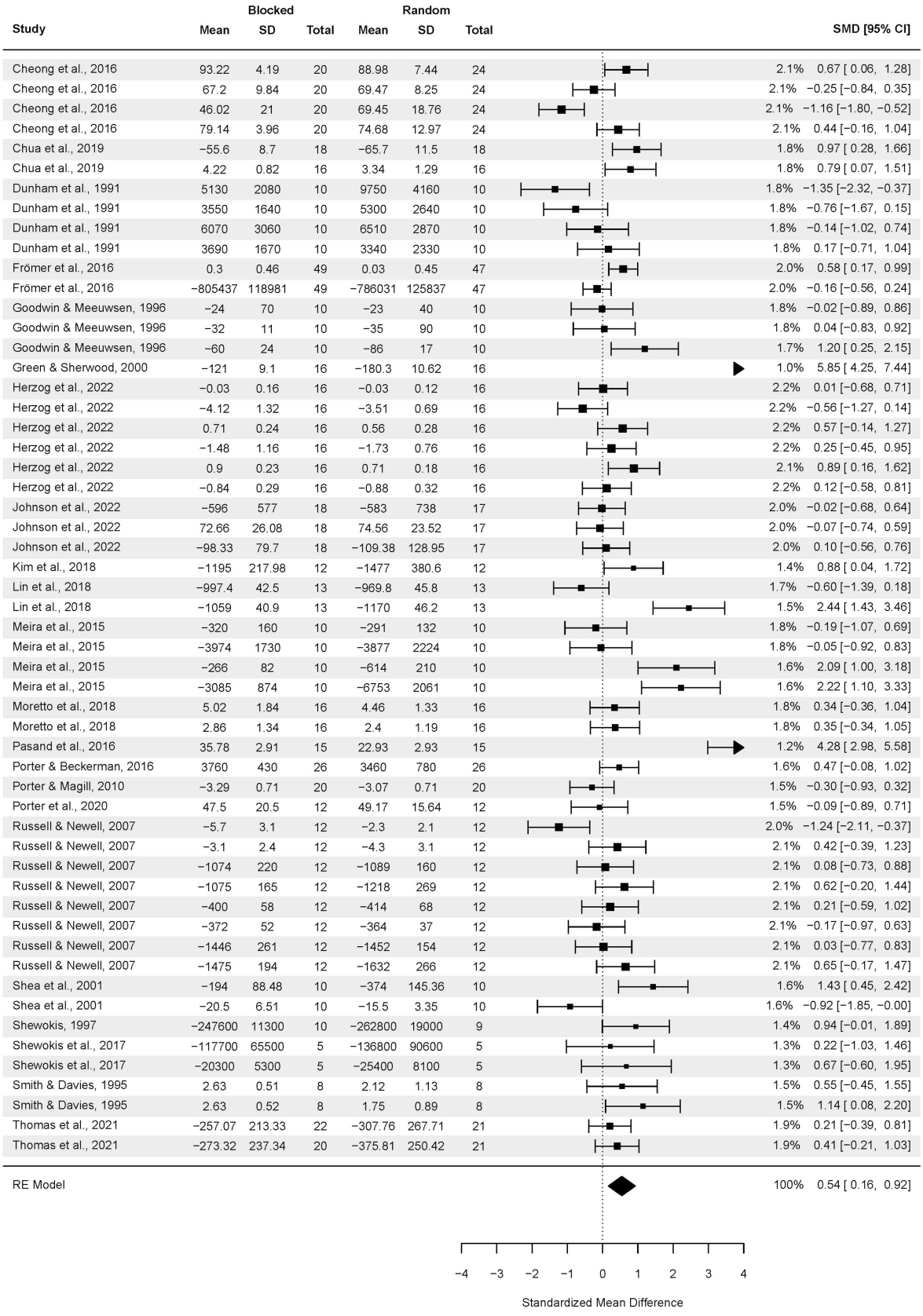


FIGURE 7
Analysis of adult participants' transfer test results: random vs. blocked practice. The forest plot presents the transfer test results obtained by participants aged 18–59, including various motor tasks and different outcome measures.

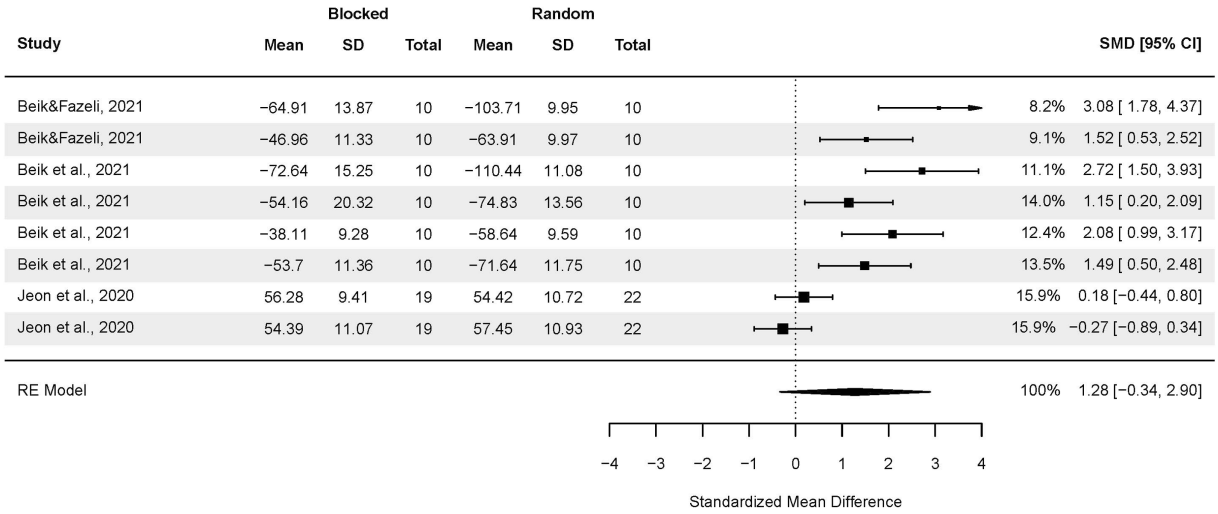


FIGURE 8
Analysis of older adults' transfer tests results: random practice vs. blocked practice. The forest plot presents the transfer test results obtained by participants aged 60–82, including a variety of motor tasks and different outcome measures.

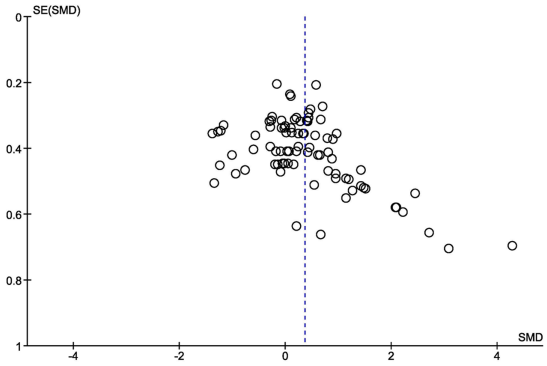


FIGURE 9
Risk of bias assessment—funnel plot.

Unfortunately, data from 23 primary studies included in his meta-analysis were unavailable. On the other hand, 27 primary studies included in our meta-analysis (yielding 69 effect sizes) were not included in Brady's.

The overall results of our review partially corresponded with those reported in the meta-analysis by Brady (2004). In line with the constantly advancing methodology of conducting meta-analyses, the inclusion criteria implemented in this review were more thoroughly detailed than those presented in Brady's. Consequently, 13 following studies included in Brady's meta-analysis (Brady, 2004) were considered irrelevant in the present review and, therefore, excluded. The primary studies by Wulf and Lee (1993), Sekiya et al. (1994, 1996), Landin and Hebert (1997), and Sekiya and Magill (2000) described serial practice order instead of random schedule.

In the studies by Wrisberg and Liu (1991), Hebert et al. (1996), Smith (2002), and Smith et al. (2003) alternating practice instead of a random schedule was presented. In the article by Hall and Magill (1995), an experiment described by Lee et al. (1992), and a study by Shea and Titzer (1993), multiple task learning was implemented. In the article by Bortoli et al. (2001), included in Brady's meta-analytic study, constant and variable practice schedules were compared. Additionally, 15 studies did not include transfer tests. Three other studies described immediate transfer; therefore, our meta-analysis did not include the results.

Our results are different from those reported by Ammar et al. (2023). We found that the pooled effect size was medium (SMD = 0.55) and statistically significant, while Ammar et al. reported small (SMD = 0.243) and non-significant. In both studies, random practice was favored. Probably the differences between these studies may be attributed to the search strategies, number of studies and effects sizes included in both meta-analysis. Ammar et al. omitted EBSCO database (including APA PsycArticles, APA PsychInfo, SPORTDiscus with Full Text, Medline, and Academic Search Complete), specifying their focus differently (sport-specific). They finally included 16 studies and 38 ES referring to sport settings whereas in our meta-analysis 34 studies and 86 ES were included in general analysis and 17 studies and 40 ES in applied studies. Similarly, the differences in subgroups analysis can be explained in methods applied.

Low quality and bias problem

The studies included in our analysis were of poor quality in general. None of the included studies was assessed as strong. Quality of two articles were assessed moderate. Hence, one could re-state our question if the studies about CI effect are biased? The question is justified given 26 studies scored weak on the *Selection Bias* criteria. One of the possible explanations of the week scores, in general, could be the tool we used, i.e., *Quality Assessment Tool for Quantitative Studies* (Thomas et al., 2004), which is rather strict. However, another explanation could be that the researchers' bias toward specific results in laboratory setting affected the final effect size favoring random practice.

One of the possibilities to decrease the effect of low-quality studies the meta-analysis result would be to exclude all studies rated as *weak*. This is what Thomas and colleagues postulated (Thomas et al., 2004). However, it would leave our analysis with only two papers! Therefore, we decided to include all the studies, though it could have impacted the heterogeneity statistics, increasing the I^2 value.

Heterogeneity problem

In all our analyses, the heterogeneity was substantial (with $I^2 > 70\%$). There may be a few explanations for why the heterogeneity was so high. Firstly, we included many studies and outcomes: more studies and outcomes, the higher the I^2 value (Rücker et al., 2008). One could decrease the I^2 value by limiting the number of studies included in the analysis and including only those with fewer participants (Schroll et al., 2011). However, this would question the validity of the presented review because a low I^2 value is not necessarily linked with a lower probability of heterogeneity but may be linked to the lower sensibility of detecting it (Schroll et al., 2011). Alba et al. (2016) noted "*I^2 can also mislead in large studies with precise results in which a low degree of inconsistency* (i.e., *studies report similar point estimates) can nevertheless result in high I^2*" (p. 134). They added that we are not able to do much about it. Moreover, there is little advice for the researchers on how to do it (Schroll et al., 2011).

Secondly, we included studies of low quality (see Low quality and bias problem section). Thirdly, the source of high heterogeneity may be linked with the differences in populations, such as age and origin, followed by a variety of included motor tasks and outcome measures or different methodologies used, e.g., experiment duration.

Lastly, we used I^2-test to assess the heterogeneity level. Unlike the Q-test (used by Brady in 2004), I^2 index not only informs about the presence or absence of heterogeneity but also quantifies its magnitude (Huedo-Medina et al., 2006).

Limitations

Limitations of our analysis have to be acknowledged. Firstly, 34 included studies yielded 86 effect sizes. As a result, some of the studies contributed multiple effect sizes. We treated them as independent, similarly to Toth et al. (2020). Thus, the combined significance values have to be interpreted with caution since they may be inflated of combined probability level.

Secondly, we tried to update Brady's meta-analysis (Brady, 2004), nevertheless, we failed at obtaining all results (outcomes) Brady included. These not-included results could affect the overall effect of our analysis.

Thirdly, we advanced our objectives based on Brady's. One could perform more specific analyses (more specific PICOs) that could lead to different results.

Recommendation for future research

Given that studies on CI effect on retention and transfer, were mostly of poor quality, a strong emphasis has to be put on the methodological issues.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

SC: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. AW: Data curation, Formal analysis, Investigation, Resources, Validation, Writing – original draft, Writing – review & editing, Methodology. PS: Data curation, Investigation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1377122/full#supplementary-material

All appendices are available at: https://osf.io/tqchf/?view_only=663162ef579347509b632b971b503eba

SUPPLEMENTARY TABLE S1
Summary of the included studies.

SUPPLEMENTARY TABLE S2
Characteristics of the tasks, participants, tests, and outcomes of the included studies.

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Effect of fatigue on intermuscular EMG-EMG coupling during bench press exercise at 60% 1RM workload in males

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Objective: To explore the neuromuscular control mechanism and quantifying the fatigue response during bench press exercise is important references to prescribe an appropriate exercise program. However, current literature struggles to provide a concrete conclusion on the changes of intermuscular EMG-EMG coupling between synergistic and antagonist muscles during the exercise. Thus, the current study was designed to reveal fatigue-related changes of intermuscular EMG-EMG coupling during bench press exercise.

Methods: Thirty-one healthy male participants performed a bench press exercise on the Smith machine at 60% One Repetition Maximum (1RM) workload to exhaustion, while surface electromyographic signals (sEMG) were collected from triceps brachii (TB), biceps brachii (BB), anterior deltoid (AD), posterior deltoid (PD), and pectoralis major (PM). Surface EMG signals were divided into the first half and second half of the bench press exercise. Phase synchronization index (PSI) was calculated between sEMG of synergistic muscle pairs AD-TB, AD-PM and antagonist muscle pairs BB-TB, AD-PD.

Results: EMG power of TB, AD, PD, PM muscles in alpha (8–12 Hz) frequency band and EMG power of each muscle in beta (15–35 Hz), and gamma (35–60 Hz) frequency bands were all increased during the second half of contraction compared with the first half of contraction. PSI of gamma frequency band was significantly decreased in BB-TB muscle pair while EMG-EMG coupling of AD-TB in gamma frequency band was significantly increased during the second half of contraction compared to the first half of contraction.

Conclusions: The results indicated a decrease of interconnection between synchronized cortical neurons and the motoneuron pool of BB and TB, and an increase of interconnection between AD-TB muscles during fatiguing bench press exercise at 60% 1RM workload. The changes of intermuscular coupling may be related to the supraspinal modulations to compensate for the decrease of muscle force as well as a result of unbalanced changes of agonist and antagonist muscle contractility.

KEYWORDS

bench press, muscle fatigue, EMG, intermuscular coupling, phase synchronization analysis

1 Introduction

Bench press is a classic type of exercise which is commonly accompanied with measuring or training upper-body strength (Schick et al., 2010; Golas et al., 2017). During exercise and training, bench press are often carried out for a number of sets at submaximal loads of a certain percentage of 1-RM to exhaustion, which may induce severe muscle fatigue of upper extremity (van den Tillaar and Saeterbakken, 2013; Tsoukos et al., 2021). As a commonly occurred phenomenon during training, muscle fatigue has been suggested to be a necessary stimulus for training gains while excessive local muscle fatigue may also lead to potential musculoskeletal disorder and injury risks (Schott et al., 1995; Delvaux et al., 2017). To explore the neuromuscular control mechanism and quantifying the fatigue response during bench press exercise is important references to prescribe an appropriate exercise program (Byrne et al., 2004; Carroll et al., 2017; Wang et al., 2021).

Muscle fatigue is an exercise-induced reduction in the muscle's maximal capacity to generate force or power output (Vøllestad, 1997). It represents a complex phenomenon encompassing both peripheral and central mechanisms (Danna-Dos et al., 2010). Muscle fatigue may lead to an increase in muscle force fluctuations, alternating levels of single muscle activity as well as changes in the muscle coordination patterns as a result of descending drive adjustment. Electroencephalographic (EEG)—electromyography (EMG) synchronization analysis is an effective approach to explore the central modulation information of co-contracted muscles (Boonstra and Breakspear, 2012; Farina et al., 2014). In previous researches, the synchronization of co-contracted muscles oscillations has been mainly evaluated in frequency (coherence analysis) and phase (phase synchronization analysis) domain (van Asseldonk et al., 2014; Pizzamiglio et al., 2017; Wang et al., 2015). In particular, EEG and EMG signals have been revealed to be phase locked (Mima et al., 2000; Ushiyama et al., 2011), which demonstrates that phase synchronization activities of EMG signals between co-contracted muscles may reflect cortical related modulation information (Wang et al., 2015).

In exercise-induced muscle fatigue related intermuscular EMG-EMG coupling changes, an enhancement of EMG-EMG coupling between synergistic and antagonist muscles has been observed during sustained isometric contractions and dynamic motor tasks for both healthy participants as well as patients, which may indicate an increased intermuscular common neural inputs as a result of muscle fatigue (Kattla and Lowery, 2010; Charissou et al., 2016, 2017). However, fatigue-related decrease of intermuscular coupling has also been found in previous researches (Dos Santos et al., 2020). Up to now, current literature struggles to provide a concrete conclusion on the changes of intermuscular EMG-EMG coupling between synergistic and antagonist muscles during bench press exercise.

The aim of this study was to investigate fatigue-related changes of intermuscular EMG-EMG coupling of both synergistic and antagonistic muscles during bench press exercise. Surface EMG signals of agonist muscles triceps brachii (TB), anterior deltoid (AD), pectoralis major (PM) and antagonist muscles biceps brachii (BB), posterior deltoid (PD) were recorded during bench press of 60% 1RM workload till exhaustion. EMG-EMG coupling of antagonistic muscles were compared between the first half (stage 1 with minimal fatigue) and second half (stage 2 with severe fatigue) of the exercise.

2 Materials and methods

2.1 Subjects

Thirty-one young man volunteers (age 19.39 ± 2.01 years, height 174.86 ± 4.86 cm and weight 63.80 ± 7.44 kg) participated in this study. The subjects were all healthy with no known neuromuscular disorders or musculoskeletal injuries of the neuromuscular system. Participants were excluded from the study if they had musculoskeletal pain, injury, illness that might reduce maximal effort or experienced pain during testing. The participants were instructed to refrain from any additional resistance training targeting the upper body during the 72 h before testing to avoid fatigue. Each participant was informed of the test protocol and was volunteered to participate the experiment. The experiment was approved by the Ethics Committee of Tongji University (No. 2020TJDX006).

2.2 Data recording

2.2.1 Experimental setup

The experiment was conducted in laboratory with the indoor temperature of about 24°C. The formal experiment comprised of two sessions. During the first testing session, subjects performed a One Repetition Maximum (1RM) bench press test to determine the workload of 1RM for each participant. The second testing session occurred at least 7 days after the 1RM bench press test. During the second session, participants performed a fatiguing bench press exercise at 60% 1RM workload on a Smith Machine (Matrix Fitness, Johnson Health Tech, Cottage Grove, MN, USA).

During the fatiguing bench press test, participants started the exercise lying in the supine position on the bench and grasped the barbell at a comfortable width. The elbows performed flexion comfortably within the coronal, and the wrists were kept in a neutral position. Upon verbal command, subjects concentrically pushed the barbell until executing full elbow Extension and then immediately eccentrically lowered the barbell until the chest was touched, ~3 cm superior to the xiphoid process (Orange et al., 2019). To maximize external validity, lifting cadence was determined by the tempo that each subject felt was most natural to him (Schick et al., 2010), with a 2-s rest between the two successive repetitions. During the whole exercise, the participant's head and back (thoracic area) were kept in contact with the bench to prevent any inertial motion. The participants were encouraged to perform the bench press at a certain pace of 4.096 s for one bench press trial for as many repetitions as possible till they cannot complete the motor task at the certain rhythm.

During the fatiguing bench press exercise, triaxial acceleration data of barbell were sampled at 100 Hz using a triaxial accelerometric sensor (Kinv TS) fixed to the right edge of the barbell. To ensure accurate results, the X-, Y-, and Z-axes were consistently perpendicular to the sagittal, coronal, and horizontal

planes, respectively. Besides, surface EMG signals of right triceps brachii (TB), biceps brachii (BB), anterior deltoid (AD), posterior deltoid (PD), and pectoralis major (PM) muscles were recorded. The example diagram of fatiguing bench press exercise has been showed as Figure 1.

2.2.2 1RM test

Subjects performed a 1RM bench press test with a standard barbell and typical load according to the National Strength and Conditioning Association's guidelines for maximal strength testing. A self-selected load bench press warm-up was first performed, the workload of which allowed each subject to finish 6–10 repetitions (~50% predicted 1 RM) of the exercise. Then, after 1–5 min of rest, subjects then select a weight based on the previous effort which allows them to perform three repetitions (~80% predicted 1 RM). Subjects then progressively increased resistance by 5–10% of the previous attempt. The 1RM was determined within five attempts, and a 3–5-min rest period was provided between each attempt.

2.2.3 EMG measurement

Surface EMG was recorded from the long head of right TB, BB, AD, PD, and PM using a wireless EMG system (BTS FREEEMG 1000, BTS, Garbagnate Milanese MI, Italy) with a 2-cm inter-electrode distance. Specifically, the electrodes were placed as follows: on the TB long head at 50% on the line between the posterior crista of the acromion and the olecranon at two finger widths medial to the line, on the BB at the line between the medial acromion and the fossa cubit at 1/3 from the fossa cubit, on the AD at 1.5 cm distal and anterior to the acromion, on the PD at the area about two fingerbreadths behind the angle of the acromion, and on the PM upper portion at the midclavicular line over the second intercostal space (Rodriguez-Ridao et al., 2020). Prior to positioning the electrodes, the skin was shaved, lightly abraded with fine emery paper and cleaned with alcohol to obtain low inter-electrode resistance. Signals were converted from analog to digital with a sampling rate of 1,000 Hz (Rodriguez-Ridao et al., 2020).

2.3 Data processing and analysis

2.3.1 EMG amplitude, median frequency, and power analysis

Raw EMG signals recorded from BB, TB, AD, PD, and PM muscles were inspected and signals recorded during the rest time between each two successive repetitions were discarded. EMG signals were then band-pass filtered at 5–500 Hz offline using a 4th order zero-phase-shift Butterworth filter. The EMG median frequency (MF) and power spectrum were acquired based on Fourier transform of the filtered EMG signals. The filtered EMG signals were full wave rectified. Following full wave rectification, the EMG signals were root mean squared with a 100 ms moving rectangular window to create a linear envelope. EMG root mean square (RMS) of each muscle was calculated based on the EMG envelope. EMG power, MF and RMS were calculated for each non-overlapping 4.096-s epochs during the fatiguing bench press exercise. MF and RMS were time normalized to 100% contraction duration time, while EMG power in the alpha (8–12 Hz), beta (15–35 Hz), and gamma (35–60 Hz) frequency bands were averaged for each epoch during the first and second halves of the fatiguing bench press exercise.

2.3.2 Phase synchronization analysis

EMG signals was firstly divided into two equal-length segments: EMG of the first half and second half of the fatiguing bench press exercise. The EMG of the first and second half were filtered for the frequency ranges 8–12 Hz (alpha band), 15–35 Hz (beta band), and 35–60 Hz (gamma band) using a 4th order zero-phase-shift Butterworth filter. Phase synchronization index (PSI) in alpha, beta, and gamma frequency bands between EMG of synergistic (AD-TB and AD-PM) and antagonist (BB-TB and AD-PD) muscle pairs were calculated as:

$$PSI = \sqrt{\left\langle cos\,\theta_{XY}^{H}(t)\right\rangle_t^2 + \left\langle sin\,\theta_{XY}^{H}(t)\right\rangle_t^2} \quad (1)$$

Where $\langle . \rangle_t$ means the average of all the values and

$$\theta_{XY}^{H}(t) = n\theta_{X}^{H}(t) - m\theta_{Y}^{H}(t) \quad (2)$$

In which $\theta_{X}^{H}(t)$ is the phase angle calculated based on the Hilbert transformation of the EMG signals. In all cases, m and n were assigned a value of 1 according to previous study (Quian et al., 2002). PSI was devised to quantify the phase synchronization between two oscillators of different frequencies. PSI = 0 indicated independent phases, i.e., a complete lack of interaction, and PSI = 1 indicated perfect interaction (Rosenblum et al., 2006).

Data processing was performed using MATLAB 2017Ra software (The MathWorks Inc., Natick, MA, USA).

2.4 Statistical analysis

Statistical analysis was performed using SPSS 19.0 for windows (SPSS, Inc., Chicago, IL, USA). Normality was tested by means of the Kolmogorov–Smirnov test. A repeated-measures analysis of variance was used to determine the significance of EMG RMS, MF in different contraction periods. Pearson cross-correlation analysis was used to observe the correlation between EMG indices (RMS and MF) and contraction duration time (20, 40, 60, 80, and 100% of contraction duration time). The difference of average EMG power and phase synchronization index in the alpha (8–12 Hz), beta (15–35 Hz), and gamma (35–60 Hz) frequency bands during first and second half contraction were tested using paired sample *t*-test. All significance thresholds were fixed at $\alpha = 0.05$.

3 Results

In this study, the workload of 1RM and 60% 1RM were 43.79 ± 5.58 and 26.27 ± 3.35 kg, respectively. Figure 2 showed EMG RMS and MF changes of all subjects during the sustained fatiguing contraction. The number of repetitions for the fatiguing bench



FIGURE 1
Example diagram of fatiguing bench press exercise. All participants started the exercise lying in the supine position on the bench. During the whole exercise, the participant's head and back (thoracic area) were kept in contact with the bench to prevent any inertial motion. The participants were encouraged to perform the bench press as many repetitions as possible till exhaustion.

press exercise was 15.35 ± 5.34. As illustrated in Figure 3, during the fatiguing contraction EMG RMS of TB, AD, PD, BB, and PM all increased and EMG MF decreased progressively during the fatiguing bench press exercise. A repeated-measures analysis of variance results revealed that EMG RMS of BB, TB, AD, PD, and PM muscles all showed a significant difference among five contraction periods (BB: $F = 7.635$, $P < 0.001$; TB: $F = 22.566$, $P < 0.001$; AD: $F = 52.440$, $P < 0.001$; PD: $F = 11.536$, $P < 0.001$; PM: $F = 31.671$, $P < 0.001$), as well as EMG MF (BB: $F = 32.258$, $P < 0.001$; TB: $F = 30.061$, $P < 0.001$; AD: $F = 52.262$, $P < 0.001$; PD: $F = 14.035$, $P < 0.001$; PM: $F = 31.959$, $P < 0.001$). Besides, a significant positive correlation between EMG RMS and contraction duration time was observed in all muscles except for BB muscle (BB: $r = 0.065$, $P = 0.424$; TB: $r = 0.265$, $P = 0.001$; AD: $r = 0.309$, $P < 0.001$; PD: $r = 0.202$, $P = 0.012$; PM: $r = 0.333$, $P < 0.001$), while significant negative correlations between EMG MF and contraction duration time were observed for all the five tested muscles (BB: $r = -0.425$, $P < 0.001$; TB: $r = -0.403$, $P < 0.001$; AD: $r = -0.384$, $P < 0.001$; PD: $r = -0.275$, $P = 0.001$; PM: $r = -0.305$, $P < 0.001$).

The average EMG power of BB, TB, AD, PD, and PM in alpha (8–12 Hz), beta (15–35 Hz), and gamma (35–60 Hz) frequency bands during the first and second half of contraction were presented in Figure 3. It can be observed from the figure that EMG power of TB, AD, PD, PM muscles in alpha (8–12 Hz) frequency band and EMG power of each muscle in beta (15–35 Hz), and gamma (35–60 Hz) frequency bands were all increased during the second half of contraction (black bar) compared with the first half of contraction (white bar).

Figure 4 displayed comparisons of PSI between the first and second half of the fatiguing contraction. There was a significant decrease of PSI in the gamma frequency band for BB-TB muscle pair during the second half of the contraction compared to the first half contraction ($P = 0.006$). A significant increase of PSI in the gamma frequency band for AD-TB muscle pair was also found during the second half of contraction compared to the first half contraction ($P = 0.013$). No significant difference of PSI was found between the first and second half of contraction in other frequency bands for BB-TB and AD-TB muscle pair, and in alpha, beta and gamma frequency bands for the other two muscle pairs.

4 Discussion

The aim of this study was to investigate fatigue-related changes of EMG-EMG coupling between synergistic and antagonistic muscles during bench press exercise. It was found that PSI of gamma frequency band was significantly decreased in BB-TB muscle pair while EMG-EMG coupling of AD-TB in gamma

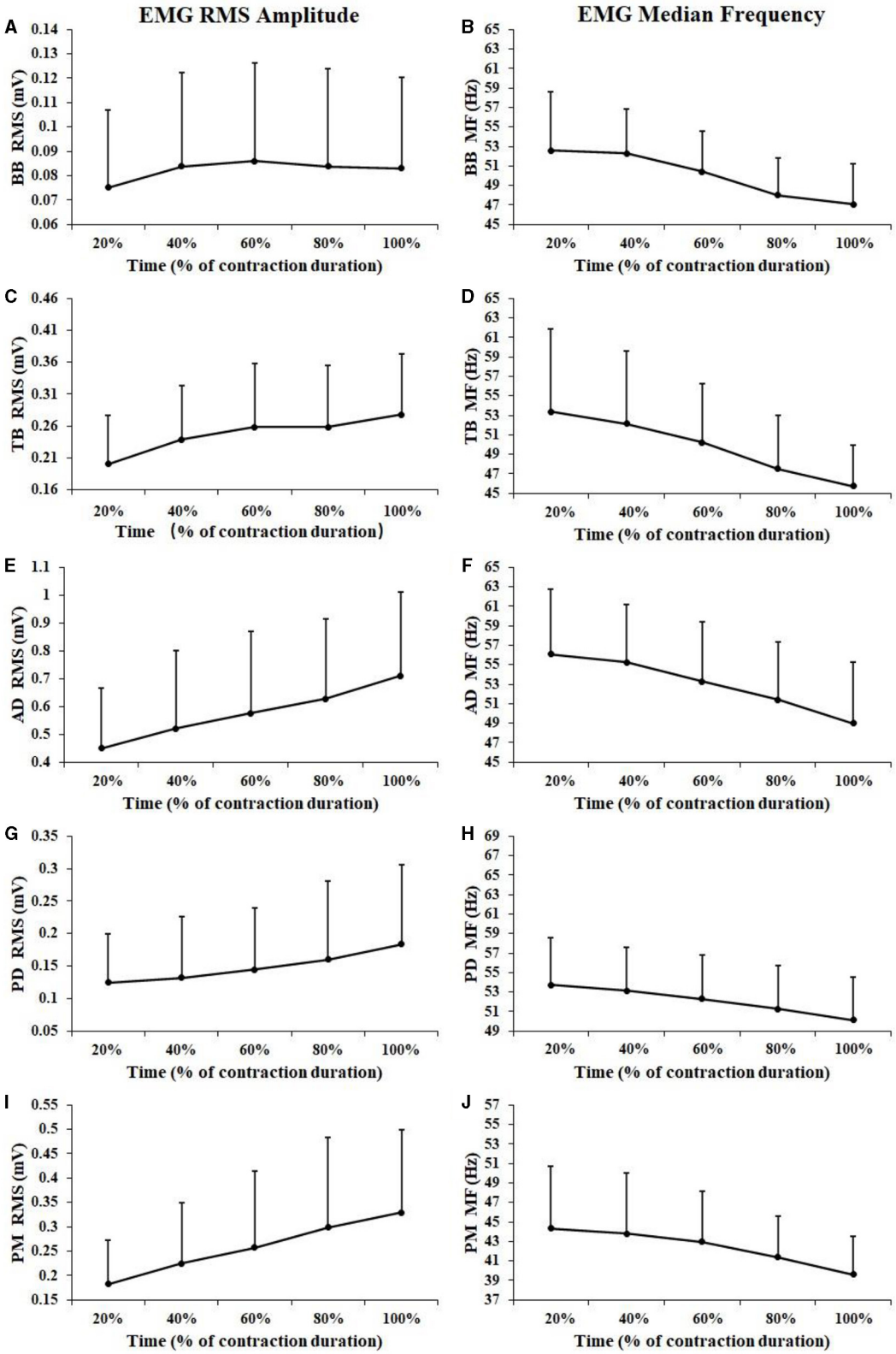


FIGURE 2
EMG RMS and MF changes of all subjects during the sustained fatiguing contraction of the BB **(A, B)**, TB **(C, D)**, AD **(E, F)**, PD **(G, H)**, and PM **(I, J)** muscle. For each subject, data of EMG RMS and MF has been normalized relative to the values at the beginning of the contraction and the time base has been normalized to 100%.

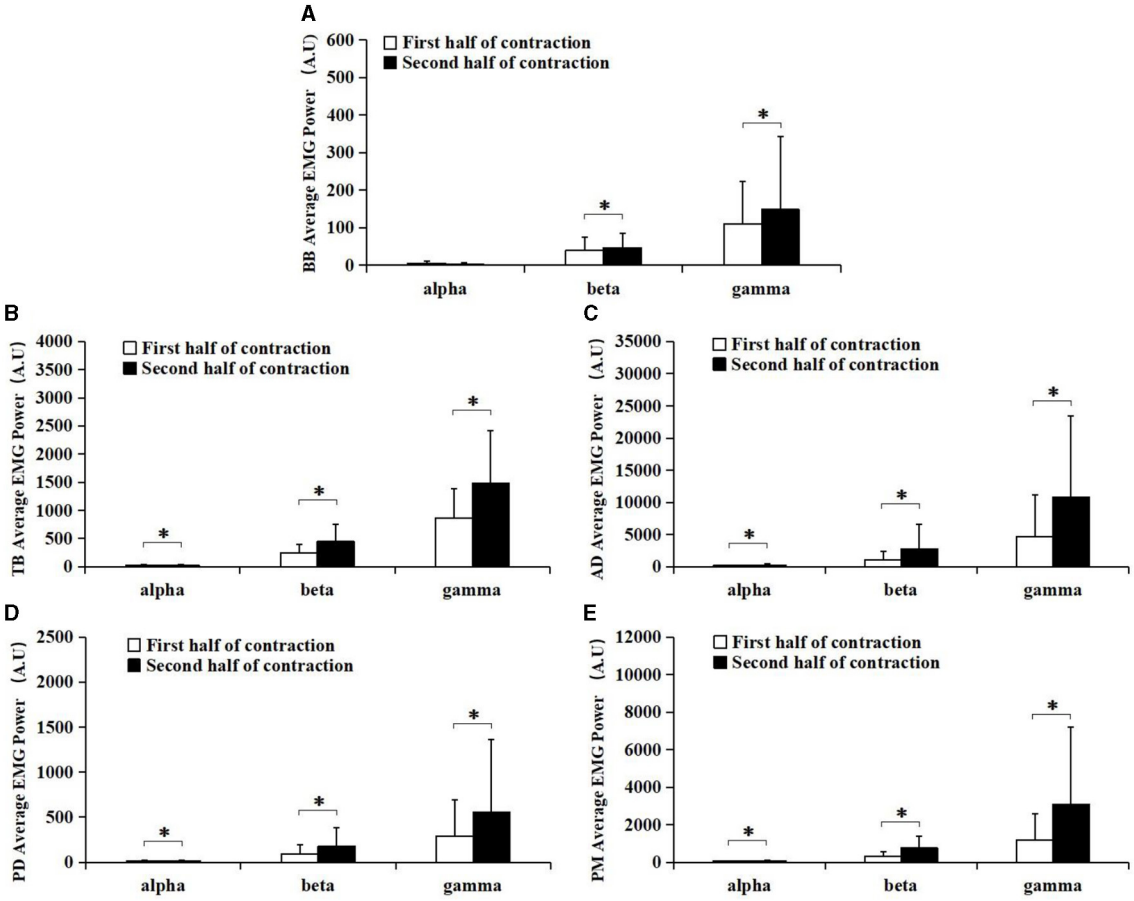


FIGURE 3
Comparisons of the average EMG power of BB **(A)**, TB **(B)**, AD **(C)**, PD **(D)**, and PM **(E)** muscles at alpha (8–12 Hz), beta (15–35 Hz), and gamma (35–60 Hz) frequency bands between the first (white bar) and second (black bar) half of the contraction. Except for the average EMG power of BB muscle in the alpha band, all muscles in the alpha, beta, and gamma band were significantly higher during the second half of contraction compared to the first half of contraction. *Demonstrated a significant difference of observed index between the first and the second half of contraction.

frequency band was significantly increased during the second half of contraction compared to the first half of contraction. As far as we know, it is the first study to explore the effect of muscle fatigue on intermuscular coupling during bench press exercise.

During the fatiguing contraction of bench press exercise, EMG RMS of both agonist muscle (TB, AD, and PM) and antagonist muscles (BB and PD) increased progressively with the increase of movement repetitions, while EMG median frequency showed significantly decrease tendency during the fatiguing task. The increase of EMG RMS and decrease of EMG MF have been suggested to be classical characteristics of muscle fatigue induced by exercise. The enhancement of EMG RMS may suggest the increase of motor unit recruit number as well as motor unit firing rates as a result of muscle fatigue, while the decrease of EMG MF may also demonstrate series of changes occurred in peripheral and central sites induced by muscle fatigue (Cifrek et al., 2009; Enoka et al., 2011). Therefore, the results demonstrated that the fatigue of tested muscles developed progressively as the increase of exercise time and repetition numbers during the fatiguing bench press test.

In previous researches concerning fatigue-related changes of intermuscular coupling, an enhancement of EMG-EMG oscillatory activities between synergistic and antagonist muscles has been mainly observed during sustained isometric contractions and dynamic motor tasks for both healthy participants as well as neuromuscular impaired patients (Charissou et al., 2017; Walker et al., 2018; Dos Santos et al., 2020). However, decreases of intermuscular coupling have also been found as a result of muscle fatigue in previous researches (Millet and Lepers, 2004; Padua et al., 2006). Up to now, current literature struggles to provide a concrete conclusion on the changes of intermuscular EMG-EMG coupling between synergistic and antagonist muscles during bench press exercise.

In this study, PSI in gamma frequency band for antagonist muscle pair BB-TB was significantly decreased while PSI of synergistic muscle pair AD-TB was significantly increased during the second half of contraction compared to the first half of contraction, which may indicate a weakening of EMG-EMG coupling between BB-TB and an enhancement of coupling between AD-TB muscle pairs as a result of muscle fatigue. In previous researches, PSI in gamma frequency band has been suggested to be closely related to the common neural inputs of the co-contracted muscles in strong isometric and dynamic voluntary contractions

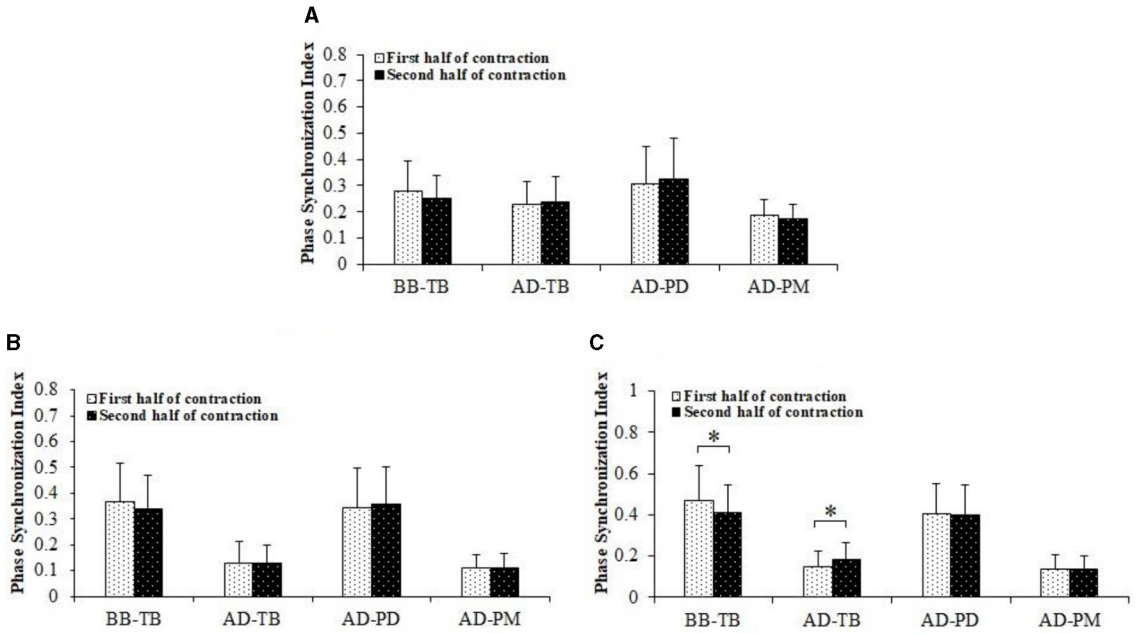


FIGURE 4
Comparisons of PSI between the first and second half of the fatiguing bench press exercise. The data have been averaged over all subjects. The PSI of BB-TB in the gamma band was significantly decreased while PSI of AD-TB was significantly increased in gamma frequency band during the second half of contraction compared to the first half of contraction. **(A)** Alpha band. **(B)** Beta band. **(C)** Gamma band. *Demonstrated a significant difference of observed index between the first and the second half of contraction.

(Gwin and Ferris, 2012; Ushiyama et al., 2012). Therefore, the lower PSI found in BB-TB may indicate a decreased descending common drive of antagonist muscle pair BB-TB and an increased common drive of synergistic muscle pair AD-TB as a result of muscle fatigue during bench press exercise. As both agonist and antagonist muscles performed dynamic contractions during bench press exercise in the current research, central control activities may be predominant related to the dynamic contractions of upper limb muscles, thus the significant changes of EMG-EMG coupling in gamma frequency band can be explained.

During bench press exercise, it has been revealed that EMG activity of TB and AD was found to be higher than other muscles, indicating a significant role of TB and AD as prime mover during the bench press exercise, and thus may be more fatigued and would receive more central modulations during the fatiguing bench process exercise (Moras et al., 2010; van den Tillaar and Saeterbakken, 2014; Stronska et al., 2022). The fatigue would increase the number of recruited motor units and more fast fibers of AD and TB would be recruited (Walker et al., 2018; Griffin et al., 1998). It has been suggested that synchronization of motoneuron inputs may help to overcome reduced excitability of the motoneuron pool during fatigue (Kattla and Lowery, 2010). Synchronized inputs are more effective at recruiting neurons than asynchronous inputs (Murthy and Fetz, 1994; Shen et al., 2024). As a result, muscle fatigue would induce a more synchronized control strategy of AD and TB muscles and thus increase the PSI of AD-TB muscle pair. Therefore, the increase of intermuscular coupling between synergistic muscle pair AD-TB may be related to the supraspinal modulations to compensate for the decrease of muscle contractility as a result of fatigue.

On the other hand, BB has been suggested to act as one of the most important stabilizer and antagonist muscle during bench press exercise, while owing to the lower intensity contraction and increased stability offered by the Smith machine, the stabilizing role of AD and PD may be weakened in the current research (Schick et al., 2010; Saeterbakken et al., 2011, 2016). However, the antagonist muscles of BB would not fatigue during the fatiguing contraction. Specifically, EMG amplitude of BB muscle showed no significant changes during the fatiguing contraction, which may indicate insignificant changes of motor unit number and motor unit firing rate during the second half of contraction compared to the first half. Therefore, the desynchronous changes of BB and TB would result in the decrease of PSI between BB-TB muscle pair (Wang et al., 2015). So the decline of intermuscular coupling between antagonist muscle pair BB-TB may be explained as a result of unbalanced changes of muscle contractility induced by bench press exercise.

However, limitations should also be acknowledged in the current research. First, in order to maximize external validity, subjects performed bench press exercises at their natural pace, which may induce different speeds of movement among subjects and influence muscle activation in the current study. Second, data were only collected and analyzed from the upper limbs of the right side, and the influence of imbalance performance between the left and right sides has not been considered. Thirdly, in this study, we only collected five main muscles according to previous research studies, and other muscles, such as the middle deltoid, upper trapezius, and latissimus dorsi, have not been tested and analyzed (Dunnick et al., 2015). Lastly, the influence of cross-talk has raised concern in previous researches. In the current study, the electrodes

were placed by the same experienced researcher according to the previous recommendations, and repeated measurements were conducted for each participant, which may be helpful in reducing the effects of crosstalk.

It should be noted that a majority of subjects in the current study have also participated in another experiment, the results of which have been published by Wang et al. (2022). However, the previous research has conducted a comparison of muscle activation and concomitant intermuscular coupling of antagonist muscles among bench presses with three different instability degrees, while in the current study, the effect of fatigue on intermuscular EMG-EMG coupling during bench press exercise has mainly concerned. Although the two studies shared nearly the same research method, the experiments of the two study have been conducted separately and the research objectives were completely different.

5 Conclusion

In conclusion, significant decrease of BB-TB and increase of AD-TB intermuscular phase synchronization index in gamma frequency band were observed in the second half of 60% 1RM fatiguing bench press exercise compared to the first half contraction. The results indicated a decrease of interconnection between synchronized cortical neurons and the motoneuron pool of BB and TB, and an increase of interconnection between AD-TB muscles. The changes of intermuscular coupling may be related to the supraspinal modulations to compensate for the decrease of muscle force as well as a result of unbalanced changes of agonist and antagonist muscle contractility.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics Committee of Tongji University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

LW: Formal analysis, Investigation, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing, Resources. HT: Data curation, Formal analysis, Investigation, Writing – original draft. QC: Formal analysis, Writing – review & editing. MQ: Data curation, Methodology, Writing – review & editing. XS: Data curation, Methodology, Writing – original draft. WN: Conceptualization, Methodology, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The Motivation MAP: an exercise-message framework to foster positive affect, challenge all-or-nothing thinking, and prioritize self-care

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Introduction

Why do so many people, despite knowing the potent benefits from exercise and having the best of intentions, quickly lose their motivation? Curiosity about this phenomenon ignited my career in the science and practice of cultivating sustainable exercise motivation and participation, and has sustained it for 30 years.

In 1994, I was confronted with an unanticipated problem while conducting my Kinesiology master's thesis (Segar et al., 1998): The cancer survivors who had been motivated to sustain exercise during the study *for our research* lost their motivation to stick with it *just for themselves* when the study ended.

This conundrum showed how deeply this problem was embedded within our cultural psyche. I needed to learn more: getting an MPH in health-behavior intervention design and evaluation, testing out and refining my ideas through real-world delivery of a theory-based intervention, and eventually getting a doctorate in personality psychology, the original home of motivation scholarship.

This psychological perspective brought me back to my original epiphany: the need for a map that enables people to free themselves from the cultural expectations that lead to repeated motivation failures. I now call this The Motivation MAP, a flexible motivation framework that utilizes three strategic messages to reframe exercise and cultivate positive new exercise beliefs, meanings, and experiences to support increased, sustainable movement among inactive individuals and populations.

Strategic messaging is a framing tactic to shape perceptions and persuade behavior (The Framing Institute, 2005). Frames are rooted in culture and influence how people see a behavior, including their beliefs about why and how to do it (Cooke-Jackson and Rubinsky, 2023; Gray and Harrington, 2011; Smith et al., 2010). Our frames influence what a behavior means to us and how we experience doing it (e.g., Does exercise feel hard or easy? Is exercise a chore or a gift?), thus exercise frames constitute a powerful cognitive map with affective and motivation consequences (Segar et al., 2016).

While research exists about exercise messaging strategies, similar to exercise science more generally, it has been dominated and limited by theoretical frameworks emphasizing rationality and conscious reflection (Brand and Ekkekakis, 2017). With the recent emergence of science on motivation states and dual-process theories' emphasis on exercise affective experiences (Kwan et al., 2017; Stults-Kolehmainen et al., 2023) there is a critical need for messaging and framing research to incorporate this new science.

I constructed The Motivation MAP to help inactive people reframe the meaning of exercise, reorienting it in ways that theory, science, and experience show cultivate positive affective experiences exercising and support the ability to fit in, prioritize, and regulate physical activity. The pilot version of The Motivation MAP was developed in 1997 for real-world commercial use. It has continued to be refined with scientific advancements and ongoing implementation, and others have recently started using it in federally funded behavioral interventions. Emerging theory, mounting science, and decades of real-world experience offer support for the unique contribution that The Motivation MAP can make to next-generation exercise research, hypothesis testing, and behavioral outcomes.

The Motivation MAP

When people are psychologically oriented toward exercise in maladaptive ways, it is critical to reorient them to more adaptive ways of thinking.

The acronym MAP reflects the framework's three-part reframing structure: Meaning, Awareness, and Permission to Prioritize. It can be difficult for people to truly understand the psycho-social exercise context that they live within. Thus, The Motivation MAP and its underlying methods guide people to critically evaluate their past exercise beliefs and experiences and invite them to cognitively and experientially reorient toward exercise.

The Motivation MAP's messages ask people to reflect on what they've learned from society about *why* and *how* they should exercise and gives them permission to reframe exercise, opening a cognitive door for rethinking their exercise motives, approaches to exercising, and priorities. This shift in thinking is concurrently accompanied by methods that invite people to experiment with participating in new physical activities, intensities, durations, and contexts in order to cultivate new positive affective experiences during exercise. Specifically, it aims to influence three hypothesized mediators of change: 1. Exercising in pleasurable ways; 2. Believing all movement is valid and worth doing; and 3. Perceiving exercise as self-care and prioritizing time for self-care and exercise. As a whole, The Motivation MAP intervention constitutes an embodied resocialization process, empowering people to transform their mindset about and relationship with exercising and movement (Segar, 2015; Segar et al., 2002).

Meaning

Much of what we experience has a deep, complex personal meaning for us that influences our behavioral choices across life arenas (Chan et al., 2021; Spruijt-Metz, 1995).

For many, especially inactive individuals, the objective meaning of exercising to improve health is often complicated by below-the-surface meaning of exercise as a painful, inconvenient, body-shaping, and obligatory "chore" (Segar et al., 2017a, 2007). As a result, despite an initial deep commitment, many quickly lose their motivation and stop exercising.

Message #1: "***Move in ways that feel good to you***."

The *Move in ways that feel good to you* message gives people permission to move away from exercise plans that feel self-defeating and instead choose physical activities that are personally inspiring, intrinsically motivating, and positively self-affirming. This message strategy encourages people to reframe physical movement as a daily option for cultivating positive affective experiences that they like and want (i.e., converting it into a "gift" they want to give themselves; Berridge et al., 2009).

Empirical support

Decision-making science suggests that it is how people expect to *immediately* feel from their behavioral choices, not the *future* value of these choices, that better drives their in-the-moment decisions (Chang and Tuan Pham, 2013). Exciting new science and dual-process models of physical activity (Brand and Ekkekakis, 2017; Conroy and Berry, 2017; Kwan et al., 2017) support the high value of helping people learn to have and expect positive experiences exercising, such as *feeling good,* generally proposing that positive affective experiences during physical activity result in a "greater likelihood of future physical activity behavior" (Stevens et al., 2020).

Awareness

Giving oneself *permission to exercise in ways that feel good* requires Awareness of our social conditioning regarding what "counts" as exercise. Until recently, "threshold messages" (communications prescribing specific amounts, durations, and intensities) have dominated the exercise messaging space in everything from PSAs to clinician advice (Segar et al., 2020). Yet, threshold messaging is not evidence-based (Warburton and Bredin, 2016) and may unintentionally create all-or-nothing standards for exercising that thwart decisions to move (Arena et al., 2018; Knox et al., 2014). When people believe they have to do it "right" to count and "right" isn't feasible, they often believe it's not worth doing at all (Segar, 2022). Because threshold messages emphasize *achieving* criteria, they may also inadvertently prevent people from seeking feel-good *experiences* through exercise.

To internalize the first "*feel-good*" Motivation MAP message, people need to gain Awareness about the newest physical activity recommendations suggesting that when it comes to movement, everything counts and adds up (Bull et al., 2020).

Message #2: "***Everything counts. It all adds up.***"

The "Everything counts. It all adds up" message guides people to start believing that all activity—every step, every minute of moving—*counts* as exercise, adds up, and is worthwhile. This message signals that no single movement, including housecleaning,

shopping, or standing up should be discounted nor devalued (Arena et al., 2018).

This message reduces real-life constraints, increases competence, and validates claiming micro-movements, integrating with the *Move in ways that feel good to you* message to help people transform their overarching Meaning for exercise from a "*chore* to a *gift*" (Segar, 2015).

Empirical support

Accumulating evidence suggests that messages teaching more inclusive and flexible definitions of movement are associated with better outcomes than traditional threshold messages (Mailey and Hsu, 2019; Walters et al., 2022; Zahrt and Crum, 2020). The *Everything Counts* messaging strategy is supported by the physical activity recommendations' removal of the 10-minute bout criterion, which aligned our global promotion of physical activity with behavioral science, helping people more easily integrate movement into their daily life (Arena et al., 2018).

Leading-edge research finds that motivation states are dynamic, random, and transient throughout the day, and influence self-regulation (Stults-Kolehmainen et al., 2023). Thus, cultivating *Everything Counts* thinking may help people better notice, and act on, numerous daily internal and external cues that encourage movement but which they had not previously felt nor sufficiently valued. Furthermore, if people *feel positive* from or about their choice to claim these micro-movement opportunities, this positivity may further increase incentive salience for these cues, reinforcing future decisions to move (Van Cappellen et al., 2018).

Permission to Prioritize

Starting from infancy, we learn what to prioritize through socialization within our families, cultures, and larger society. This unconscious process results in deeply rooted beliefs and priorities that influence our daily decisions (Eccles and Wigfield, 2002).

Even after people reframe exercise from a chore to a gift, they may still need to convert it into a priority that justifies making time for it. This can be achieved through perceiving exercise as a type of self-care and permitting themselves to make self-care a priority.

Self-care is often misperceived as selfish and leaves many feeling guilty. For people juggling competing priorities, this can interfere with their exercise motivation. Thus, there is a need to also help individuals rethink exercise as a strategic self-care tactic for supporting their other life priorities.

Message #3: "***Give yourself permission to prioritize self-care.***"

The *Give yourself permission to prioritize self-care* message guides people to feel comfortable prioritizing time for physical activity as acts of essential self-care. Similar to the chore-to-gift transformation process, this is also a fundamental resocialization, aimed at helping people reframe exercising as a strategic choice to *fuel what matters most* (Segar, 2015).

Empirical support

I learned that even motivated cancer survivors had difficulty prioritizing exercise and self-care back in 1994. Evidence over the subsequent decades establishes the de-prioritization of self-care as a core barrier to exercising, especially among parents and women (Mailey et al., 2014; Segar et al., 2017a; Vrazel et al., 2008). This makes sense because exercising doesn't occur in a vacuum, but within the context of numerous competing daily responsibilities (Gebhardt and Maes, 1998).

Perceiving exercise as compatible with and supporting one's other life priorities is associated with adherence and self-care practices (Zhang et al., 2015). Yet, little is known about how to increase the prioritization of self-care as a motivational gateway to exercising. In addition, my ongoing academic research and experiences coaching clients toward *giving themselves permission to prioritize their exercise as self-care* show that, while possible, this mindset shift can be challenging to achieve due to conflicting societal pressures and competing goals (Segar et al., 2017b).

Messages are more than just a string of words

Messages are more than just communications. They are a gateway to experiences. They guide people to beliefs, perceptions, experiences, and desires—or lack thereof. Moreover, the need to guide people and populations to perceive and approach exercise in new, more adaptive ways has become a recognized imperative (Segar et al., 2011; Arena et al., 2018; Mailey et al., 2018). "Reframing exercise" was recently adopted as a formal science-based strategy within the United States National Physical Activity Plan to boost population-level physical activity (Physical Activity Alliance, 2023).

The Motivation MAP's three messaging categories, "*Feel Good, Everything Counts*, and *Prioritize Self-care*," supported by their respective methodologies described in detail elsewhere (Segar, 2015), constitute a comprehensive reframing of exercise (Clifton et al., 2009). They guide individuals to develop new, consciously self-affirming, constraint-reducing, and priority-aligning beliefs that open the door for new experiential possibilities: choosing positive exercise experiences, developing positive affective associations and action tendencies, and noticing and responding to dynamic motivation states.

I designed these three messages to work *together* synergistically because of the specific barriers they aimed to overcome (i.e., 1. exercise is a chore; it feels bad to do and is a "should", 2. exercise takes too much time and is all-or-nothing, and 3. discomfort with and low competence for prioritizing time for self-care behaviors like exercise; Segar, 2015). Thus, each message may not be impactful if used alone, as other research using single messaging strategies has found (Mailey et al., 2023).

Findings from an earlier NIH-funded evaluation of the long-term impact from the pilot version of The Motivation MAP with its full methodology showed a 65% ($P < 0.01$) increase in physical activity participation from baseline to the study follow-up, which was 9 months or more post-program for 78% of the participants (Segar et al., 2002). It is important to note that this mixed-method evaluation was limited by being a convenience sample with no control group. The results, however, suggested that the intervention did impact the hypothesized mediators of change. *Taking a pleasure-based approach to exercising*, assessed

quantitatively, increased from baseline to follow-up by 54% ($P < 0.01$). Qualitative comments suggested that participants transformed physical activity from a chore into an activity that that felt good to do. One participant noted that she started choosing to participate in different activities so she could feel good "*during the process*" of exercising and another said that instead of thinking that she "*had to*" take a walk, she thought about it as something "*to enjoy...*" Other qualitative comments indicated that they developed more inclusive and flexible definitions of exercise, helping them overcome past absolutist thinking (i.e., "*Everything counts. It all adds up.*"). One participant noted "*Before the class I wouldn't go [to the gym] unless I had a good hour…and after [the intervention] I would go, even if I could only take a 30- or 15-min walk around the track.*" In addition, quantitative data showed a 29% ($P < 0.01$) increase in the *prioritization of self-care* from baseline to follow-up, suggesting that participants may have started internalizing this important value.

This intervention was built for and implemented across real-world community and healthcare settings, giving this past research high external validity. Though The Motivation MAP was developed prior to the emergence of measures (Zenko and Ekkekakis, 2019) and methods (Antoniewicz and Brand, 2016; Maltagliati et al., 2024) that target automatic exercise processes, it aligns with the integration of reflective and experiential processes seen in dual-process theories and constructs within other contemporary behavior change frameworks. For example, the "Move in ways that feel good to you" and "Everything Counts. It all adds up" messages would support the *autonomy* and *competence* human needs posited by self-determination theory. In addition, it maps onto the COM-B model's three core components: capability, opportunity, and motivation (Michie et al., 2011). The "Everything Counts. It all adds up" message supports *capacity* by reducing the perceived and real barriers people have to exercising and it supports *opportunity* by emphasizing how easy it is to claim the opportunities to move that exist all day long. The "Move in ways that feel good to you" message supports *motivation* by giving people permission to autonomously design exercise to deliver positive affective experiences with the intention of helping them develop new positive affective associations (e.g., "tags") (Brand and Ekkekakis, 2017) that they want to approach. Finally, the "Give yourself permission to prioritize self-care" message may support *capacity* and *motivation* by reducing some of the barriers to prioritizing exercise into daily life as necessary self-care and helping people perceive self-care as a true tactic to fuel themselves for their top priorities.

Because The Motivation MAP was built over 25 years ago for real-world use and was described in detail for non-academic audiences nearly a decade ago (Segar, 2015), many behavioral scientists and interventionists do not know about this theory-based, scientifically supported framework, nor that they can use it within their own research. The Motivation MAP is inherently flexible; each message category and its respective methods can be adapted for different populations and prevention/disease contexts, using formative research with experts and/or community and organizational partners, to identify the terms, concepts, and/or methods that might be most relevant and compelling *to them*. For example, The Motivation MAP's three messaging strategies were adapted for a recent, NIH-funded RO1 intervention targeting cancer prevention, showing promising initial data for engagement (Buis et al., 2024).

Messages matter more than many think; they influence people's exercise frames, beliefs, meanings, experiences, associations, inclinations, and motivation (Hadfield et al., 2023; Segar et al., 2012). The Motivation MAP is a flexible framework to help people reframe and re-experience exercise that is supported by emerging theory, mounting science, and decades of real-world use. It can be adapted to advance and accelerate our next generation of science, practice, and behavioral outcomes.

Author contributions

MS: Conceptualization, Writing – original draft.

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Conflict of interest

The author would like to disclose that she has a coaching, speaking, and consulting company and has authored two books about creating sustainable changes in behavior.

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Normative data for instrumented posturography: a systematic review and meta-analysis

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Postural control is a multisensory adaptive system performing predictive (anticipatory) and/or reactive (compensatory) actions, with varying degrees of accuracy, to maintain balance in a changing environmental context. Common instrumentation to evaluate balance includes static and dynamic force platforms; added sway-referenced perturbations on the dynamic platform constitute its main advantage. Clinical applications notwithstanding, normative data are needed for interpretation in clinical settings. Posturography norms are used to compare a reference group (healthy individuals) and a specific patient population. This work, to the best of our knowledge, represents the first attempt to synthesize the literature on normative data for computerized posturography using a combined mixed method. The search strategy resulted in the retrieval of 1,244 articles from PubMed, Web of Science, and Science Direct. After deduplication, 689 articles were screened based on title and abstract. One hundred and seven articles met the criteria after the first screening. In-depth, full-text screening resulted in the inclusion of 44 studies for the systematic review and 17 studies for the meta-analyses. The main findings of the systematic review are (1) extensive heterogeneity was found in methodological characteristics, (2) there was insufficient risk of bias mitigation, (3) the majority of tasks evaluated less than four components of the systems framework for postural control (SFPC), and (4) studies mostly used distance domain sway parameters and did not report the influence of other variables on postural sway. Based on the multilevel meta-analyses, females appeared to outperform males in eyes closed (EC) conditions significantly. Based on the network meta-analyses, we found that younger children swayed more than those aged between 8 and 14 years both in eyes open (EO) conditions and EC conditions significantly. The results also revealed a significant difference in sway between individuals of age range between 50 and 79 years old and younger individuals, with more instability observed in older participants both in EO conditions and in EC conditions. Thus, future studies need to ensure that enough information about participants is provided. Standardization of experimental conditions and sway parameters harmonization are still needed to ensure high-quality assessment (QA). Finally, evidence-based postural impairment management requires both age- and sex-related normative data.

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KEYWORDS

normative data, postural control, systematic review, meta-analysis, Posturography test

1 Introduction

Balance arises from a multisensory adaptive system performing predictive (anticipatory) and/or reactive (compensatory) actions, with varying degrees of accuracy, to impact balance in changing environmental contexts (Pollock et al., 2000). Numerous techniques and methods are employed to evaluate postural control at a functional and neurophysiological level, in static and

dynamic conditions (Paillard and Noé, 2015). Basic non-instrumented tests, such as the Timed Up and Go test (Podsiadlo et al., 1991), the Berg Balance Scale (Berg et al., 1992), and the Tinetti Balance Scale (Tinetti, 1986), among others, are well known and widely used by clinicians. However, these tests give a broad overview of the functional state. In contrast, instrumented tests offer the possibility to carry out in depth quality of movement assessment under different conditions and difficulty levels. Instrumented tests evaluating balance are carried out through computerized force platforms calculating the displacements of the center of pressure in static and dynamic conditions (Bizzo et al., 1985). When standing and walking, the point of application of the ground reaction forces can be measured as the center of the pressure signal using linear and non-linear variables (Quijoux et al., 2021).

Many instrumented devices are available on the market for clinical and research use. Common instrumentation includes static and dynamic force platforms. Both platforms can assess postural control; the added sway-referenced perturbations on the dynamic platform constitute its main advantage. These perturbations allow the evaluation of sensory integration, reweighting, and the use of sensory strategies while standing and walking. The most used static platforms are laboratory-grade force plates manufactured by AMTI (AMTI, Watertown, MA, United States) and Kistler (Kistler, Winterthur, Switzerland). Other low-cost alternatives also exist, such as the Wii Balance Board (WBB; Nintendo, Kyoto, Japan), which is considered a reliable and valid tool [for review, see Clark et al. (2018)]. In general, studies investigating the reliability and validity of the Wii Balance Board mostly used path length as a sway parameter to evaluate healthy participants. Numerous studies have used conventional force platforms manufactured by Neurocom International, Inc., Clackamas, OR, USA. EquiTest® device—a Computerized Dynamic Posturography (CDP) system—is considered a gold standard instrument. The concept of CDP—an apparatus and method for sensory integration and motor coordination analysis—was developed and patented by Nashner in 1988. The sensory and motor components of human postural control can be assessed by different standardized tests (Sensory Organization Test [SOT], Motor Coordination Test [MCT], Adaptation Test [ADT], and Limits of Stability) for which manufacturers have commercially published normative data. For these tests, balance is measured using equilibrium and composite scores as well as sway energy and maximal voluntary movement parameters (e.g., directional control and reaction time).

Furthermore, instrumented posturographic tools have been used to investigate balance deficits, especially in populations at higher risk of falls (Achour Lebib et al., 2006; Bloem et al., 2003). For example, the CDP's role has been widely studied in neurotology (Black et al., 1983; Horak et al., 1990; Nashner et al., 1994; Nashner and Peters, 1990; Wall et al., 1983). Increased instability has been reported in patients with vestibular disorders. SOT results have shown that patients exhibit impaired performances during conditions 5 (fixed visual surround and sway-referenced platform) and 6 (sway-referenced visual surround and platform), which is indicative of a vestibular deficit affecting the postural functioning of the individual (Black et al., 1988). Furthermore, the results of dynamic posturography in a broad spectrum of patients with peripheral and central vestibular disorders revealed varying degrees of functional capacity within each group. Psychometric properties for dynamic posturography have been mainly studied in this specific population (Di Fabio, 1995, 1996; Hamid et al., 1991). Analogous to CDP, computerized static posturography, using a foam-supported platform as a perturbation, offers a low-cost and portable alternative. Thus, the Clinical Test of Sensory Interaction on Balance (CTSIB) can evaluate balance in eyes open (EO) and eyes closed (EC) conditions with/without foam. Increased sway was observed in patients compared to controls during foam posturography, particularly with EC, measured using amplitude and velocity (Baloh et al., 1998) as well as velocity, area, and Romberg's ratio (Fujimoto et al., 2009). In the CTSIB, integrated with virtual reality, instability was condition dependent—patients with vestibular disorders sway more during more challenging sensory conditions (i.e., foam surface, EC, and optokinetic stimulus) (Macedo et al., 2015).

Clinical applications notwithstanding, normative data are needed for interpretation in clinical settings. Normative data (SpringerReference) are observational data summarizing and describing a population's characteristics at a specific time. Posturography norms are used to compare a reference group (healthy individuals) and a specific patient population. Thus, variations between patients and healthy individuals can be observed and interpreted in a clinical setting to determine pathological profiles. Descriptive information (e.g., total sample size, age groups, and sex) and statistics (e.g., median; other summaries of distribution; indicators of central tendency and dispersion; and standard scores) are needed to report such datasets. Some studies have focused on establishing reference values for CDP, mostly using the NeuroCom EquiTest (NeuroCom International, Inc), for which normative data are already available. Normative data have also been published by the BTrackS Balance Plate (Balance Tracking systems) parent company for static computerized posturography.

However, one significant limitation has been noted: the lack of stratification and socio-demographic information. Many studies have demonstrated that sex and age influence postural control (Farenc et al., 2003; Hageman et al., 1995; Ionescu et al., 2005). For static computerized posturography, a systematic review of postural sway in children revealed that age stratification was arbitrary in majority of studies, leading to conflicting results concerning postural control development (Verbecque et al., 2016b). Furthermore, results showed that stability increased with age, and children swayed more when visual input (in EC condition) was removed. These results have also been observed in adults. Other variables such as anthropometric characteristics (Alonso et al., 2012; Chiari et al., 2002), feet positioning (Gibbons et al., 2019; Kollegger et al., 1989), and physical activity (García-Soidán et al., 2020; Gauchard, 2003; Lelard and Ahmaidi, 2015) can also affect balance. Thus, lack of stratification and reporting might lead to misinterpretation of patient postural performance in clinical practice and healthy individuals undergoing behavioral and balance assessments. Therefore, there is room for improvement, and this work aspires to complement previous studies.

The purpose of this study is to systematically review the reported normative data, assessed by computerized posturography, in a healthy population and to discuss the strengths and limitations of these norms to outline future perspectives and needs. Overall, we aimed to identify methodological characteristics of computerized posturography assessment in this systematic review and investigate the impact of age and sex in the meta-analysis.

2 Methods

2.1 Information sources, search strategy, and inclusion criteria

This systematic review and meta-analysis included studies that provide normative data assessed using instrumented platforms in

healthy populations (Registration: CRD42023378144). It was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) statement. A comprehensive literature search was performed in PubMed, Web of Science, and Science Direct electronic database platforms. A search string was used with keywords (1) "normative data", (2) "posturography", (3) "instrumented platform" combined using the Boolean operators "OR" and "AND" for interaction among sets of keywords. The searches were conducted in May 2022 and updated in January 2023. The studies were screened based on *a priori* defined inclusion and exclusion criteria using Rayyan, a web-based application (Ouzzani et al., 2016). The literature search was limited to articles published between 1 January 1980 and 1 January 2022. Computerized posturography was created in 1980 (Nashner, 1982). Therefore, only studies published as of this date were included in this review. In each article, the use of instrumented platforms as evaluation tools was sought. Reference lists and citations of the included articles were manually screened to identify additional studies of interest. The literature search was limited to full-text articles that were written in English and French. The articles meeting the criteria based on their titles and abstracts were included, and their full-text versions were then extracted. AJ and EV performed screening. Full-text articles were checked if information in the title and abstract was insufficient to determine eligibility.

2.2 Selection criteria and strategy

To select relevant literature, the following selection criteria were applied:

- Healthy participants were a combination of men and women (absence of any other impairments that can influence balance). The normative data had to be representative of the average population of healthy people. However, studies that included athletes, soldiers, and one of the sexes were exclusively considered relevant to the research question. A minimum sample size of 30 participants was considered an adequate representative sample.
- Instrumented equipment during static or dynamic bipedal balance measurement had to be included. Citations were excluded when data were collected during gait and functional measures (e.g., Timed Up and Go, climbing stairs, 6-min walk test, Y-Balance Test, Star Excursion Balance Test, treadmill walking or during running, turning, stepping tasks lateral, forward, backward, etc.). Balance assessment through mobile devices was excluded as well.
- Original research including full-length articles that were written in English or French. Reviews, meta-analyses, case–control studies/series, conference proceedings, abstract only, books/book chapters, letters to the editor, study protocols, pilot studies, editorials, or opinion pieces were excluded.
- Studies that had explicitly reported normative data were included.

2.3 Data extraction and study quality assessment

Data extraction was *a priori* defined using a codebook which included the following information: (1) Study characteristics (authors, year of publication, etc.); (2) methodological details, such as population and measurement characteristics, tasks, and sway parameters; and (3) equations used and psychometric properties (if provided). Authors were contacted to obtain any unavailable data. At a systematic review level, we evaluated the stratification of age and sex and the significance of other factors tested in each study. These are expressed as significant (S), not significant (NS), and not reported (NP).

Studies used a combination of different support and visual conditions, which can be divided into distinct groups and subgroups. In this review, balance tasks were described according to measurement and movement control type as well as sensory perturbations based on a classification process used by Herssens et al. (2020): without sensory perturbations, with proprioceptive perturbations (foam, moving platform and/or foot placement), with visual perturbations (deprivation and/or altered surround), with vestibular perturbations (head movements), and with multiple sensory perturbations. A distinction between measurement and movement control types was made to describe performance in the present review. External conditions determine measurement type during balance assessment. It is classified as dynamic when tasks are executed in altered visual and/or tactile environments and static when tasks are executed in stable visual and/or tactile environments. Movement control type is considered activity-based conditions represented as tasks consisting of quiet standing (static) and voluntary body movements (dynamic). In addition, we used the Systems Framework of Postural Control (Sibley et al., 2015) to determine the nine components of balance (functional stability limits, underlying motor systems, static stability, verticality, reactive postural control, anticipatory postural control, dynamic stability, sensory integration, cognitive influences) which were assessed in the different tasks.

To the best of our knowledge, no quality assessment (QA) tool exists for reference values. However, we adapted the quality assessment tool for diagnostic accuracy studies (QUADAS) scale reported? (Whiting et al., 2003, 2006) and selected the following relevant questions (1, 2, 5, 9, 12, and 13) based on our study objectives: (1) Was there adequate sampling of normative data? (2) Were selection criteria clearly described? (5) Was a motor scale (i.e., other than posturographic measurement) used as part of the test battery? (9) Was the description of instruction and position/setup for the patient, type of equipment, and the outcomes at least reported? (12) Was the age and sex of a sample at least available? (13) Were drop-outs and falls collected (e.g., was it reported that a portion of the participants fell) and reported? Answers were scored in "Yes" or "No" forms, and missing or ambiguous details were scored as "Unclear." The total score has not been defined for the QUADAS tool. Therefore, studies were considered high quality (low risk of bias) if four or more items out of six items were scored "Yes." AJ and EV independently performed a QA for each article, and each assessor was blind to the score the other gave. Any disagreement over the final score for each article was discussed until consensus.

Studies providing summary statistics were included in the meta-analysis. Quantitative analysis was done after extraction by categorizing and grouping according to population type (adults, children, and both) and sex distribution (females and males) as well as posturography type (static and dynamic), tasks, and sway parameters. We performed a meta-analysis on sway parameters used by at least three publications in similar measurement conditions. Priority was given to age and/or sex-stratified reference values to

mitigate inter study variability. When possible, participants' mean age and groups were converted and pooled according to decade for adults and biological ages for children to reduce heterogeneity. We used a broad age categorization to ensure enough studies were included in the quantitative analysis to allow for meaningful interpretation. Using to the Cochrane Handbook (Higgins et al., 2020), subgroups were combined into a single group to compare males and females separately and to compare specific age groups whenever possible. When possible, specific terms were attributed to sway parameters based on the definitions in the literature (Prieto et al., 1996) to aggregate data and comparison for meta-analysis purposes. Homogeneity should have been particularly present across age/sex stratification and test conditions. Additionally, quantitative analysis was not conducted when an insufficient number of identified studies were available per task condition (EO and EC, foam, etc.) ($n > 5$). We found that 38 studies used sway parameters used by at least three publications. After further inspection, we removed studies that had no age and/or sex comparisons, insufficient statistics, or were owned by a company ($n = 21$). Instead, these studies were summarized narratively (see Figure 1). The majority of the excluded studies had reported a decrease in sway with increasing age for children whereas an increase was observed for aging adults. Sensory perturbations tended to increase instability, and overall, females outperformed males. Studies assessing children did not investigate the influence of other factors.

2.4 Statistical analysis

Statistical analyses were performed in R version 4.2.3[1] using the packages, metafor (Viechtbauer, 2010), clubSandwich (Pustejovsky, 2024), and netmeta (Balduzzi et al., 2023). Age and sex were analyzed in each sensory condition using different models with effect sizes nested within outcomes, and the latter within studies. We undertook meta-analyses if participants, interventions, outcomes, and comparisons were sufficiently similar. Potential modifiers included population characteristics and intervention details, which are considered sources of heterogeneity.

2.4.1 Measures of group effect

The standardized mean difference was calculated to pool effect sizes to quantify the difference in performance between age and sex groups. For measures where a higher score represented better performance (e.g., equilibrium scores in EO and EC), the direction of the scale was reversed by multiplying by −1 to ensure interpretability across studies. Furthermore, we accounted for a hierarchical dependence structure as multiple effect sizes were extracted from the same studies, experiments, and outcomes across samples for the multilevel meta-analysis.

2.4.2 Outliers and influential cases

Standardized deleted residuals and Cook's distance were used to identify outliers and influential studies. Residuals larger than ±1.96 indicated that studies did not fit the model and thus represented outliers. Moreover, influential cases were removed when Cook's distance was over $4/n$, where n is the total number of data points.

2.4.3 Assessment of heterogeneity

In the multilevel meta-analysis, we assessed heterogeneity using the I2 statistic to quantify the percentage of variation attributable to each level – study, outcome, and effect size (low: 25%, moderate: 50%, high: 75%; Higgins et al., 2020). In the network meta-analysis, global and local approaches were used to assess heterogeneity (i.e., variation in effect modifiers within comparisons) and inconsistency (i.e., imbalance in effect modifiers between comparisons). Specifically, we fitted Cochran's Q (χ^2) statistic decomposition to evaluate the contribution of each design to the heterogeneity "within designs" and consistency "between designs." Moreover, a design by treatment (in our case, age groups) interaction model was also fitted for the global approach. Local inconsistency between direct and indirect evidence was evaluated using the Separate Indirect from Direct Evidence (SIDE) method (Dias et al., 2010). To explore sources of heterogeneity, a meta-regression was conducted.

2.4.4 Assessment of publication bias

The potential publication bias was addressed by estimating the funnel plot asymmetry and was tested via Egger's regression when more than 10 studies were included.

2.4.5 Multilevel meta-analysis using robust variance estimation

We conducted a multilevel meta-analysis using robust variance estimation (RVE) to synthesize studies comparing females and males. To account for the complexity of the data structure, an RVE method can be used to model dependencies between effect sizes and their correlated sampling errors. To obtain robust confidence intervals and p-values, the Sandwich estimator (package clubSandwich) was used in combination with the model. For smaller numbers of included studies, valid analysis results are ensured by an adjustment matrix based on the bias-reduced linearization CR2 method. An assumption of the degree of correlation was estimated at $r = 0.6$. The RVE model provides a valid overall average effect size even if the correlation assumption is inaccurate. Several sensitivity analyses for varying values of r were nonetheless conducted.

2.4.6 Frequentist network meta-analysis: multiple interventions

We conducted a network meta-analysis (NMA) to estimate the relative effects for all possible comparisons between different age groups. The frequentist random-effects network meta-analysis considers direct and indirect evidence, also called mixed evidence (i.e., direct—studies comparing A vs. B; indirect—studies comparing A vs. C) (Rouse et al., 2017). Thus, this method estimates the relative effects of comparisons between groups via one or more intermediate comparators or direct ones. The network structure was inspected, and subnetworks (i.e., not fully connected networks) were analyzed separately. Furthermore, studies with missing or inconsistent group estimates and variances were also excluded from the network meta-analysis. The age groups (i.e., interventions) were ranked using the surface under the cumulative ranking curve (SUCRA) method (Salanti, 2011) to account for the entire distribution of the relative effects. This score is expressed as a percentage, with the best ranking corresponding to 100%. This analysis allowed us to include all possible direct and indirect comparisons of different age groups and determine their rankings. Furthermore, we assessed the certainty of

1 https://www.r-project.org/

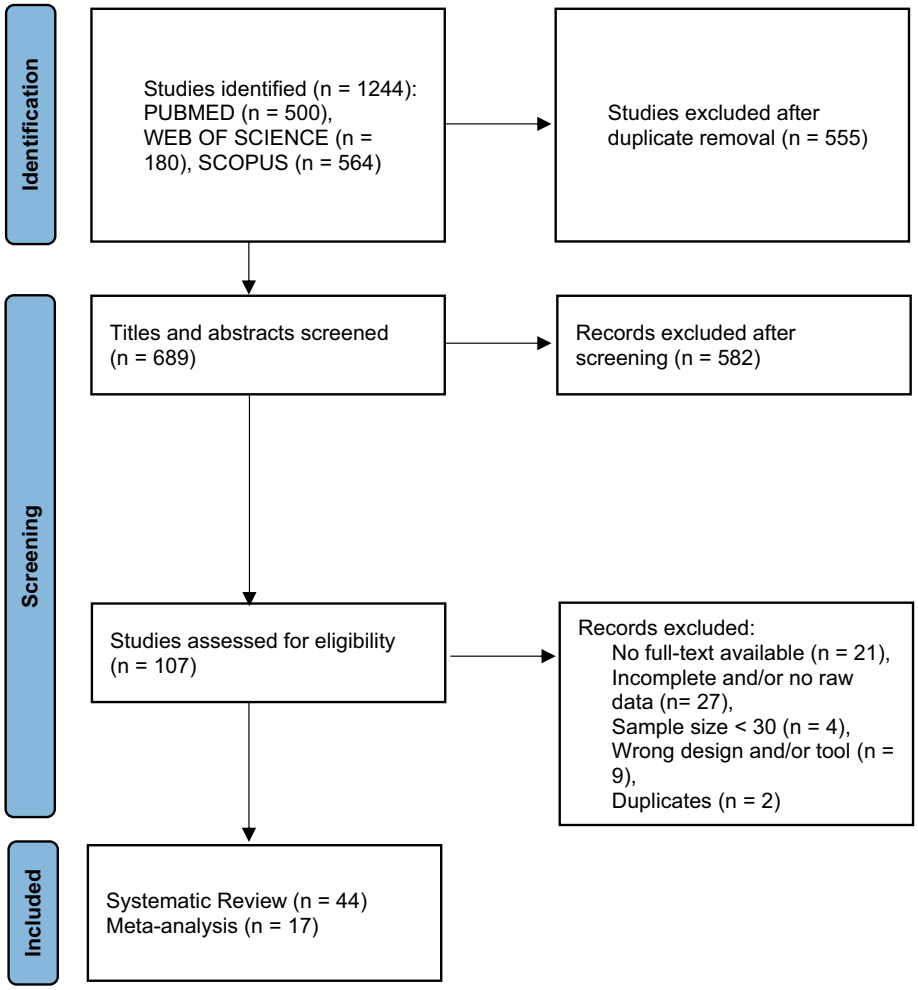


FIGURE 1
Flowchart for the systematic review and meta-analysis.

the evidence for each comparison using Confidence in Network Meta-Analysis (CINeMA), a web application used to evaluate the confidence of the evidence estimates from network meta-analysis. It is based on the following six domains: within-study bias (risk of bias), reporting bias (publication bias), indirectness (i.e., relevance to the research question), imprecision (comparing the range of effects with the range of equivalence), and incoherence (disagreement between direct and indirect evidence). We excluded two studies (Libardoni et al., 2018; Micarelli et al., 2020) from the meta-analysis in EO and EC conditions due to inconsistent group estimates and variances.

3 Results

3.1 Information sources and search strategy

The search strategy resulted in the retrieval of 1,244 articles from PubMed, Web of Science, and Science Direct, on 9 May 2022 and a second search on 31 December 2022. After deduplication, 689 articles were screened based on title and abstract. One hundred and seven articles met the criteria after the first screening. In-depth, full-text screening resulted in the inclusion of 44 studies for the systematic review. An overview of the study design is summarized in the PRISMA flowchart (Figure 1).

3.2 Descriptive synthesis: risk of bias assessment and methodological characteristics

The risk of bias assessment reveals extensive variation in methodological characteristics (see Supplementary Table S1). Ten studies had high-quality assessment and took measures to reduce risk of bias (Figure 2). The majority of the problematic aspects were in questions 1, 5, and 13 of the adapted QUADAS.

3.2.1 Participants

The general characteristics of the included studies are presented in Table 1. The sample size of publications included in the systematic review ranged between 30 and 16,357 participants. In total, 42,408 participants (12,043 women, 13,761 males) were included and represented mostly regular individuals (77%). Children and adults

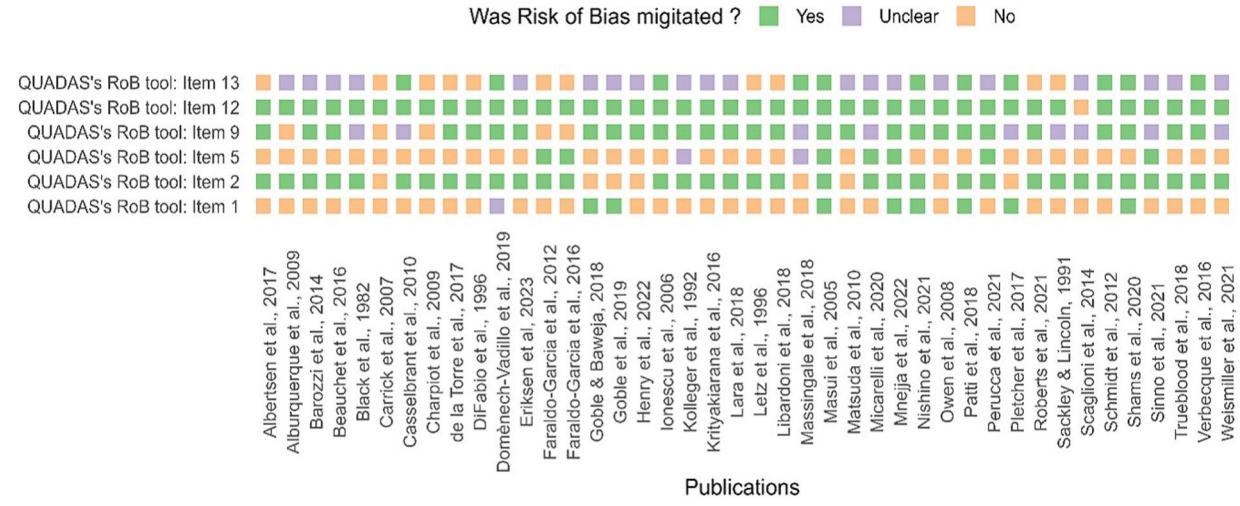


FIGURE 2
Assessment of study quality (QA) and risk of bias. The risk of bias, using QUADAS's tool, for each study, is included in the systematic review. Answers were scored "Yes" or "No," and missing or ambiguous details were scored as "Unclear." Unreported details were scored as an 'unclear' risk of bias.

combined were primarily represented in the sample (48%). Specific cohorts were included in a few studies, such as athletes (11%), military (6.8%), and mixed (4.5%). The majority of the studies were conducted in Europe (41%) and North America (36%). The study population represented a large range of ages and participants comprising of children, adolescents, and adults. Age and sex were stratified, respectively, in 64 and 45% of the publications. Regarding age stratification, majority of the studies did not provide age groups (34%) (Albertsen et al., 2017; Beauchet et al., 2016; Carrick et al., 2007; de la Torre et al., 2017; Goble et al., 2019a; Henry et al., 2022; Krityakiarana and Jongkamonwiwat, 2016; Lara et al., 2018; Letz et al., 1996; Matsuda et al., 2010; Owen et al., 1998; Pletcher et al., 2017; Scaglioni-Solano and Aragón-Vargas, 2014; Schmidt et al., 2012; Weismiller et al., 2021); some reported values per biological age (18%) (Barozzi et al., 2014; Casselbrant et al., 2010; di Fabio and Foudriat, 1996; Ionescu et al., 2005; Libardoni et al., 2018; Micarelli et al., 2020; Mnejja et al., 2022; Verbecque et al., 2016a) and per decade (16%) (Black et al., 1982; Eriksen and Hougaard, 2023; Faraldo-García et al., 2012, 2016; Goble and Baweja, 2018b; Sackley and Lincoln, 1991; Trueblood et al., 2018), or academic level associated with school year (11%) (Charpiot et al., 2010; Goble et al., 2019b; Massingale et al., 2018; Shams et al., 2020; Sinno et al., 2021). Others used an unconventional stratification method (Alburquerque-Sendín et al., 2009; Domènech-Vadillo et al., 2019; Goble and Baweja, 2018a; Kollegger et al., 1992; Masui et al., 2005; Nishino et al., 2021; Patti et al., 2018; Perucca et al., 2021; Roberts et al., 2021). Several studies did not provide explicit reasons for omitting age stratification. However, a few studies decided to pool data as they did not observe age-based differences. We speculate that sample size constraints and the complexities of recruiting older participants may have been contributing factors, as suggested by a few studies.

3.2.2 Tasks and sway parameters

The included studies investigated postural sway using a variety of tasks. Measurement conditions varied largely regarding arm and foot position, use of the visual target, the number and duration of trials and sequence of the conditions. Twenty-three studies used static measurement, whereas static movement control was described in 40 studies. When possible, tasks were converted into standardized tests commonly used in clinical practice based on specified conditions. If a task did not correspond to a known test, we coded it according to precise sensory conditions. Overall, 17 different tasks were used. The majority of studies used multiple sensory perturbations (70%) and did not report psychometric properties (80%). Using the Systems Framework of Postural Control, components of postural control measured in each task were determined (Figure 3A). Three out of 17 tasks evaluated the majority of the components of the systems framework for postural control (SFPC) (4 items); only one task was used in more than three studies, the Motor Control Test (MCT). Other mostly used tasks were the Modified Clinical Test of Sensory Interaction in Balance (mCTSIB) and the SOT, which evaluated three components of the SFPC (static stability, underlying motor systems, and sensory integration) as well as Vision + FIRM (visual perturbation with firm surface) and EC + FIRM (EC with firm surface) which evaluated two components (static stability and sensory integration). Finally, EO + FIRM (EO with firm surface) was also used and evaluated one component, static stability. The four SFPC components evaluated in the MCT were static stability, underlying motor systems, reactive postural control, and sensory integration.

A large variety of parameters for postural sway led to semantic heterogeneity in the reported data. Therefore, whenever possible, specific terms were attributed to sway parameters in this review based on the definitions in the literature to allow comparison between different studies. The publications used 45 different sway parameters to assess balance performance; only a few provided equations for calculating sway parameters (27%). Thirteen sway parameters were used by more than three studies, which were distance domain features: review of center of pressure (COP) area, COP path, and COP velocity in either the anteroposterior (AP) and mediolateral (ML) direction or in a combined plane, COP range in AP and ML direction as well as SOT ratios, SOT equilibrium scores, SOT and MCT composite scores which are non-domain specific features (Figure 3B).

TABLE 1 General characteristics of included studies.

Characteristic	$N = 44$[1]
Population group	
Adults	14 / 44 (31.8%)
Both	21 / 44 (47.7%)
Children	9 / 44 (20.4%)
Individuals' category within each population	
Athletic	5 / 44 (11%)
Military	3 / 44 (6.8%)
Mixed	2 / 44 (4.5%)
Regular	34 / 44 (77%)
Region	
Africa	1 / 44 (2.3%)
Asia	5 / 44 (11%)
Central/South America	4 / 44 (9.1%)
Europe	18 / 44 (41%)
North America	16 / 44 (36%)
Sample size	30–16,357; 42,408
Females	0–4,292; 12,043
Not reported	3
Males	0–6,624; 13,761
Not reported	3
Stratified by age	
No	16 / 44 (36%)
Yes	28 / 44 (64%)
How was age stratified?	
Academic	5 / 44 (11%)
Biological	8 / 44 (18%)
Decade	7 / 44 (16%)
None	15 / 44 (34%)
Unconventional	9 / 44 (20%)
Stratified by gender	
No	24 / 44 (55%)
Yes	20 / 44 (45%)
Post-urographic assessment type	
Dynamic	21 / 44 (48%)
Static	23 / 44 (52%)
Movement control type	
Dynamic	4 / 44 (9.1%)
Static	40 / 44 (91%)
Sensory perturbations used in tasks	
Multiple	32 / 44 (72.7%)
Proprioceptive	3 / 44 (6.8%)
Visual	8 / 44 (18.1%)
Without	5 / 44 (11.3%)
Were equations for calculating sway parameters provided?	
No	32 / 44 (73%)
Yes	12 / 44 (27%)
Were psychometric properties reported?	
No	35 / 44 (80%)
Yes	9 / 44 (20%)

[1]n / N (%); Range; Sum.

Other variables were also reported as factors influencing postural control (Supplementary Figure S2A). Five studies reported a significant effect of sensory conditions in adults, whereas height mainly was reported as a non-significant variable in children ($n = 3$) and mixed populations ($n = 4$). However, the majority of the studies did not report the influence of other variables on postural sway.

3.3 Quantitative analysis

In the multilevel or network meta-analysis, we pooled data from seventeen studies involving 5,194 participants (females: 2,630; males: 2,564). Furthermore, we did not conduct quantitative analysis for Foam conditions and sway-referenced conditions (SOT 3, SOT 4, SOT 5, and SOT 6) as well as for composite score and ratio outcomes as there was insufficient number of studies ($n < 5$).

3.3.1 Effect of sex on postural sway

In the EO condition (Figure 4), an overall summary meta-analysis found an average sex difference of sensory modulation disorder (SMD) = −0.17, $t(7.6) = -2.02$, $p = 0.08$, 95% CI: −0.36, 0.01. The overall I2 value indicates that 79.1% was due to heterogeneity, with the variance component accounting for about 28.6% of the total variance at the study level, 25.3% at the outcome level, and 25.3% at the effect size level. The remaining 20.9% was a sampling variance. There were no influential outliers found. Subgroup analyses were conducted since high heterogeneity was detected, and no influential cases were found. Population group, region, and risk of bias were determined *a priori* as potential modifiers. However, none of them could explain explicitly the overall high heterogeneity (Supplementary Table S5). The overall average effect size was not sensitive to our assumption about the correlation between effect size estimates, with estimates varying from −0.187, 95% CI: −0.382, 0.008 assuming ρ = from 0.0 to −0.168, 95% CI: −0.372, 0.036 assuming $\rho = 0.9$. The total variation in true effect sizes was similarly insensitive, with a total standard deviation (SD) ranging from 0.220 to 0.255. However, individual variance component estimates were more sensitive to the assumed ρ (see Supplementary Table S4A).

In EC condition (Figure 5), an overall summary meta-analysis found an estimated overall significant SMD = −0.22, $t(4.6) = -4.20$, $p = 0.01$, 95% CI (−0.34, −0.10), with non-significant low heterogeneity (I2 = 11.6%) after removing one outlier. The overall average effect size was not sensitive to our assumption about the correlation between effect size estimates, with estimates varying from −0.233, 95% CI: −0.396, −0.069 assuming ρ = from 0.0 to −0.211, 95% CI: −0.347, −0.076 assuming $\rho = 0.9$. The estimated total variation in true effect sizes was similarly insensitive, with a total SD ranging from 0.11 to 0.141. However, individual variance component estimates were more sensitive to the assumed ρ (see Supplementary Table S4B).

3.3.2 Effect of age on postural sway

Network meta-analysis in EO and EC conditions included each of the 10 studies and revealed two subnetworks, which consisted of 22 groups, 358 comparisons, and 8 study designs. The 10 characteristics were relatively similar across groups in each subnetwork, indicating an acceptable transitivity assumption (see Supplementary Table S5). The first and second subnetworks

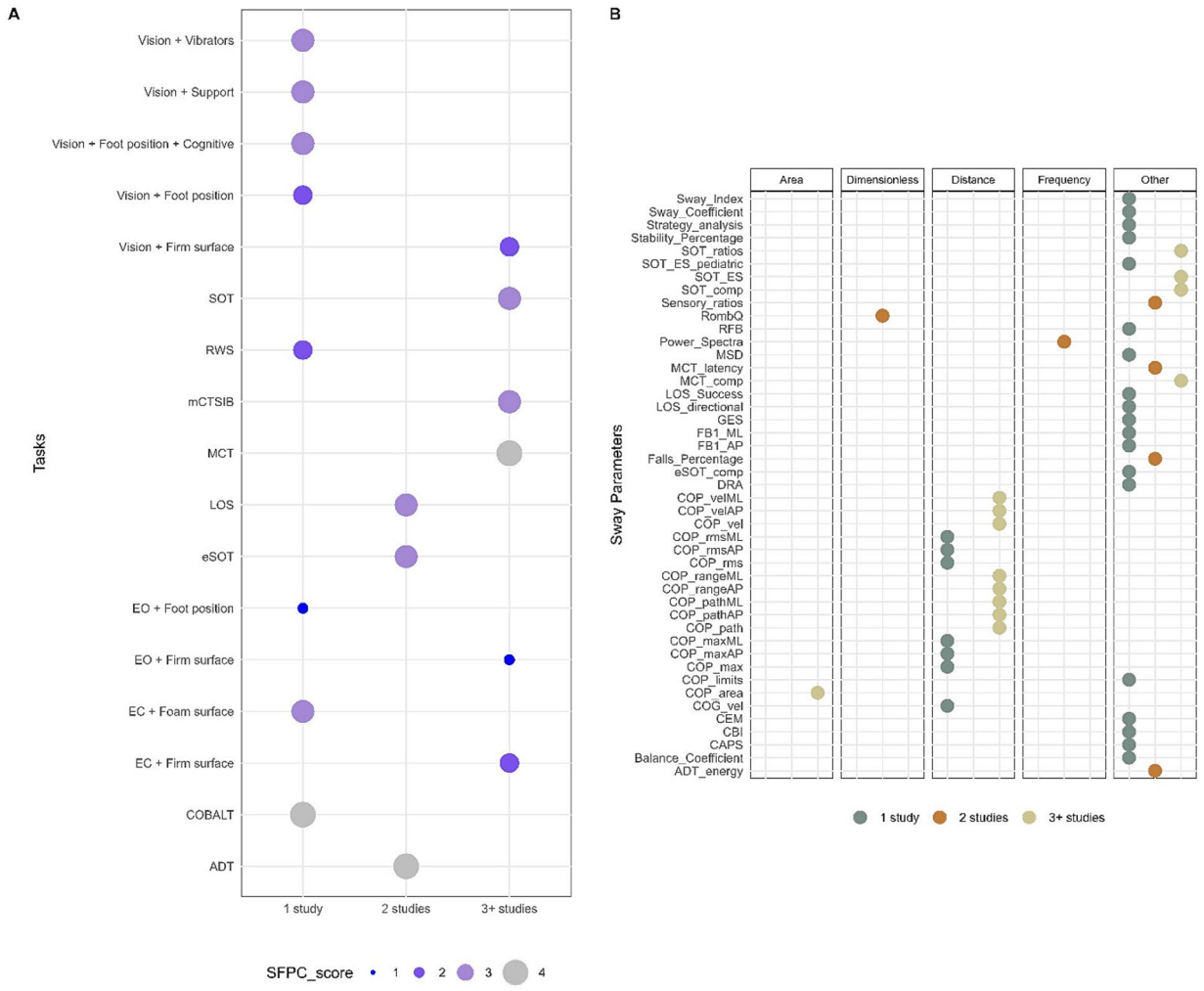


FIGURE 3
Methodological characteristics for tasks and sway parameters. **(A)** Tasks reported in n ≥ 3 number of studies based on the Systems Framework of Postural Control components evaluated in each task. **(B)** Sway parameters used in *n* ≥ 3 number of studies and grouped by domain.

represented adults aged between 20 and 79 years old and children aged between 3 and 14 years old (Supplementary Figure S4). The subnetworks were analyzed separately.

3.3.2.1 Effect of age within adults +20 years

The first subnetwork analysis, 20–29-year-old participants were used as the reference group. Figures 6A,B shows the first connected subnetworks for both EO and EC conditions. The most frequently examined comparisons were among age groups (in years) 20–29 vs. 30–69 and 30–39 vs. 40–69, and 40–49 vs. 50–69 and 50–59 vs. 60–69. Supplementary Table S6 summarizes the main results of both direct and indirect evidence and the first subnetwork meta-analysis for EO and EC. Figures 7A,B show the treatments' relative rankings with the group of the age range (in years) 20–29 as the reference group. Figures 7C,D shows the relative rankings with group 14 as the reference .The lowest ranked was the group of the age range (in years) 70–79 (SUCRA: 0.09 for EO and 0.09 for EC) followed by 60–69 (SUCRA: 0.28 for EO and 0.14 for EC) and 50–59 (SUCRA: 0.29 for EO and 0.38 for EC). We present the summary of relative effects in league tables (see top table, Figure 8).

In the EO condition, older groups of the age ranges (in years) 50–59, 60–69, and 70–79 were significantly more instable than the reference group 20–29 (EO: SMD range 0.43–0.66). The groups of the age ranges (in years) 30–39 and 40–49 were more stable than older groups 60–69 (EO: SMD range 0.61–0.75) and 70–79 (EO: SMD range 0.53–0.59).

In EC condition, older groups of the age ranges (in years) 50–59, 60–69, and 70–79 were significantly more instable than the reference group 20–29 (EC: SMD range 0.51–0.85). The groups of the age ranges (in years) 30–39 and 40–49 were more stable than the older group 70–79 (EC: SMD range 0.70–0.84). A statistically significant difference was also found for the age ranges (in years) 50–59 compared to 30–39 (SMD = 0.50, 95% CI: 0.10, 0.90) and 60–69 (SMD = 0.25, 95% CI: 0.03, 0.46); indicating that older individuals swayed more for EC.

The heterogeneity and global inconsistency were low in the first subnetwork (EO: I2 = 0, 95% CI: 0, 62.4%, $\chi^2 = 8.59$, $df = 9$, $p = 0.47$; EC: I2 = 0, 95% CI: 0, 62.4%, $\chi^2 = 8.41$, $df = 9$, $p = 0.49$). Inconsistency between designs appeared to be not an issue in this subnetwork (EO: $p = 0.7$; EC: $p = 0.6$). Supplementary Tables S8A,B summarizes the local inconsistency between direct and indirect evidence using the SIDE method for the EO and EC conditions. The results show that

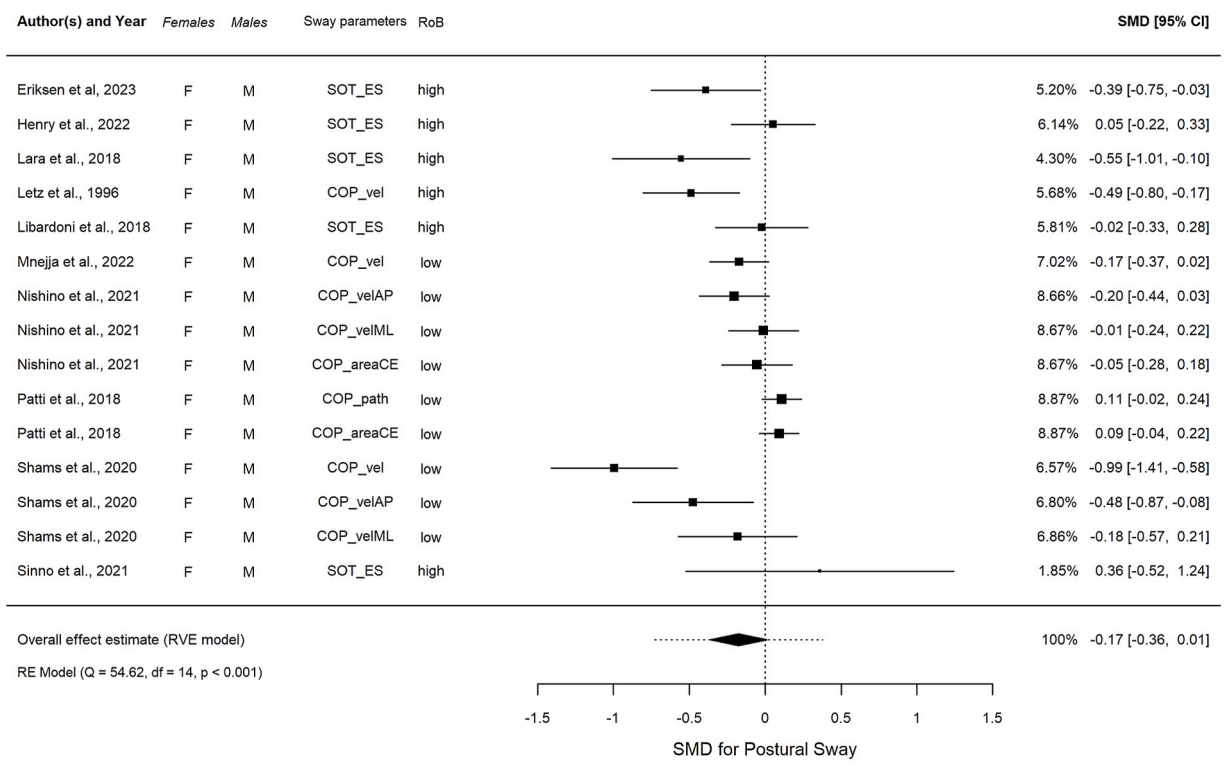


FIGURE 4
Forest plot visualizing the overall effect in EO, calculated using robust variance estimation (RVE). SMD, standardized mean difference between females and males, CI, confidence interval.

there are 11 pairwise comparisons contributing both direct and indirect evidence, for none of which there is evidence of inconsistency for the EO condition (Supplementary Table S8A). However, a handful of comparisons with inconsistency for EC was observed ($p < 0.10$ refer to Supplementary Table S8B).

3.3.2.2 Effect of age within children ≤14 years

In the second subnetwork analysis, 14-year-old participants were used as the reference group. Figures 6C,D shows the second connected subnetworks for both EO (Figure 5C) and EC (Figure 5D) conditions. The most frequently examined comparisons were between 8 vs. 9, 8 vs. 10, and 9 vs. 10. Supplementary Table S7 summarizes the main results of both direct and indirect evidence and the first subnetwork meta-analysis for EO and EC. Figures 6C,D shows the relative rankings with group 14 as the reference. The lowest ranked was group 5 (SUCRA: 0.06 for EO and 0.04 for EC), followed by 4 (SUCRA: 0.13 for EO and 0.08 for EC), 3 (SUCRA: 0.19 for EO and 0.17 for EC), 6 (SUCRA: 0.21 for EO and 0.26 for EC), and 7 (SUCRA: 0.19 for EO and 0.17 for EC). The summary relative effects from the network meta-analysis are presented in league tables of each subnetwork (see bottom table, Figure 8).

In the EO condition, children aged between 3 and 7 years swayed significantly more than the reference group 14 (EO: SMD range 1.00–1.78). Between 3 and 6 years of age group, children were more instable than older groups: 9 years (EO: SMD range 0.93–1.36), 10 years (EO: SMD range 0.90–1.33), 11 years (EO: SMD range 1.0–1.50), 12 years (EO: SMD range 1.26–1.68), and 13 years (EO: SMD range 1.38–1.80). A statistically significant difference was also found for the group of age 7 years compared to that of 11 years (EO: SMD = 0.73, 95% CI: 0.03, 1.42), 12 years (EO: SMD = 0.91, 95% CI: 0.23, 1.59) and 13 years (EO: SMD = 1.03, 95% CI: 0.34, 1.72). A significant difference was also observed between groups 5 vs. 7 for EO (SMD = 0.77, 95% CI: 0.03; 1.51). For children aged 8 years, a significant difference was reported compared to the younger children for EO (SMD for the age group of 4–6 years range 0.87–1.10) and to group 13 years (SMD = 0.70, 95% CI: 0.01, 1.39). Children aged 5 years swayed significantly more than those aged 7 for EO (SMD = 0.77, 95% CI: 0.03, 1.51).

In EC condition, children aged between 3 and 7 years swayed significantly more than the reference group of age 14 years (EC: SMD range 0.75–1.56). Between 3 and 6 years of age, children were more instable than the older groups of age 9 years (EC: SMD range 0.65–1.15), 10 years (EC: SMD range 0.44–0.94), 11 years (EC: SMD range 0.78–1.28), and 12 years (EC: SMD range 0.86–1.35), and 13 years (EC: SMD range 0.80–1.30). A statistically significant difference was also found for the age group of 7 years compared to 11 years (EC: SMD = 0.47, 95% CI: 0.09, 0.86), 12 years (EC: SMD = 0.55, 95% CI: 0.18, 0.91), and 13 (EC: SMD = 0.49, 95% CI: 0.12, 0.87). A significant difference was also observed between younger children and the age group of 7 years for EC (SMD for groups 3–6 years range 0.31–0.81). A significant difference was reported for children aged 8 years compared to older children (EC SMD for 11–12) range 0.27–0.34 and 14 (EC SMD = 0.55, 95% CI: 0.03, 1.06). Children aged 5 years swayed significantly more than the age group of 3 years for EC (SMD = −0.29, 95% CI: −0.57, −0.02). A significant difference was observed between age groups 7 and 9 years (SMD = 0.34, 95% CI: 0.00, 0.69) as well as between age groups 10 years and older children (SMD for 12–14 years range 0.36–0.62).

The heterogeneity and global inconsistency were significantly high for EO (I2 = 79.8, 95% CI: 70.2, 86.3%, $\chi^2 = 104.06$, $df = 21$, $p < 0.0001$)

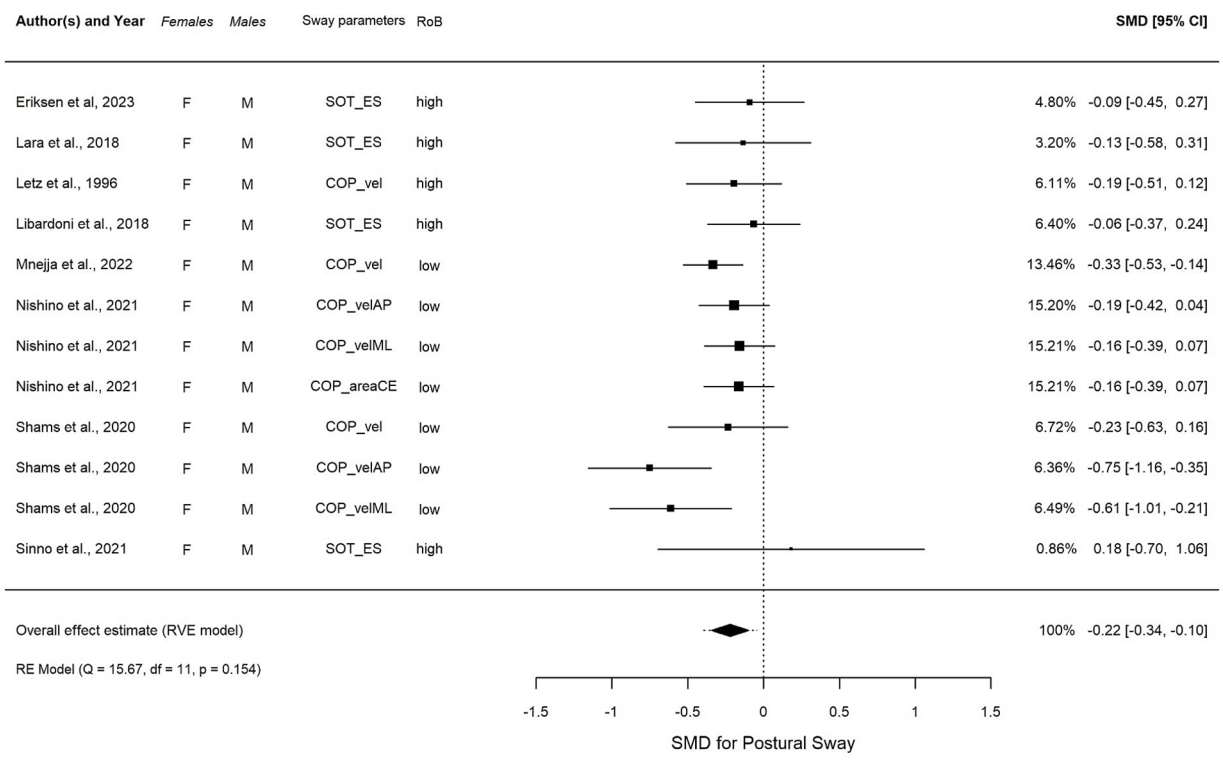


FIGURE 5
(A–D) Forest plot visualizing the overall effect in EC, calculated using robust variance estimation (RVE). SMD, standardized mean difference between females and males; CI, confidence interval.

and low for EC (I2 = 35.4, 95% CI: 0, 61.5%, $\chi^2 = 32.53$, $df = 21$, $p = 0.0517$). Inconsistency between designs appeared to be an issue in this subnetwork ($p < 0.0001$ for EO and EC). The results for detaching single designs show that the between-design heterogeneity can largely be traced back to the comparison of 4 vs. 5 for EO ($\chi 2 = 46.45$, $df = 4$, $p < 0.0001$) and EC ($\chi^2 = 15.90$, $df = 4$, $p < 0.0001$). Results for the full design-by-treatment interaction model show evidence of inconsistency between designs for EO ($\chi^2 = 91.11$, $df = 5$, $p < 0.0001$) and for EC ($\chi^2 = 26.72, df = 5, p < 0.0001$). Supplementary Tables S8C,D. summarizes the local inconsistency between direct and indirect evidence using the SIDE method for EO and EC. The results show 47 pairwise comparisons contributing both direct and indirect evidence. There is evidence of inconsistency for a few comparisons among age groups (in years) ($p < 0.10$ for 3 vs. 4, 3 vs. 5, 4 vs. 6, 5 vs. 8 for EO, and 5 vs. 7 for EC).

3.3.2.3 Certainty of evidence

We estimated within-trial bias as the weighted average of the overall risk of bias and reporting bias was considered of some concern in the first subnetwork. Furthermore, we had no concerns about indirectness, and a clinically significant threshold was SMD = 0.20. For EO, no concern was reported about incoherence because no comparison had a global or local inconsistency. The certainty of the evidence was low or very low for the majority of the comparisons, mainly due to within-study bias and reporting bias (Supplementary Table S9A). For EC, some concerns were reported about incoherence because some comparisons had a global or local inconsistency. The certainty of the evidence was low or very low for the majority of the comparisons, mainly due to within-study bias and reporting bias (Supplementary Table S9B).

We estimated within-trial bias as the weighted average of the overall risk of bias, and reporting bias was considered low in the second subnetwork. Furthermore, we had no concerns about indirectness, and a clinically significant threshold was SMD = 1.0. We were concerned about incoherence because a few comparisons had a global or local inconsistency. The certainty of the evidence was low or very low for majority of the comparisons, mainly due to within-study bias and incoherence (Supplementary Table S9C). For EC, the certainty of the evidence was moderate or low for majority of the comparisons, mainly due to within-study bias and incoherence (Supplementary Table S9D).

3.3.2.4 Publication bias

There was no clear evidence of publication bias according to a cluster robust Egger's test for EO of sex comparisons ($p = 0.46$). For the funnel plot, see Supplementary Figure S3. We could not run this analysis for EC of sex comparisons after excluding the influential outliers (≥10 needed).

4 Discussion

4.1 Summary of main results

This review aimed to map age and gender-related reference values in a healthy population, assessed by computerized posturography in static and dynamic conditions, and discuss the strengths and limitations of these norms to outline future perspectives and needs. To the best of our knowledge, this work represents the first attempt to synthesize the literature on normative

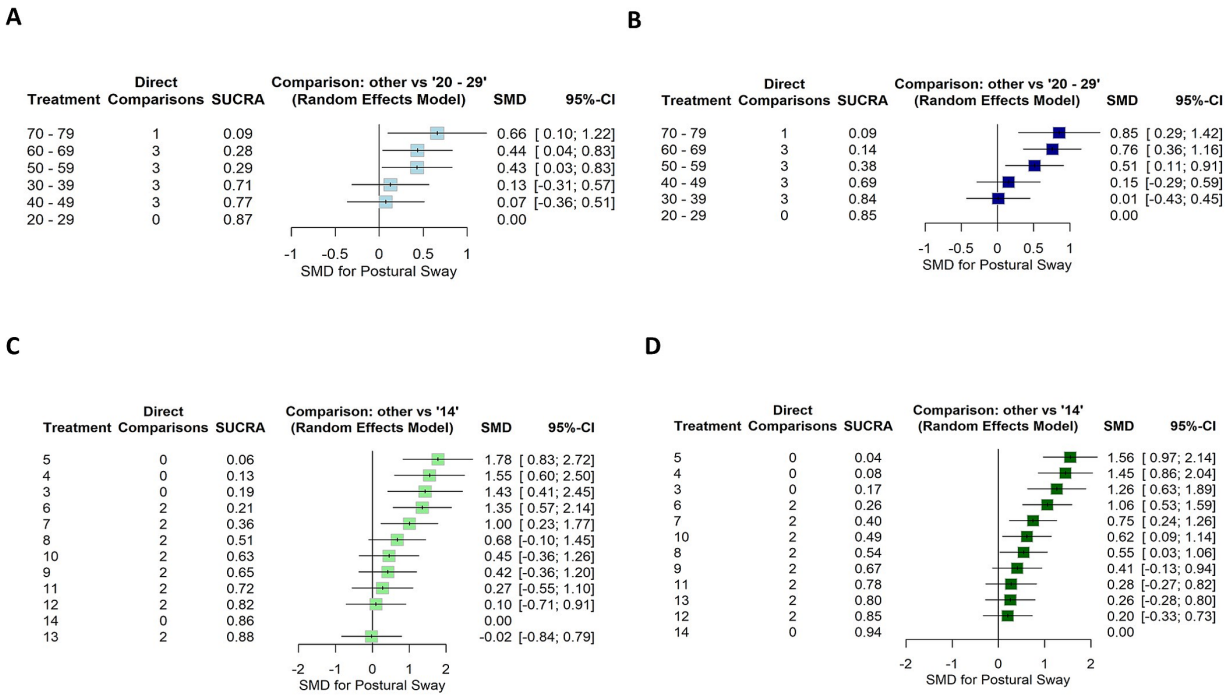


FIGURE 6
Forest plot showing the SUCRA ranking and effect estimates for EO (left) and EC (right) conditions. **(A,B)** The age group 20–29 years was used as a reference for the first subnetwork analysis. **(C,D)** The age group 14 years was used as a reference for the second subnetwork analysis. SMD, standardized mean difference; CI, confidence intervals.

data for computerized posturography using a combined mixed method. The main findings of this systematic review are as follows: (1) Extensive heterogeneity was found in methodological characteristics, (2) there was insufficient risk of bias mitigation, (3) the majority of tasks evaluated less than four components of the SFPC, and (4) studies mostly used distance domain sway parameters and did not report the influence of other variables on postural sway.

Furthermore, we conducted quantitative analyses on the age- and sex-stratified data from these sway parameters of studies with similar interventions, comparisons, and groups. We included 17 studies for sex and age comparisons, involving 5,194 participants (females: 2,630; males: 2,564), in the multilevel or network meta-analyses. We could only conduct quantitative analysis for EO and EC conditions as there was an insufficient number of studies for other conditions. Based on the multilevel meta-analyses, females appeared to significantly outperform males in EC conditions. A significant difference was observed only in EC condition. Based on the network meta-analyses, we found a significant difference in sway among individuals between 50 and 79 years of age and younger individuals, with more instability observed in older participants in both EO and EC conditions. The results also revealed that younger children swayed significantly more than those aged between 8 and 14 years in EO condition. In EC condition, older children were significantly more stable than those aged 8 years and younger.

4.2 Methodological characteristics

We were able to draw some conclusions on methodological characteristics of normative data assessed by computerized posturography. Experimental standardization and reporting are lacking, leading to a low risk of bias mitigation. Specific details are provided in the following.

Only a few studies provided age-stratified reference values. However, some reported values per biological age, decade, or academic level, which made their comparison difficult. We also observed that various tasks and sway parameters were used, leading to semantic heterogeneity. The performances were most often evaluated through distance domain features. However, some questions have been raised about the relevance and reliability of these parameters (Hébert-Losier and Murray, 2020; Ruhe et al., 2010). Hébert-Losier and Murray (2020) found that the sway area and path of the center of pressure appeared to be the most reliable. However, an evaluation of the quality of the studies revealed that only four had good methodological quality. We also found that measurement conditions varied largely regarding arm and foot position, use of visual target, the number and duration of trials, and sequence of the conditions. The majority of studies did not report the influence of other variables (i.e., height, weight, foot placement) on postural sway. These factors need to be considered as they may influence postural control (i.e., anthropometric characteristics) (Chiari et al., 2002), feet positioning (Gibbons et al., 2019), and physical activity (Lelard and Ahmaidi, 2015). These discrepancies highlight methodological disparities that may impact the generalizability of these normative data. These findings agree with systematic reviews by Verbecque et al. (2016a,b) and Quijoux et al. (2020), where a need for standardization in posturography assessment was recommended for reliable and conclusive results.

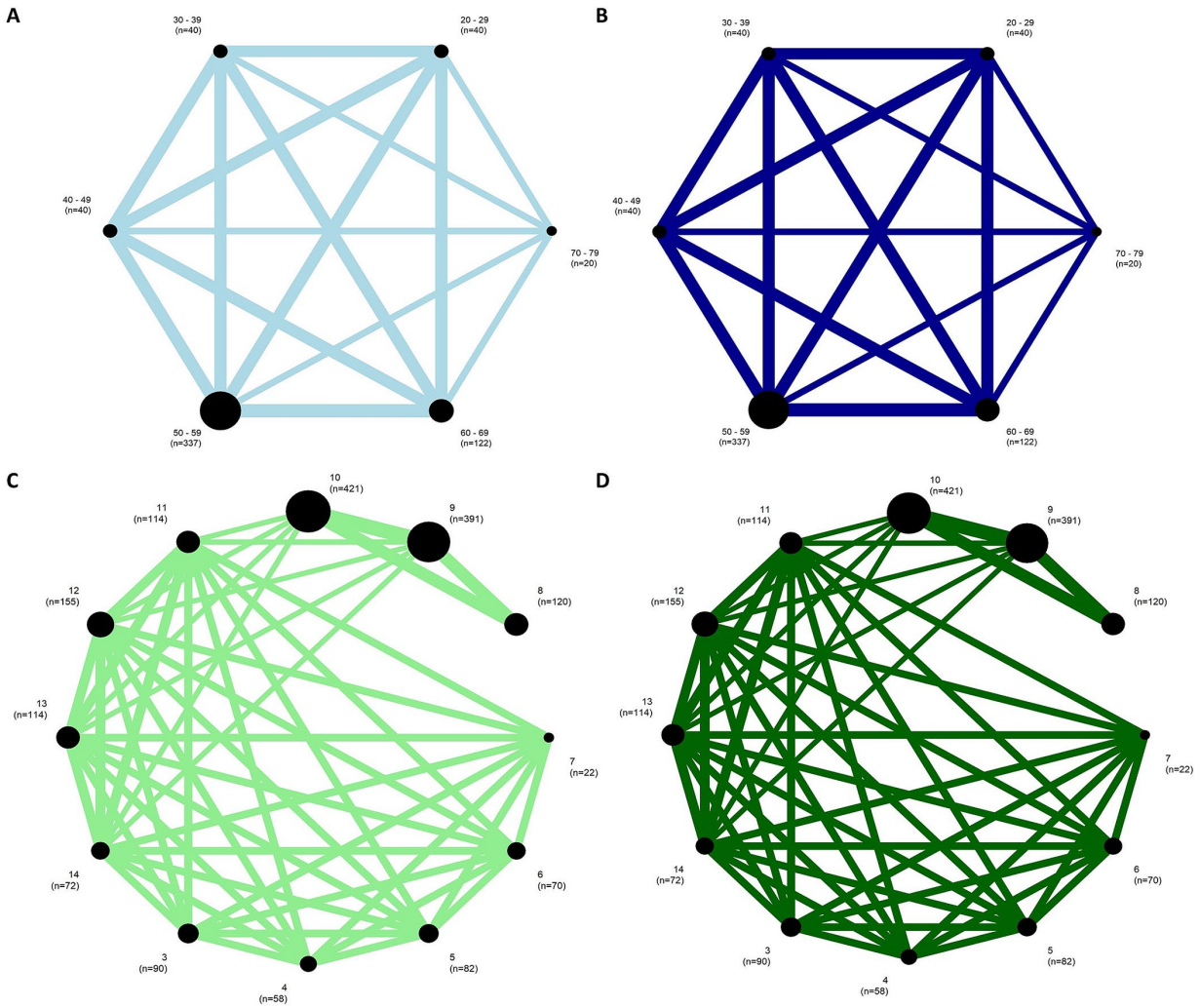


FIGURE 7
Network plots for EO condition (left) and EC condition (right) of the **(A,B)** first and **(C,D)** the second subnetworks. The width of the lines represents the number of studies comparing each pair of groups. The size of the circle represents the sample size in each arm.

Overall, participants in the included studies mostly represented regular individuals, with approximately equal numbers of females and males. The sample population largely consisted of children and young adults combined. Only a few studies investigated postural sway in elderly adults (Eriksen and Hougaard, 2023; Goble and Baweja, 2018b; Masui et al., 2005; Nishino et al., 2021; Perucca et al., 2021; Trueblood et al., 2018), as well as specific athletic (Goble et al., 2019b; Krityakiarana and Jongkamonwiwat, 2016; Massingale et al., 2018; Matsuda et al., 2010; Scaglioni-Solano and Aragón-Vargas, 2014; Schmidt et al., 2012; Weismiller et al., 2021) and military cohorts (Henry et al., 2022; Pletcher et al., 2017; Roberts et al., 2021). Age-related declines in balance have been widely reported in adults (Eriksen and Hougaard, 2023; Goble and Baweja, 2018b; Kollegger et al., 1992; Masui et al., 2005; Nishino et al., 2021; Perucca et al., 2021), yet few normative data are available on the geriatric population. This first observation demonstrated the under-representativeness of older adults, a critical gap given that this population is significantly more vulnerable to postural decline and related health issues. Older adults experience age-related changes in sensory, neuromuscular, and cognitive systems, which collectively impact balance and increase the risk of falls and injury. The research gap not only hinders the generalizability of findings to this high-risk group but also leaves clinicians without age-specific data that could inform tailored assessment, prevention, and treatment strategies. Additionally, this cohort did not include reference values for specific populations, such as athletes or military personnel, who may be at higher risk of developing balance impairments. Highly active individuals such as athletes and service members are at high risk of concussion, which can lead to functional impairments (Massingale et al., 2018). Highly active individuals, such as athletes and service persons, are at high risk of concussion that can lead to functional impairments (Massingale et al., 2018). As noted by Pletcher et al. (2017), differences in postural control can be observed across different military branches of the United States Special Operations Forces. The authors suggested that their training, mission environment, and equipment could have impacted their performances. Thus, reference values from civilian populations may not reflect the postural control of highly trained athletes or military personnel with higher and varying physical capacities. Age and sex-related reference values.

Sex-related instability has also been observed and appeared to be condition-dependent. We found that females were more stable than males in EC conditions. This has been corroborated in previous studies, which suggested that better control in females could be explained by

A

70 - 79	0.09 [-0.43; 0.62]	0.34 [-0.18; 0.86]	**0.70 [0.14; 1.26]**	**0.84 [0.28; 1.40]**	**0.85 [0.29; 1.42]**
0.22 [-0.30; 0.75]	60 - 69	**0.25 [0.03; 0.46]**	**0.61 [0.21; 1.00]**	**0.75 [0.35; 1.15]**	**0.76 [0.36; 1.16]**
0.23 [-0.29; 0.75]	0.01 [-0.21; 0.22]	50 - 59	0.36 [-0.04; 0.76]	**0.50 [0.10; 0.90]**	**0.51 [0.11; 0.91]**
0.59 [0.03; 1.15]	0.36 [-0.04; 0.76]	0.36 [-0.04; 0.75]	40 - 49	0.14 [-0.30; 0.58]	0.15 [-0.29; 0.59]
0.53 [-0.02; 1.09]	0.31 [-0.09; 0.70]	0.30 [-0.09; 0.70]	-0.05 [-0.49; 0.39]	30 - 39	0.01 [-0.43; 0.45]
0.66 [0.10; 1.22]	**0.44 [0.04; 0.83]**	**0.43 [0.03; 0.83]**	0.07 [-0.36; 0.51]	0.13 [-0.31; 0.57]	20 - 29

EO

EC

B

3	-0.19 [-0.46; 0.09]	**-0.29 [-0.57;-0.02]**	0.20 [-0.24; 0.65]	**0.51 [0.07; 0.96]**	**0.72 [0.26; 1.18]**	**0.86 [0.37; 1.34]**	**0.65 [0.13; 1.16]**	**0.99 [0.45; 1.52]**	**1.06 [0.54; 1.58]**	**1.01 [0.48; 1.53]**	**1.26 [0.63; 1.89]**
-0.12 [-0.59; 0.35]	4	-0.10 [-0.31; 0.11]	**0.39 [0.01; 0.78]**	**0.70 [0.32; 1.08]**	**0.91 [0.51; 1.31]**	**1.05 [0.62; 1.48]**	**0.84 [0.38; 1.30]**	**1.18 [0.69; 1.66]**	**1.25 [0.78; 1.72]**	**1.19 [0.72; 1.67]**	**1.45 [0.86; 2.04]**
-0.35 [-0.81; 0.12]	-0.23 [-0.62; 0.17]	5	0.50 [0.12; 0.88]	**0.81 [0.43; 1.18]**	**1.01 [0.62; 1.40]**	**1.15 [0.72; 1.57]**	**0.94 [0.48; 1.39]**	**1.28 [0.80; 1.76]**	**1.35 [0.89; 1.81]**	**1.30 [0.83; 1.77]**	**1.56 [0.97; 2.14]**
0.08 [-0.76; 0.91]	0.20 [-0.55; 0.95]	0.42 [-0.32; 1.17]	6	**0.31 [-0.02; 0.64]**	**0.51 [0.17; 0.85]**	**0.65 [0.28; 1.02]**	**0.44 [0.06; 0.83]**	**0.78 [0.37; 1.20]**	**0.86 [0.46; 1.25]**	**0.80 [0.40; 1.20]**	**1.06 [0.53; 1.59]**
0.43 [-0.40; 1.26]	0.55 [-0.20; 1.29]	**0.77 [0.03; 1.51]**	0.35 [-0.25; 0.95]	7	0.20 [-0.11; 0.52]	**0.34 [0.00; 0.69]**	0.13 [-0.22; 0.49]	**0.47 [0.09; 0.86]**	**0.55 [0.18; 0.91]**	**0.49 [0.12; 0.87]**	**0.75 [0.24; 1.26]**
0.75 [-0.08; 1.59]	**0.87 [0.12; 1.63]**	**1.10 [0.35; 1.85]**	**0.68 [0.07; 1.29]**	0.33 [-0.26; 0.92]	8	0.14 [-0.22; 0.50]	-0.07 [-0.44; 0.29]	**0.27 [-0.13; 0.67]**	**0.34 [-0.03; 0.72]**	0.29 [-0.09; 0.67]	**0.55 [0.03; 1.06]**
1.01 [0.16; 1.87]	**1.13 [0.36; 1.90]**	**1.36 [0.59; 2.13]**	**0.93 [0.31; 1.56]**	0.59 [-0.03; 1.20]	0.26 [-0.36; 0.87]	9	-0.21 [-0.60; 0.18]	0.13 [-0.29; 0.55]	0.20 [-0.19; 0.60]	0.15 [-0.26; 0.55]	0.41 [-0.13; 0.94]
0.98 [0.03; 1.93]	**1.10 [0.23; 1.97]**	**1.33 [0.46; 2.20]**	**0.90 [0.20; 1.60]**	0.55 [-0.12; 1.23]	0.23 [-0.46; 0.91]	-0.03 [-0.73; 0.66]	10	0.34 [-0.07; 0.75]	**0.41 [0.03; 0.80]**	**0.36 [-0.04; 0.76]**	**0.62 [0.09; 1.14]**
1.16 [0.20; 2.12]	**1.28 [0.39; 2.16]**	**1.50 [0.62; 2.39]**	**1.08 [0.36; 1.79]**	**0.73 [0.03; 1.42]**	0.40 [-0.30; 1.10]	0.14 [-0.57; 0.86]	0.18 [-0.56; 0.92]	11	0.07 [-0.34; 0.49]	0.02 [-0.41; 0.44]	0.28 [-0.27; 0.82]
1.33 [0.38; 2.28]	**1.45 [0.58; 2.33]**	**1.68 [0.81; 2.55]**	**1.26 [0.55; 1.96]**	**0.91 [0.23; 1.59]**	0.58 [-0.11; 1.26]	0.32 [-0.38; 1.02]	0.35 [-0.37; 1.08]	0.18 [-0.56; 0.92]	12	-0.06 [-0.46; 0.35]	0.20 [-0.33; 0.73]
1.45 [0.50; 2.41]	**1.57 [0.69; 2.45]**	**1.80 [0.92; 2.68]**	**1.38 [0.67; 2.08]**	**1.03 [0.34; 1.72]**	**0.70 [0.01; 1.39]**	0.44 [-0.26; 1.15]	0.47 [-0.26; 1.21]	0.30 [-0.45; 1.05]	0.12 [-0.61; 0.85]	13	0.26 [-0.28; 0.80]
1.43 [0.41; 2.45]	**1.55 [0.60; 2.50]**	**1.78 [0.83; 2.72]**	**1.35 [0.57; 2.14]**	**1.00 [0.23; 1.77]**	0.68 [-0.10; 1.45]	0.42 [-0.36; 1.20]	0.45 [-0.36; 1.26]	0.27 [-0.55; 1.10]	0.10 [-0.71; 0.91]	-0.02 [-0.84; 0.79]	14

EO

EC

FIGURE 8
Net league tables for the EO and EC conditions of first subnetwork (upper) and second subnetwork (lower). Relative effect estimates for the contrasts between the different intervention and control arms for the EO condition (lower triangle) and the EC condition (upper triangle). Statistically significant effects are shown in bold letters and highlighted in white cells. SMD, standardized mean difference; CI, confidence intervals.

physiologic and morphologic characteristics (Farenc et al., 2003; Kollegger et al., 1992). In EO condition, such differences are not observed due to the stabilizing effect of vision on postural sway in males.

Adults become more instable with age due to a natural decline in sensory systems' functioning, which are less accurate and slower (Hageman et al., 1995). Eriksen and Hougaard (2023) demonstrated a progressive decline in SOT composite scores between healthy individuals aged over 70 and those aged between 20–39 years. Similarly, Perucca et al. (2021) and Cohen et al. (1996) demonstrated an influence of age on the scores of the same test. Their participants were divided into two older age groups: 80–84 and 85–89 years. The results revealed a significant effect of age on balance and sensory systems. These authors demonstrated that balance becomes less stable after the age of 85 years, and more marked changes were observed during vestibular-perturbed conditions. These age-related changes appeared more pronounced with sex as females were more stable (Goble and Baweja, 2018b; Kollegger et al., 1992; Masui et al., 2005). These results on the effect of age are corroborated by studies using other sway measures (Goble and Baweja, 2018b; Masui et al., 2005; Nishino et al., 2021).

4.3 Quality of the evidence: risk of bias and publication bias

The risk of bias in the included studies appears to be globally high. These results could be explained by the extensive variability in the methodological characteristics and lack of reporting. In fact, we found considerable evidence of heterogeneity in the sex-related comparisons for EO or in the age-related comparisons for EO in the second network involving children. We could only evaluate publication bias for EO conditions in sex-related comparisons as there was insufficient data for the other conditions and age-related comparisons. There was no clear evidence of publication bias. Overall, our confidence in the group estimates for age-related comparisons was low as we downgraded the certainty of the evidence for within-study bias and incoherence in comparisons involving children and for within-study bias and reporting bias in comparisons involving adults.

4.4 Strengths and limitations

We performed an extensive search, but some limitations must be considered. A potential limitation is the classification of some tasks and sway parameters based on definitions presented in the literature. In addition, some studies did not provide sufficient details to extract outcomes and adequately assess quality. Confidence in our results was only assessed using CINeMA (Nikolakopoulou et al., 2020), and care must be taken in interpreting these results as we included a small sample of studies in the quantitative analyses.

4.5 Implications for practice and research

This systematic review discussed the strengths and limitations of age and sex-related normative data and methodological characteristics to outline future perspectives and needs. We pointed out low methodological quality, sparse reporting, and variability in measurement characteristics. As noted, there was variability in the definition of tasks and sway parameters. The classification of these tasks showed that majority of the studies focused on static movement control (i.e., activity-based conditions), which is different from static measurement (external conditions). There is a need for reference values

in dynamic movement control-based tasks (i.e., voluntary body movements). Furthermore, there could be a benefit in exploring the movements evaluated concerning the SFPC (Sibley et al., 2015). The MCT, the ADT, and the Concussion Balance Test (COBALT) evaluated the majority of the components of the SFPC (4 items). However, only one task was used in more than three studies, the MCT. The four SFPC components evaluated in the MCT were static stability, underlying motor systems, reactive postural control, and sensory integration. This framework can be used to identify underlying postural deficits for better patient management. Therefore, there is a need to evaluate balance using standardized tasks or designing future tasks encompassing the majority of the components of the SFPC to understand the underlying postural mechanisms. This recommendation also applies to exergaming interventions in the geriatric population (Tahmosybayat et al., 2018).

From a clinical perspective, there is a need for stratified normative data that considers normal aging processes separately for children, adults, and highly active individuals. Cohen et al. (1996) demonstrated that age-appropriate reference values per decade should be used for adults as postural control continues to decline up to the ninth decade. These deficits become more pronounced in high-risk concussion populations. It has been noted that differences could be expected among biological ages as children are still in the developing stages (Verbecque et al., 2016b). Therefore, reference values per decade for adults and biological ages for children might be necessary for better comparisons in clinical practice. Furthermore, our findings appeared to suggest a turning point in children and adults. Age-related differences point to improved stability for children approximately the age of 8 years, whereas adults swayed more from middle age and upward.

5 Conclusion

In summary, our results revealed sex and age-related effects on balance, with females demonstrating more stability than males in EC conditions. In addition, we also observed that children younger than 8 years of age and adults over 50 years of age swayed more in EO condition and EC, suggesting a turning point. To improve future research and clinical applicability, we recommend that studies stratify reference values by age and sex and include detailed participant information (e.g., anthropometric data) to allow for meaningful comparisons. Standardizing experimental conditions and harmonizing sway parameters will also enhance the reliability and comparability of findings across studies. Finally, evidence-based postural impairment management requires age- and sex-related normative data to inform targeted interventions and improve outcomes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AJ: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. EV: Methodology, Writing – review & editing. SB: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnhum.2024.1498107/full#supplementary-material

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Effects of virtual reality motor games on motor skills in children with cerebral palsy: a systematic review and meta-analysis

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Background: Enhancing motor skills is crucial for the functional development of children with cerebral palsy. Virtual reality has emerged as a promising technology for rehabilitating these children.

Objective: The objective of this study was to systematically evaluate the effects of virtual reality motor games on the gross and fine motor skills of children with cerebral palsy.

Methods: A comprehensive search was conducted in databases including PubMed, ProQuest, EBSCOhost, Web of Science, and Wanfang Data, covering publications from their inception to June 1, 2024, to identify randomized controlled trials (RCTs) investigating the effects of virtual reality motor games on the gross and fine motor skills of children with cerebral palsy. The quality of the included studies was assessed using the PEDro scale, and data were analyzed with RevMan software (version 5.4).

Results: Nineteen studies involving 850 children with cerebral palsy were included. The results indicated that virtual reality motor games significantly improved gross motor skills [mean difference (MD) 1.67, 95% confidence interval (CI): 0.75–2.56; $P < 0.001$] and fine motor skills [standardized mean difference (SMD) 0.73, 95% CI: 0.30–1.16; $P = 0.00008$] in children with cerebral palsy.

Conclusions: Virtual reality motor games have the potential to significantly enhance both gross and fine motor skills in children with cerebral palsy.

Systematic review registration: https://www.crd.york.ac.uk/prospero/, PROSPERO [CRD42024558713].

KEYWORDS

virtual reality, cerebral palsy, gross motor skills, fine motor skills, children

1 Introduction

Cerebral palsy (CP) is a collection of permanent motor and postural developmental disorder, characterized by limited movement resulting from non-progressive brain abnormalities occurring during fetal or early infant development (Colver et al., 2014). As the most prevalent physical disability in childhood, CP affects approximately 1 in 500 live births (Novak et al., 2017). Typically, CP is diagnosed clinically before the age of two, based on a combination of symptoms and neurological signs such as spasticity, dyskinesia, ataxia, hyperreflexia, and, in rare cases, hypotonia (Brandenburg et al., 2019). Around

6–15% of children with CP experience involuntary movements, including athetosis and chorea, which are marked by changes in muscle tone and involuntary movements. Ataxic CP primarily presents with balance and coordination difficulties, potentially accompanied by involuntary movements and tremors of the limbs. Hypotonia, or hypotonic CP, is a rare occurrence, found in only 2% of cases, and is characterized by excessively floppy muscles (Twum and Hayford, 2004). Furthermore, over 80% of children with CP exhibit spasticity (Arneson et al., 2009). Despite being considered a non-progressive disease, the movement impairments associated with CP often become more pronounced as children grow (Jiang et al., 2024).

The development of motor skills in individuals with CP is diverse, with some children demonstrating significant progress while others continue to face challenges. Gross motor skills, which involve the use of large muscle groups for position changes and balance maintenance, and fine motor skills, which include movements of the fingers, hands, and wrists for tasks such as object manipulation, writing, and dressing, are typically less developed in children with CP compared to their normally developing peers. This is evident in various aspects of motor skill development, including strength, balance, agility, flexibility, coordination (particularly hand-eye coordination), proprioception, and reaction time. These movement disorders not only impede daily activities but can also lead to secondary musculoskeletal issues, such as hip dislocation and impaired hand function. Therefore, enhancing the movement capabilities of children with CP is crucial for improving their quality of life.

The motor rehabilitation of children with CP has garnered significant attention from a multitude of departments and governmental agencies both domestically and internationally. Among the myriads of rehabilitation technologies available, virtual reality (VR) technology distinguishes itself due to its interactive nature, patient-centric methodology, and cost-efficiency. VR constitutes an interactive computer simulation system grounded in a three-dimensional environment. This system predominantly offers users an immersive experience via auditory and visual feedback, with occasional incorporation of tactile feedback (Gorini and Riva, 2008). VR technology has gained significant traction in the field of neurorehabilitation, owing to its engaging, interactive, patient-centric, and relatively cost-effective attributes (Bargeri et al., 2023). In the context of rehabilitation, VR actively promotes the involvement of children with CP by stimulating their visual, auditory, tactile, and kinesthetic senses. This stimulation synchronizes central neural conduction with peripheral motor control, thereby contributing to their rehabilitation progress (Liu et al., 2022). Traditional rehabilitation training methods are often monotonous, leading to decreased motivation and participation, which in turn can negatively impact the effectiveness of the rehabilitation process. In contrast, highly interactive and immersive VR exercise games have been shown to enhance treatment compliance and increase the frequency of repeated movements (Zhang et al., 2024). Consequently, individuals who might be disinclined to engage in conventional CP treatments for children may prefer VR-based rehabilitation (Harris and Reid, 2005). These VR exercise games not only bolster the gross motor functions and daily living skills of children with cerebral palsy but also mitigate spasticity and elevate their quality of life. Studies indicate that VR exercise games are particularly effective in enhancing upper limb function and hand mobility, especially when used as an adjunct to traditional treatments (Soleimani et al., 2024).

The application of virtual reality (VR) technology in rehabilitation is increasingly prevalent, prompting researchers to examine its short-term and long-term impacts on the motor skills of children with cerebral palsy (CP). Studies suggest that VR rehabilitation training positively influences the upper limb motor functions of children with hemiplegic cerebral palsy. Sajan et al. (2017) conducted a study involving virtual rehabilitation training on ten children with cerebral palsy, finding an improvement in hand coordination post-training. Similarly, Juan et al. (2023) demonstrated that virtual reality rehabilitation effectively enhances upper limb functional motor skills and movement quality in children with spastic hemiplegia and cerebral palsy. These findings indicate that VR technology can rapidly improve the motor skills of children with cerebral palsy. Regarding gait training, a meta-analysis by Han Jing et al. revealed that VR rehabilitation training, when combined with conventional rehabilitation training, can significantly facilitate the recovery of lower limb function in children with cerebral palsy.

Winter et al. (2021) implemented an immersive virtual reality walking training program for 16 children aged 7–16 years, who were diagnosed with cerebral palsy. The training was conducted over a period of 4 weeks, with a frequency of 5 times per week and a duration of 30 min per session. The results indicated a significant improvement in the gross motor function test scores in area D (standing) and area E (walking, running, jumping) of the table (GMFM), compared to the baseline period. Additionally, there was a notable enhancement in walking speed, as well as hip and ankle joint mobility. These findings not only validate the short-term effectiveness of VR technology, but also suggest that its benefits are relatively enduring. Consequently, these results underscore the potential of VR technology in the rehabilitation of children with cerebral palsy, particularly in terms of enhancing motor skills and fostering long-term functional improvements (Winter et al., 2021).

Previous meta-analyses have demonstrated that VR technology can substantially improve children's gross motor function and fine motor skills (Liu et al., 2022; Ren and Wu, 2019; Abdelhaleem et al., 2022; Bell et al., 2024; Montoro-Cárdenas et al., 2022). The primary objectives of this study were to address the following questions: (1) Can the introduction of new evidence enhance the assessment of the effectiveness of VR motor games in improving motor skills in children with CP? (2) Is there a difference in the improvement of motor skills in children with CP based on different frequencies and durations of VR motor game training? (3) Do the results measured using different assessment scales affect the study's conclusions? Addressing these questions will provide a scientific basis for developing an effective VR motor game training program for children with CP.

2 Methods

This study adhered to international guidelines for conducting meta-analyses, specifically following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement, which provides a framework for selecting and applying

methods in evaluating healthcare interventions. The registration number was CRD42024558713 in the PROSPERO.

2.1 Search strategy

Two independent researchers conducted a comprehensive search of five databases: PubMed, ProQuest, EBSCOhost, Web of Science, and Wanfang Data. The objective was to identify randomized controlled trials (RCTs) that assessed the effects of virtual reality motor games on motor skills in children with cerebral palsy. This search encompassed the timeframe from the inception of each database up until June 1, 2024. In addition to this primary search, relevant systematic reviews and citations from the selected studies were also considered as supplementary sources. The search strategy incorporated both subject-specific terms and free-text keywords. Boolean operators such as "AND" and "OR" were used to effectively combine and sequence these terms, following iterative prechecks. Key search terms encompassed "virtual reality game," "exergame," "active video game," "PlayStation," "video game," "Wii," "Kinect," "children," "cerebral palsy," "little disease," "infantile palsy," "spastic diplegia," "motor skill," "gross motor skill," "fine motor skill," and "training upper extremity function."

2.2 Inclusion criteria

The inclusion criteria were as follows:

(1) Participants: Children with a clinical diagnosis of spastic CP, up to 18 years of age; no restrictions were placed on race or gender.

(2) Intervention: VR motor games or VR motor games combined with rehabilitation training.

(3) Comparison: Daily physical activity, standard or integrated rehabilitation training.

(4) Outcome: Fine motor skills were assessed using the Peabody Developmental Motor Scales-Second Edition (PDMS-2), the Manual Ability Classification System (MACS), the Multidimensional Assessment of Interoceptive Awareness Version 2- Chinese (MA-2), the Box and Block Test (BBT), the Quality of Upper Extremity Skills Test (QUEST), the Minnesota Manual Dexterity Test (MMDT), and the Nine-Hole Peg Test (NHPT). Gross motor skills were evaluated using the Gross Motor Function Measure (GMFM), including the GMFM-66 and GMFM-88, and the Movement Assessment Battery for Children - Second Edition (MABC-2).

(5) Study design: Randomized controlled trials only. The study design exclusively involved randomized controlled trials (RCTs) as the research type. This choice was informed by the unique benefits of RCTs in assessing intervention effects. Randomized controlled trials are widely recognized as the gold standard for evaluating medical interventions, primarily due to their capacity to minimize selection bias and confounding variables. By randomly assigning participants to either experimental or control groups, we ensured that both groups were comparable at baseline. This increases the probability that any observed difference in effect is attributable to the intervention itself, rather than other uncontrolled factors.

Considering the importance of early intervention, we selected subjects under 18 years old. The theory of "peak motor skill development" suggests that the age range from 1 to 12 years is a sensitive period for motor skill development, and the entire childhood period before 18 years old is a critical period for the development and evaluation of basic motor skills. Therefore, it is particularly important to intervene and evaluate children in this age range. Interventions and assessments during this time are crucial for promoting long-term motor skill development, physical health, and mental health of children. By selecting this age group and using a strict RCT design, we can obtain the most convincing evidence on the effectiveness of VR motor games and rehabilitation training combined with VR motor games in improving motor skills in children with spastic cerebral palsy.

2.3 Exclusion criteria

The exclusion criteria were implemented as follows:

(1) Studies were excluded based on titles and abstracts if they were theoretical studies, systematic reviews, or if the subjects were adults or older adults.

(2) Studies lacking a control group or those using other interventions were excluded.

(3) Articles were excluded if the outcome indicators did not meet the analysis requirements or if the outcome data were missing. In cases where studies were excluded due to insufficient data, efforts were undertaken to contact the respective authors to procure Supplementary material.

2.4 Literature screening and data extraction

Two investigators (ZX and NZ) independently extracted the basic information and outcome data for the included studies within 2 months. If there were any discrepancies between their extractions, a third researcher (JC) would discuss with them to reach a consensus. The extracted data included details such as author, publication year, country, age, sample size, and type of CP, content and frequency of intervention, and outcome indicators. The detailed tables were made by carefully reviewing and recording the relevant information in the articles that met the inclusion criteria.

2.5 Quality assessment of included studies

Two independent assessors (PM and KY) evaluated the risk of bias in the included studies using the PEDro scale. In disagreements, a third assessor (PZ) facilitated a discussion to reach a consensus. Once consensus was achieved, the assessors decided on the study quality. The evaluation considered the following 11 criteria, each worth one point: (a) eligibility criteria were clearly defined; (b) subjects were randomly allocated to groups; (c) allocation was concealed; (d) groups were similar at baseline for key outcome measures; (e) all subjects were blinded; (f) all therapists were blinded; (g) all evaluators were blinded; (h) outcome data were obtained from more than 85% of the initially assigned subjects; (i)

data for critical outcomes were analyzed using intention-to-treat when applicable; (j) statistical comparisons between groups for at least one key outcome were reported; (k) the study provided point estimates and measures of variability for at least one key outcome. The maximum score for each study was 11, with a score of 7 or higher indicating low risk of bias, 5–6 indicating moderate risk, and four or lower indicating high risk.

2.6 Data analysis

Cochrane's software (version 5.4) was used, and the PRISMA guidelines were followed. The *Q*-statistical test (*p*-value) and I^2 statistic were used to assess heterogeneity. If there was statistical heterogeneity between studies ($I^2 > 50\%$; $p < 0.10$), a random-effects model was used for meta-analysis; otherwise, a fixed-effects model was used. For gross motor skills, the results of MABC-2, GMFM-66, GMFM-88, and GMFM were combined. The data from PDMS-2, MACS, MA-2, BBT, QUEST, MMDT, and Nine-hole Peg Test were combined for fine motor skills. Therefore, the mean difference (MD) was used to calculate gross motor skills, and the standardized mean difference (SMD) was used to calculate fine motor skills. There were no significant differences in outcome variables between groups at baseline. After the study, effect sizes were calculated by comparing the scale scores of the intervention group with those of the control group. Each effect size is presented as a point estimate with a 95% confidence interval (CI). A significant difference was found between the intervention and control groups when $p < 0.05$, which means that the meta-analysis results were statistically significant.

2.7 Tools for assessment

2.7.1 Gross motor skills

(1) Gross Motor Function Measure (GMFM): GMFM is a standardized, observational assessment tool specifically designed for children with CP. It aims to quantify gross motor function over time and includes two versions: GMFM-66 and GMFM-88. These versions evaluate a child's ability to perform a range of motor tasks, including sitting, crawling, standing, and walking. The GMFM is internationally recognized as the gold standard for assessing motor disabilities, planning rehabilitation treatments, and evaluating the effectiveness of interventions in children with CP.

(2) Movement Assessment Battery for Children - Second Edition (MABC-2): The MABC-2 is a comprehensive test designed to evaluate motor proficiency in children aged 3–16 years. It assesses a wide range of movement skills, encompassing manual dexterity, aiming and catching, and balance. This tool is instrumental in identifying children with motor difficulties and tracking changes in their motor skills over time.

2.7.2 Fine motor skills

(1) Peabody Developmental Motor Scales-Second Edition (PDMS-2): The PDMS-2 is a comprehensive assessment of early childhood motor development, providing an in-depth evaluation of both gross and fine motor skills. It consists of six subtests, including reflexes, grasping, locomotion, object manipulation, and visual-motor integration, measuring the interrelated motor abilities that develop early in life.

(2) Manual Ability Classification System (MACS): The MACS is an observational tool used to classify how children with CP use their hands in daily activities. It provides a descriptive classification of manual ability in children with CP, focusing on what the child does in terms of handling objects in everyday contexts.

(3) Multidimensional Assessment of Interoceptive Awareness Version 2-Chinese (MA-2): The MA-2 is a tool for assessing interoceptive awareness, which is the ability to perceive and understand signals from within the body. This tool is relevant for understanding how children with CP perceive their own bodies and their movements.

(4) Box and Block Test (BBT): The BBT is a simple, reliable, and valid test of fine motor function, particularly for assessing manual dexterity and hand function in children with CP.

(5) Quality of Upper Extremity Skills Test (QUEST): The QUEST is a standardized assessment tool that evaluates the quality of movement of the arms and hands in children with disabilities, including those with CP.

(6) Minnesota Manual Dexterity Test (MMDT): The MMDT is a test of manual dexterity that measures the speed and accuracy of fine motor movements, particularly useful for evaluating hand function in children with CP.

(7) Nine-Hole Peg Test (NHPT): The NHPT is a widely used test for assessing fine motor function and hand dexterity, particularly useful for evaluating the effects of interventions on hand function in children with CP.

3 Results

3.1 Search results

A total of five databases were searched: PubMed ($n = 45$), ProQuest ($n = 30$), EBSCOhost ($n = 44$), Web of Science ($n = 124$), and Wanfang Database ($n = 1$). After excluding duplicates, 179 articles remained. Following an initial screening, 73 articles were retained; after a further full-text screening, 19 articles were finally included. As a result, 24 RCTs (Decavele et al., 2020; Pin and Butler, 2019; Fidan and Genç, 2023; El-Shamy and El-Banna, 2020; AlSaif and Alsenany, 2015; Bruno Arnoni et al., 2019; Ren et al., 2016; Chang et al., 2020; Chen et al., 2013; Saussez et al., 2023; Acar et al., 2016; Kanitkar et al., 2023; Jha et al., 2021; Cho et al., 2016; Avcil et al., 2021; Chiu et al., 2014; Sharan et al., 2012; Choi et al., 2021; Zhao et al., 2018) were finally included, as shown in Figure 1.

3.2 Basic characteristics of included studies

Table 1 shows the basic characteristics of the included studies. Nineteen articles covering 24 RCTs were included, including one article in Chinese and 18 in English. The publication years of the selected literature ranged from 2012 to 2023, and the publication countries included China, Saudi Arabia, Brazil, Canada, Belgium, Turkey, India, and South Korea. A total of 850 children with

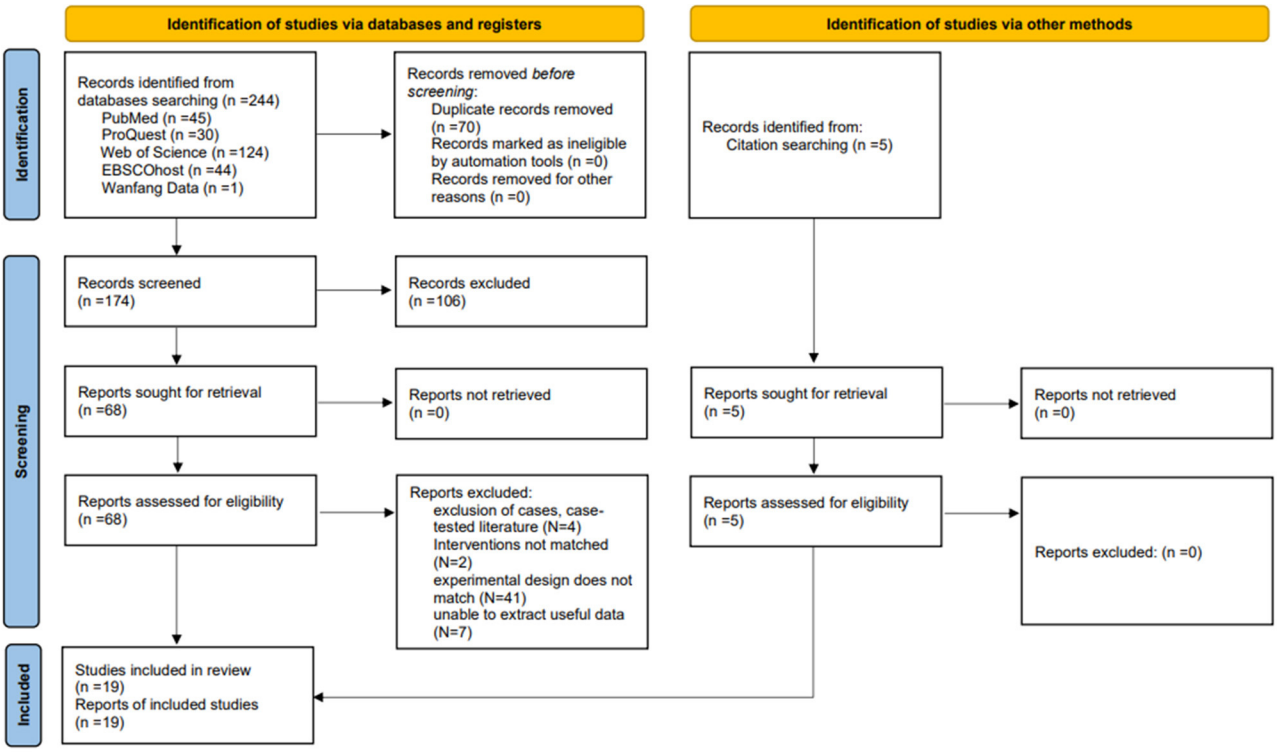


FIGURE 1
PRISMA flowchart of included and excluded studies.

CP were included in these studies, and the main types of CP included spastic diplegia and spastic hemiplegia. Interventions in the experimental group included VR training and a combination of VR training and regular rehabilitation training; the control group received interventions such as daily physical exercise or regular rehabilitation training. The duration of VR training ranged from 15 to 60 min per session, with a frequency of 2–7 sessions per week and 3 to 12 weeks.

3.3 Quality assessment of the included studies

Table 2 presents the results of the methodology quality assessment of the included studies. A total of 24 RCTs were included in this study, with methodological quality scores ranging from 5 to 10 according to the PEDro scale; higher scores indicating a lower risk of bias. Of these, 20 RCTs were assessed as being at low risk of bias, and four were assessed as being at moderate risk. All 24 RCTs described the method of generating the random sequence, and six studies (Decavele et al., 2020; Pin and Butler, 2019; Fidan and Genç, 2023; El-Shamy and El-Banna, 2020; Bruno Arnoni et al., 2019; Jha et al., 2021) depicting a detailed description of the method of allocation concealment. Seven studies (El-Shamy and El-Banna, 2020; Bruno Arnoni et al., 2019; Kanitkar et al., 2023; Jha et al., 2021; Avcil et al., 2021; Chiu et al., 2014; Choi et al., 2021) implemented blinding of subjects, and a further five studies (Pin and Butler, 2019; El-Shamy and El-Banna, 2020; Bruno Arnoni et al., 2019; Cho et al., 2016; Chiu et al., 2014) used blinding of raters. Most studies had low blinding scores due to the inherent difficulty of implementing blinding in such studies. All 24 RCTs provided complete data and were not selectively reported.

3.4 Meta-analysis

3.4.1 The effect of virtual reality motor games on gross motor skills in children with cerebral palsy

Thirteen RCTs involving 386 children with CP examined the effects of VR motor game training on their gross motor skills (Table 1). The studies assessed these skills using the MABC-2 and GMFM scales, as shown in Figure 2. The heterogeneity test results ($I^2 = 41\%$; $P = 0.06$) suggested minimal statistical heterogeneity among the studies, prompting the use of a fixed-effects model for the analysis. The meta-analysis demonstrated that VR motor game training significantly enhanced the gross motor skills of children with CP (MD = 1.67, 95% CI = 0.75–2.56; $P < 0.001$), indicating that VR training was more effective than the control group in improving gross motor skills in these children. As presented in the Table 3, the subgroup analysis categorized training frequency as $\leq$4 days per week and >4 days per week. It revealed that training more than 4 days per week significantly improved gross motor skills compared to the control group ($P = 0.001$). The training duration was divided into <8 and $\geq$8 weeks, showing that both groups experienced significant improvements in gross

TABLE 1 Basic characteristics of the included studies.

References	Country	Age (years)	Sample size (E/C)	CP type	VR intervention	Dosage	Outcome indicators
Acar et al. (2016)	Istanbul	Range 6–15	15/15	Spastic Diplegia	Nintendo Wii	15 min/d*2 d/wk*6 wk	QUEST
Avcil et al. (2021)	Istanbul	Mean:10.0 ± 3.0	15/15	Not specified	Nintendo Wii and LMC Games	60 min/d*3 d/wk*8 wk	MMDT
Chang et al. (2020)	South Korea	VR:6.08 ± 1.77 CG:4.88 ± 1.15	10/7	Not specified	RAPAEL Smart Kids	20 min/d*2 d/wk*8 wk	QUEST
Chiu et al. (2014)	China-Taiwan	Range 6–13	32/30	Spastic Diplegia	Wii Sports ResortTM	40 min/d*3 d/wk*6 wk	Nine-hole Peg Test
Choi et al. (2021)	South Korea	Mean: 5.7 ± 2.8	40/38	Not specified	RAPAEL Smart Kids	60 min/d*5 d/wk*4 wk	MA-2
El-Shamy and El-Banna (2020)	Saudi Arabia	Range 8–12	20/20	Spastic Diplegia	Nintendo Wii	40 min/d*3 d/wk*12 wk	PDMS-2
Kanitkar et al. (2023)	Canada	Range 4–10	33/30	Not specified	GRP	45 min/d*3 d/wk*16 wk	PDMS-2
Saussez et al. (2023)	Belgium	Range 5–18	20/20	Spastic Diplegia	REAtouch	Not specified	BBT
Sharan et al. (2012)	India	VR:8.88 ± 3.23 CG:10.38 ± 4.41	14/15	Not specified	Nintendo Wii fit game	–min/d*2 d/wk*3 wk	MACS
AlSaif and Alsenany (2015)	Saudi Arabia	Range 6–10	20/20	Spastic Diplegia	Nintendo Wii fit game	20 min/d*7 d/wk*12 wk	mABC-2
Bruno Arnoni et al. (2019)	Brazilian	Mean: 10 ± 3	7/8	Not specified	Xbox 360 KinectTMand Kinect sensor	45 min/d*2 d/wk* 8 wk	GMFM-88
Chen et al. (2013)	China	Range 6–12	14/13	Spastic	Eloton SimCycle	40 mim/d* 3 d/wk* 12 wk	GMFM-66
Cho et al. (2016)	South Korea	VR:10.2 ± 3.4 CG:9.4 ± 3.8	9/9	Spastic	Nintendo Wii jogging program	30 min/d * 3 d/wk* 8 wk	GMFM
Decavele et al. (2020)	Belgium	Range 6–15	14/13	bilateral spastic	MS Kinect for Windows and Nintendo Wii balance board	45 min/d*2 d/wk*12 wk	GMFM
Jha et al. (2021)	India	Range 6–12	19/19	bilateral spastic	Kinect-based virtual reality gaming	60 min/d*4 d/wk*6 wk	GMFM-88
Fidan and Genç (2023)	Istanbul	MeanVR:9.2 MeanCG:9.4	27/25	Spastic	XBox One Kinect	45 min/d*2d /8 wk*-wk	GMFM-88
Pin and Butler (2019)	China-Hong Kong	EG:8.92 ± 2.25 CG:9.59 ± 1.87	9/9	Not specified	Interactive computer play	20 min/d*4 d/wk*6 wk	GMFM-66
Ren et al. (2016)	China	Mean 55.3 ± 11.5	19/16	bilateral spastic	Q4 Situational Interactive Training System	40 min/d*5 d/wk*12 wk	GMFM-88/PDMS-2
Zhao et al. (2018)	China	VRMean: 59.38 ± 11.29 CGMean: 54.33 ± 10.93	24/24	Spastic	Xbox 360 Kinect	40m in/d*5 d/wk*3 wk	GMFM

E, experimental group; C, control group.

motor skills compared to the control group ($P < 0.00001$ and $P = 0.0007$, respectively).

3.4.2 The effect of virtual reality motor games on fine motor skills in children with cerebral palsy

Eleven RCTs involving 464 children with CP investigated the effects of VR motor game training on fine motor skills (Table 1). The results, as shown in the Figure 3, indicated significant statistical heterogeneity among the studies ($I^2 = 79\%$; $P < 0.00001$), prompting the use of a random-effects model for analysis. Subgroup analyses were conducted based on different scales to identify the source of this heterogeneity, revealing that the variability ($I^2 = 0$) in each subgroup was due to the differences in measurement scales (Figure 4). The random-effects model analysis (SMD = 0.73, 95% CI = 0.30–1.16; $P = 0.00008$) showed that VR motor game training significantly improved fine motor skills in children with CP compared to the control group. The meta-analysis results confirmed that VR motor game training effectively enhanced the fine motor skills of these children

TABLE 2 Methodological quality assessment for included studies.

References	A	B	C	D	E	F	G	H	I	J	K	Score
AlSaif and Alsenany (2015)	Yes	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	6/11
Bruno Arnoni et al. (2019) (D)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	10/11
Bruno Arnoni et al. (2019) (E)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	10/11
Chen et al. (2013)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7/11
Cho et al. (2016) (D)	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	8/11
Cho et al. (2016) (E)	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	8/11
Decavele et al. (2020)	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	7/11
Jha et al. (2021)	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	9/11
Fidan and Genç (2023)	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	8/11
Pin and Butler (2019)	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No	Yes	8/11
Zhao et al. (2018)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7/11
Acar et al. (2016)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7/11
Avcil et al. (2021)	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	8/11
Chang et al. (2020)	No	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	5/11
Chiu et al. (2014)	Yes	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	9/11
Sharan et al. (2012)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7/11
El-Shamy and El-Banna (2020)	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	10/11
Choi et al. (2021)	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	8/11
Kanitkar et al. (2023)	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes	8/11
Ren et al. (2016)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7/11
Ren et al. (2016) (D)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7/11
Ren et al. (2016) (E)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7/11
Saussez et al. (2023) (D)	Yes	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	6/11
Saussez et al. (2023) (E)	Yes	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	6/11

A. eligibility criteria were specified; B. subjects were randomly allocated to groups; C. allocation was concealed; D. the groups were similar at baseline regarding the most important outcome indicators; E. there was blinding of all subjects; F. there was blinding of all therapists; G. there was blinding of all assessors; H. measures of at least one key outcome were obtained from more than 85% of the subjects initially allocated to groups; I. all subjects for whom outcome measures were available received the treatment or, where this was not the case, data for at least one key outcome was analyzed by "intention to treat"; J. the results of between-group statistical comparisons were reported for at least one key outcome; K. the study provided both point measures and measures of variability for at least one key outcome.

(SMD = 0.73, 95% CI = 0.30–1.16; $P = 0.00008$) compared to conventional therapies.

3.4.3 Testing of publication bias

Egger and Begg funnel plots were used in the study to test for publication bias in gross motor skills and fine motor skills. Using the Egger test, publication bias was detected as $Z = 1.32$ ($Pr>|z| = 0.1874$); gross motor skill was detected as $Z = 1.52$ ($Pr>|z| = 0.1296$); and fine motor skill was detected as $Z = 0.9142$ ($Pr>|z| = 0.7555$). The publication bias detection results using the Begg test were $Z = -0.32$ ($Pr>|z| = 0.7850$); gross motor skill detection result $Z = -0.79$ ($Pr>|z| = 0.5022$); and fine motor skill detection result $Z = 0.7555$ ($Pr>|z| = 0.9142$). Therefore, there was no publication bias in this study.

4 Discussion

4.1 Principal findings

VR motor games not only offer enhanced immersion but also provide an immersive and interactive environment that can significantly enhance the engagement and motivation of children with CP during therapy (Choi et al., 2021; Chen et al., 2018). This interactive setting is particularly beneficial as it allows children to be more involved and interested in their treatment, which is crucial for the success of any therapeutic intervention (Ravi et al., 2017). This is a critical factor, as traditional therapies can often be tedious and less engaging for children (Ashwini et al., 2021). A systematic review by Feitosa et al. (2022) supports this, highlighting that VR rehabilitation induces functional improvement and brain changes that can be detected by fMRI, indicating neuroplasticity

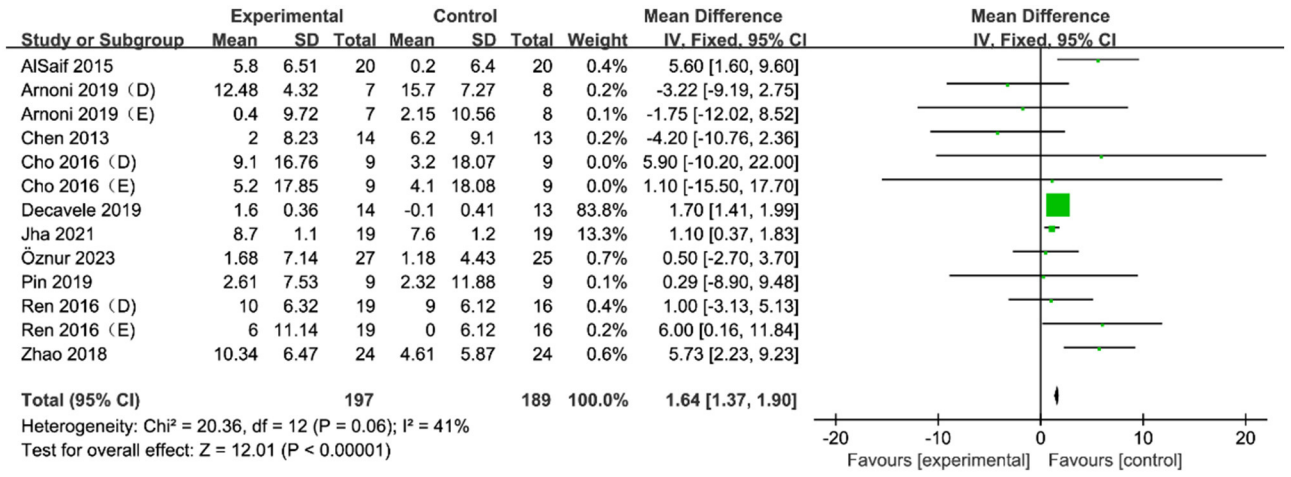


FIGURE 2
Forest plot of the effect of a VR motor game on gross motor skills in children with CP.

TABLE 3 Subgroup analysis of the effects of VR motor game training on gross motor skills in children with CP.

Group	Study, n	I^2 (%)	Model	SMD (95% CI)	*P*-value
Training frequency					
≤4 days/week	6	18	Fixed effects model	1.60 (1.33, 1.87)	<0.00001
>4 days/week	7	27	Fixed effects model	3.35 (1.63, 5.07)	=0.001
Training cycle					
<8 weeks	5	41	Fixed effects model	1.72 (1.43, 2.01)	<0.00001
≥8 weeks	8	26	Fixed effects model	1.19 (0.50, 1.88)	=0.0007

SMD, standardized mean difference.

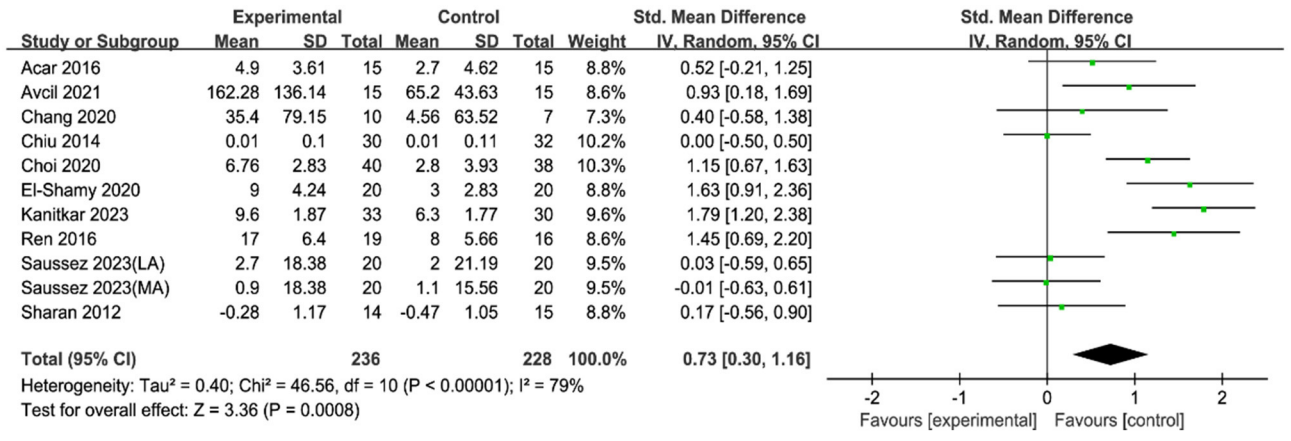


FIGURE 3
Forest plot of the effect of a VR motor game on fine motor skills in children with CP.

resulting from these treatments. Moreover, VR interventions have been shown to be equally or more efficacious than traditional treatment methods in a majority of the studies reviewed, suggesting that VR provides a promising alternative to traditional therapies.

The primary goal of this study was to thoroughly assess the effects of VR motor games compared to other therapies on gross and fine motor skills in children with CP. The analysis included 24 RCTs, all involving children diagnosed with CP. The MABC-2 and GMFM scales were used to evaluate the gross motor skills of

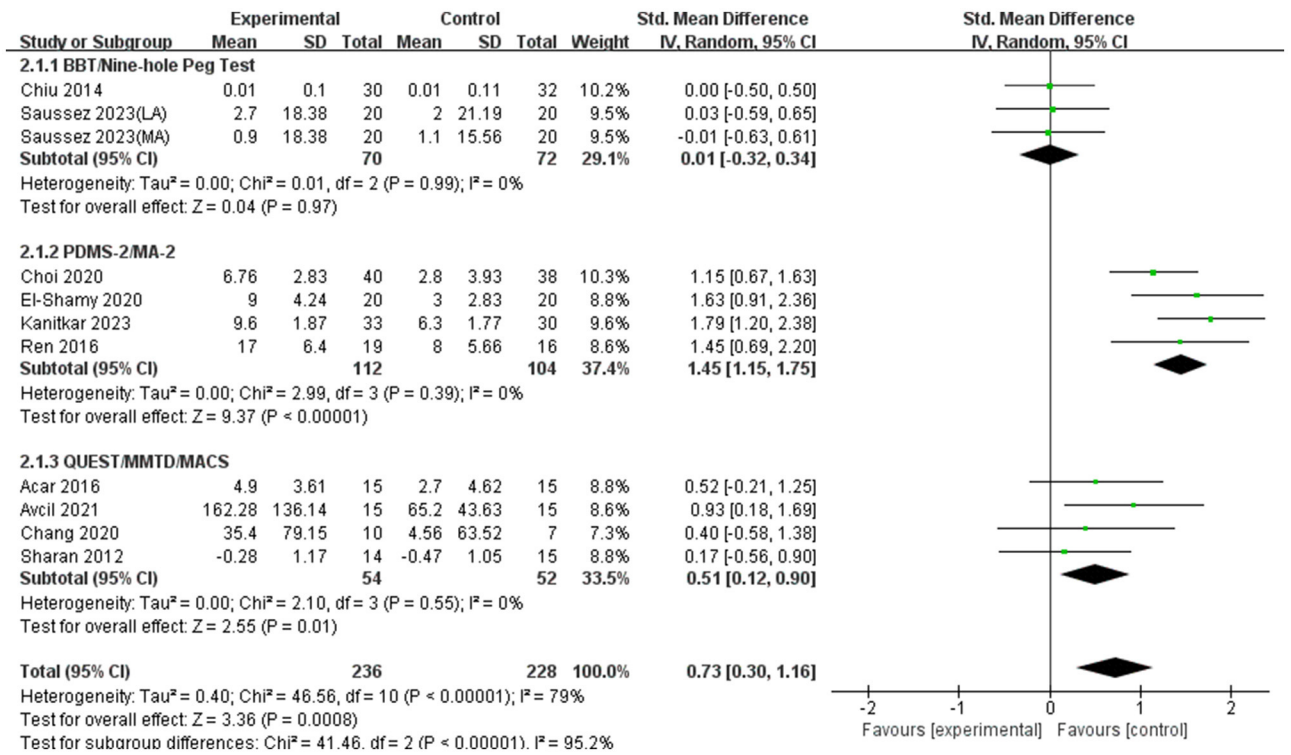


FIGURE 4
Subgroup analysis of the effects of VR motor game training on fine motor skills in children with CP.

these children. The methodological quality assessment revealed a 41% likelihood of bias, and the meta-analysis indicated a combined effect size was 1.67. This result suggests that VR motor games significantly improved gross motor skills in children with CP compared to other therapies. This finding was confirmed by a meta-analysis by Ren and Wu (2019), which systematically evaluated the rehabilitation effects of VR games on gross motor skills and found that VR games could improve these skills. Furthermore, a study by Wu et al. (2019) supports our results, showing the rehabilitative effects of VR games on balance performance among children with CP, which is closely related to gross motor skills. These studies collectively suggest that VR motor games are an effective therapeutic intervention for improving gross motor skills in children with CP, reinforcing the potential of VR as a valuable tool in pediatric rehabilitation.

Fine motor coordination is crucial for daily activities such as eating, drinking, personal care, and manipulating small objects. It is particularly important for school-aged children, who frequently engage in tasks requiring high levels of hand-eye coordination, like coloring and writing (Johansson et al., 2001; Piek et al., 2006; Kaiser et al., 2009). The study results showed significant heterogeneity among the included studies. To identify the sources of heterogeneity, a subgroup analysis was conducted, dividing the data into three groups based on the assessment scales used. Each subgroup exhibited no statistical heterogeneity, indicating that the variation in assessment scales was the primary source of heterogeneity. The combined effect size for fine motor skills was 0.73, demonstrating that VR motor game training significantly and positively affected the fine motor skills of children with CP. This outcome is supported by a systematic review and meta-analysis by Kilcioglu et al. (2023), which investigated the short- to long-term effects of therapies including VR on motor skill learning in children with CP. The review found a significant short-term effect of adding VR to conventional therapies on upper limb functions, which are closely related to fine motor skills (Kilcioglu et al., 2023). A systematic review by Abdelhaleem et al. (2022) concluded that VR seems to be effective for improving fine motor coordination, with a large effect size observed. A study by Alharbi et al. (2024) also indicated that VR interventions appear promising in children and adolescents, suggesting potential benefits in motor skill enhancement and rehabilitation, including fine motor skills.

The findings of this review confirm that VR motor games are an effective intervention for improving the gross and fine motor abilities of children with CP, which is consistent with previous studies. These findings provide a scientific foundation for the clinical application of VR in pediatric rehabilitation, and VR motor games play an important role in pediatric rehabilitation.

4.2 Limitations

While this study offers some evidence for the benefits of VR motor games in improving motor skills in children with CP, several limitations exist. The study included a limited number of RCTs, which may affect the generalizability and applicability of the results. Moreover, since the VR intervention protocols and evaluation

criteria were different for each of the studies, the comparability of findings was restricted. Even though a number of studies have shown that VR has a major effect on motor skills, more research is needed to determine the particular effects of VR on fine motor talents. A lack of long-term follow-up data is another issue with the majority of the studies that are currently in use, which leaves us with little knowledge of how long-term VR therapies will affect the long-term viability of these interventions. More high-quality, standardized RCTs should be used in future studies to corroborate these results and investigate the long-term consequences of various intervention conditions.

5 Conclusions

The findings from this systematic review and meta-analysis indicate that virtual reality motor games significantly enhance gross and fine motor skills in children with cerebral palsy. Among the 24 included RCTs, most studies demonstrated that virtual reality interventions improved motor skills more effectively than conventional rehabilitation training, primarily when conducted more than four times per week and lasting longer than 8 weeks. Nonetheless, some debate remains about the impact of virtual reality on fine motor skills in children with cerebral palsy. These results should be interpreted cautiously due to the limitations of the study methodology and the available studies.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

ZX: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. WZ: Project administration, Resources, Writing – review & editing. NZ: Data curation, Formal analysis, Writing – original draft. PM: Data curation, Formal analysis, Writing – original draft. KY: Investigation, Validation, Writing – original draft. PZ: Investigation, Validation, Writing – original draft. JL: Resources, Writing – review & editing. JC: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2024.1483370/full#supplementary-material

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The effect of instability resistance training on balance ability among athletes: a systematic review

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Background: Instability resistance training (IRT) has been the focus of extensive research because of its proven benefits to balance ability, core stability, and sports performance for athletes. However, there is a lack of systematic reviews explicitly evaluating IRT's impact on athletes' balance ability. This study aims to conduct a systematic review of the effects of IRT on balance ability among athletes.

Method: This study used guidelines for the systematic review and meta-analysis of PRISMA, Web of Science, EBSCOhost (SPORTDiscus), PubMed, Scopus, and Google Scholar to collect original references in electronic databases. The PICOS method was selected for the inclusion criteria. The physiotherapy evidence database (PEDro) scale was used to assess the scoring for articles' risk range of bias. The scoring of 20 studies ranges from 4–8, and study quality is moderate to high.

Results: Out of 285 identified studies, only 20 articles fulfilled all the eligibility criteria after screening. IRT could significantly improve reciprocal, static, and dynamic balance ability among judo athletes, basketball players, weightlifters, archery athletes, soccer players, rhythmic gymnasts, badminton players, track and field athletes, handball players, volleyball players, and gymnasts using unstable surfaces or environments (i.e., BOSU, Swiss, Wobble boards, Suspension trainer, Sissel pillows, Inflated disc and foam surface, Airex balance pad, Togu power ball, Thera-Band, Elastic band strap, Sand surface and so on).

Conclusion: The finding suggests that different types of IRT benefit athletes as this training method can effectively enhance reciprocal, static, and dynamic balance ability in athletes. Therefore, this review suggests that IRT should be considered in athletes' daily training routines for the physical fitness of reciprocal, static, and dynamic balance ability.

KEYWORDS

athletes, balance ability, BOSU and Swiss ball, instability resistance training, unstable environment

1 Introduction

Balance refers to the ability of the human body to automatically adjust and maintain a posture when subjected to external forces during rest or movement (Wulf and Lewthwaite, 2009; Zhu et al., 2014; Bliss and Teeple, 2005). In addition, balance is a fundamental condition for completing various sports skills such as athletics, ice skating, swimming, ball games, gymnastics, dance, martial arts, etc. The ability to balance is not only related to the

integrity and symmetry of the body structure but also closely related to the vestibular organs, visual organs, and proprioception of the human body (Wei et al., 2016). These three systems form the triple system of balance in the human body (i.e., the mutual correlation and close relationship between brain balance regulation, cerebellar ataxia coordination, and limb muscle strength) (Tayshete et al., 2020). So, the balance depends on the comprehensive coordination ability of the human body to stimuli from vestibular organs and proprioceptive receptors composed of muscles, tendons, joints, and visual organs.

Balance training has attracted the attention of many athletes, coaches, sports workers, and researchers. In improving athletic performance, balance ability can help athletes better unleash their physical potential (Bouteraa et al., 2020). The coordinated operation of various parts of an athlete is critical to achieving various sports performances. Balance can improve an athlete's flexibility and agility, enabling them to maintain balance in multiple parts, coordinate and react quickly, adjust body posture during exercise, promote smooth technical movements, and maximize strength and quality (Zech et al., 2010). Moreover, external motivational stimuli, such as music or verbal encouragement, have been shown to improve task performance significantly, particularly in untrained individuals. For example, endurance tasks performed under musical stimulation or verbal encouragement demonstrated increased task duration by over 15% compared to standard conditions. This enhancement is attributed to more effective motor unit recruitment, as evidenced by reduced electromyographic trend coefficients over time, suggesting greater neuromuscular efficiency (Biceps Brachii: −10.39%, Brachioradialis: −9.40%, $p < 0.001$) (Cotellessa et at., 2024). Integrating balance training with motivational stimuli could further amplify an athlete's ability to maintain posture, execute precise technical movements, and delay fatigue, fostering an environment that supports optimal performance outcomes. In terms of improving sports' competitive ability, balance ability helps athletes develop other physical fitness such as strength, speed, endurance, agility, coordination, etc., reasonably and comprehensively, reducing fatigue and allowing athletes to utilize their strength in training and competition fully (Gebel et al., 2020; Zemková, 2014). Poor body posture and uneven distribution of muscle strength can easily lead to excessive force on certain parts of athletes, resulting in sports injuries (Hrysomallis, 2007). In terms of preventing sports injuries, balance ability can improve the adaptability of athletes' body posture during exercise, provide better support and protection for joints and muscles, and minimize and reduce sports injuries and risks in high-intensity sports for athletes (Chang et al., 2020). In terms of promoting athlete health, good balance ability is not only beneficial for physical health during sports. Still, it can also improve the athlete's mental state, reduce anxiety and stress, promote physical and psychological balance, and enhance their confidence and emotional regulation ability (Schaal et al., 2011; Whitehead and Senecal, 2020).

To improve the balance ability of athletes, traditional resistance training (TRT) methods were used (Kibele and Behm, 2009; Šarabon and Kozinc, 2020). The advantage of the TRT effect is that it could significantly improve the development of enormous muscle group strength for proprioception and help refine and standardize athletes' balance ability and motor skills (Yu et al., 2008). However, TRT methods have two common disadvantages. The first is the stable training state or environment with relative support provided by the instrument or ground for TRT on land (Winwood et al., 2015). The second is in the process of TRT; the athlete's center of gravity is completed in a relatively stable state, and the athlete's muscle is fixed with one end for concentric isotonic training (Krzysztofik et al., 2019). As a consequence, the limitation of TRT is that the small muscles in the deep layer of the athletes (coordination between agonistic and antagonistic muscles) are not well recruited and activated. Nevertheless, these muscles play a crucial role in the balance ability of the human body (Sriwarno et al., 2008). Combining the above, although the TRT method can improve the balance ability of sports athletes to a certain extent, there must be a more effective training method. So, to improve the balance ability of athletes, the TRT method cannot be blindly used. Coaches can try new unstable training methods that can produce an "unstable training effect" rather than a "stable training effect" to improve athletes' balance ability (Gao et al., 2023).

Instability resistance training (IRT) is widely used in sports rehabilitation and physical fitness training. The main characteristic that distinguishes it from TRT is unstable conditions, surfaces, and environments (including specific equipment) (Norwood et al., 2007; Mehrpuya and Moghadasi, 2019). Another main difference is the load, since while TRT involves considerable loads, in IRT, given that there is instability, the loads must be reduced. Unstable surfaces, platforms, and environments can be built with professional equipment, such as Wobble Boards, Swiss or BOSU, suspended chains, foam rollers, and bands. In addition, unstable training conditions can use snow, water, sand, gravel materials, and so on (Colorado et al., 2020). The reasons for choosing IRT for athletes are as follows. Firstly, IRT is an advanced training stage that theoretically enhances muscle strength and balance ability to achieve core stability. This IRT method can activate and recruit deep and minor muscle groups and obtain proprioceptive neuromuscular sensation, thereby further enhancing the mobilization of muscle strength and balance ability (Mehrpuya and Moghadasi, 2019). Secondly, regarding unstable surfaces and environments, IRT could provide instruments for unstable surfaces or environments (For example, swing boards, Swiss, BOSU, elastic and suspension devices). Therefore, an unstable environment can not only provide athletes with instability loads and simulation to the maximum extent possible (Sekendiz et al., 2010; Cuğ et al., 2012; Xu et al., 2020).

Most studies have mentioned IRT's efficiency for athletes' balance ability. However, the IRT training method must be systematically sorted out in terms of its structural function and theoretical and practical application. With a relatively short history, a systematic review of the effectiveness of varying degrees of IRT intervention is still lacking. Therefore, this study aims to systematically review the current articles on IRT's impact on athletes' balance ability.

2 Materials and methods

2.1 Registration on INPLASY

The registration on the International Platform of Registered Systematic Review and Meta-analysis Protocols (INPLASY), the

TABLE 1 Inclusion and eligibility criteria.

PICOS	Detailed information on inclusion and eligibility criteria
Population	Healthy athletes or players cannot distinguish between age and gender
Intervention	IRT (with the different unstable surfaces), IRT+, another training format in, E.G., (not <4 weeks)
Comparison	Single (within group), multiple-group trials (between groups)
Outcome	The outcome must comprise the impact of IRT on balance ability among athletes and players
Study Design	Single-group and randomized controlled trials (RCT or CRCT)

study was assigned the registration number INPLASY2023100048, with a corresponding DOI number of 10.37766/inplasy 2023.10.0048, accessible on the platform's website: https://inplasy.com/.

2.2 Databases and keywords

This article used the following databases: Web of Science, EBSCOhost (SPORT Discussion), PubMed, Scopus, Google Scholar, and References until the end of 2023. The keywords in this study were: ("instability resistance training" OR "instability resistance exercise" OR "unstable surface training" OR "unstable training" OR "unstable surface exercise" OR "unstable exercise") AND ("balance" OR "balance ability" OR "reciprocal balance" OR "dynamic balance" OR "static balance" OR "reciprocal balance ability" OR "dynamic balance ability" OR "static balance ability") AND ("player" OR "athlete" OR "sportsman" OR "sportswoman" OR "sportsperson").

2.3 Eligibility criteria

The PICOS model was used in this study. This model has five parts of the population: intervention, comparison, outcome, and study design. The details of the inclusion criteria for the five parts are shown in Table 1.

2.4 Search, screening, and selection processes

Firstly, this article used the EndNote X8 citation management system to eliminate duplicate articles. Secondly, the authors conducted a first round of screening on the literature that met the requirements based on the title and abstract. Then, according to the complete text, they conducted a second screening round on the literature that had already been selected in the first round. Thirdly, literature that meets the standards was evaluated to determine the final reliability literature. Finally, at the seminar, all authors reached a consensus on which literature would be most selected for systematic review.

2.5 Data extraction and PEDro scale assessment

Based on reading the entire literature, the authors summarized the following content using standardized templates. In addition, this study used the PEDro scale (Verhagen et al., 1998), which has been proven reliable when building system reviews. PEDro scale is a Delphi series of scales specifically developed by Verhagen and colleagues for epidemiology. The same authors performed the statistical analysis.

3 Results

3.1 Article selection

This study employed the methodology recommended by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to systematically search, screen, and analyze pertinent data within the selected article. The procedure of identification, screening, and inclusion for the article is shown in Figure 1. Initially, the total number of 285 articles were the records identified through database searching. After preliminary removal of duplicate articles, there were 278 articles. After the first screening, 63 articles were removed, which included two articles not in English, 0 articles from unpublished journals, 59 articles reviewed, conference papers, books, chapters, and magazines, and two articles without full text. In the next screening phase, 215 eligibility articles were evaluated for full-text, 195 articles were removed, which included 94 articles that were not a training/intervention or RCT relevant study, 63 articles participants were not healthy, student and amateur athletes, 15 articles were not instability and unstable surface training intervention, and 23 articles were not balance outcome studies. In the end, there were only a total of 20 articles for quantitative synthesis that met the criteria. The detail is shown in Figure 1.

3.2 Study quality assessment

The PEDro scale includes 11 items to evaluate the quality of the method, with each item scoring only 0 and 1, with one representing yes and 0 representing no. If the literature score is higher, it indicates that the quality of the literature method is better. The quality valuation was interpreted as follows: 0–3 Points (poor), 4-5 points (moderate), 6–10 points (high). Table 2 shows the detailed scores in this study's PEDro scale of 20 articles. In all studies with a score of 4-7, the study quality is moderate to high. The detail is shown in Table 2.

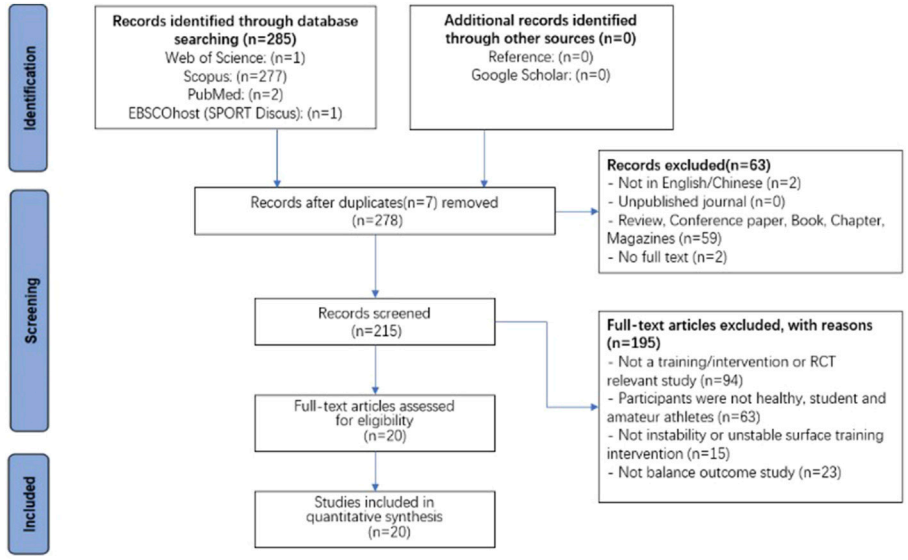


FIGURE 1
The identification, screening, and included processes for articles based on PRISMA.

TABLE 2 Summary of PEDro scale assessment scores.

N	References	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	Total PEDro Score	Study Quality
1	Norambuena et al. (2021)	1	0	0	1	0	0	0	1	0	0	1	4	Moderate
2	Thielen et al. (2020)	1	1	0	1	0	0	0	1	1	1	1	7	High
3	Kang et al. (2013)	1	1	0	1	0	0	0	1	1	1	1	7	High
4	Prasetyo et al. (2023)	1	0	0	1	0	0	0	1	0	0	1	4	Moderate
5	Makhlouf et al. (2018)	1	1	0	1	0	0	0	1	1	1	1	7	High
6	Cabrejas Mata et al. (2022)	0	1	0	1	0	0	0	1	1	1	1	6	Moderate
7	Zhao et al. (2021)	1	0	0	1	0	0	0	1	0	0	1	4	Moderate
8	Negra et al. (2017)	1	1	0	1	0	0	0	1	1	1	1	7	High
9	Romero-Franco et al. (2012)	1	1	0	1	0	0	0	1	1	1	1	7	High
10	Wee and Fatt (2019)	1	1	0	1	0	0	0	1	1	1	1	7	High
11	Hammami et al. (2022)	1	1	0	1	0	0	0	1	1	1	1	7	High
12	Hammami et al. (2023)	1	0	0	1	0	0	0	1	0	1	1	5	Moderate
13	Oliver and Brezzo (2009)	1	1	0	1	0	0	0	1	1	1	1	7	High
14	Gönener and Gönener (2020)	1	1	0	1	0	0	0	1	1	1	1	7	High
15	Zemková and Hamar (2010)	1	1	1	1	0	0	0	1	1	1	1	8	High
16	Hammami et al. (2020)	0	1	0	1	0	0	0	1	1	1	1	6	High
17	Eisen et al. (2010)	1	1	0	1	0	0	0	1	1	1	1	7	High
18	Gidu et al. (2022)	1	1	0	1	0	0	0	1	1	1	1	7	High
19	Granacher et al. (2015)	1	1	0	1	0	0	0	1	1	1	1	7	High
20	Chaouachi et al. (2017)	0	1	0	1	0	0	0	1	1	0	1	5	Moderate

Note: N1, eligibility criteria; N2, random alocation; N3, allocation concealment; N4, baseline comparability; N5, blind participants; N6, blind therapist; N7, Blind assessor; N8, Follow-Up; N9, intention to treat analysis; N10, group comparison; N11, point measure and variability. A detailed explanation for each PEDro scale item can be accessed at https://www.pedro.org.au/english/downloads/pedro-scale.

TABLE 3 Participant, intervention, and main outcome for the 20 studies.

N	Study	Subjects	Intervention							Main outcome related to balance ability
			Type of athlete	Gender	Age	Type	Instability environment	Balance ability Measured index	Frequency and duration	
1	Norambuena et al. (2021)	10	Judo athletes	Mixed: 8 Female 2 Male	15.4 ± 2.8 years	E.G.,: Instability suspension training CG: No control group	1) Suspension trainer (TRX®, United States)	Reciprocal balance test: 1) Prone instability test Dynamic balance test: 1) Y balance test	5 times/Week, 5 weeks	E.G.,: Prone instability test↔ Y balance test of right leg↑, left leg↑, right arm↑, left arm↑
2	Thielen et al. (2020)	32	Basketball player	Male	20.4 ± 1.4 years	E.G.,: Suspended load program CG: Traditional barbell load program	1) The plates suspended from the barbell using non-elastic straps	Dynamic balance test: 1) Star excursion balance test (SEBT)	4 times/Week, 6 weeks	E.G., and CG: Star excursion balance test (SEBT)↔
3	Kang et al. (2013)	32	Weightlifter	Male	MS: 14y HS: 17y	E.G.,1 (MS): Instability balance training E.G.,2 (HS): Instability balance training CG1 (MS): No training CG2 (HS): No training	1) Swiss ball	Static balance test: 1) One-leg standing with closed eyes test	Unknown times/ Week, 8 weeks	E.G.,2 (HS): One-leg standing time with eyes closed↑
4	Prasetyo et al. (2023)	12	Archery athletes	Unknown	14–17y	E.G.,: Instability suspension training CG: No control group	1) BOSU ball	Static balance test: 1) The stork stand test	18 circuit training sessions	E.G.,: Standing on one leg↑
5	Makhlouf et al. (2018)	57	Soccer player	Male	E.G.,1:11.06 ± 0.75y E.G.,2:11.29 ± 0.85y CG:10.98 ± 0.80y	E.G.,1 (BPT): Combined balance and plyometric training (instability training is a part of the program) E.G.,2 (APT): Agility-plyometric training (stable training) CG: Regular soccer training (stable training)	1)Swiss ball 2) An inflated disk 3) A foam surface progressing to a BOSU ball or inflated disk 4) Elastic band strap	Static balance test: 1) Standing stork test Dynamic balance test: 1) Y balance test	2 times/Week, 8 weeks	BTP: Standing stork ($P< 0.01$, $d = 3.17$) ↑, Y-balance ($P< 0.01$, $d = 1.48$) ↑ ATP: Standing stork ($P< 0.01$, $d = 5.53$) ↑, Y-balance ($P< 0.01$, $d = 1.20$) ↑ CG: Standing stork ($P< 0.02$, $d = 1.30$) ↑, Y-balance ($p = 0.18$, $d = 0.28$)↔
6	Cabrejas Mata et al. (2022)	44 E.G.,: 23 CG: 21	Rhythmic gymnast	Female	10.5 ± 1.8 years	E.G.,: Integrated functional core and plyometric training (instability training is a part of the program) CG: Usual training (stable training)	1) BOSU ball 2) Balance disks 3) Softballs	Static balance test: 1) Right/left support leg with eyes open test 2) Right/left support leg with eyes closed test	3 times/Week, 8 weeks	E.G.,: Right support leg with eyes open ↑; Left support leg with eyes open ↑
7	Zhao et al. (2021)	38	Badminton Player	Female	17 ± 1.1 y	E.G.,1 (HG): Integrative neuromuscular training (instability training is a part of the program)	1) BOSU ball 2) Balance board 3) Swiss ball	Dynamic balance test: 1) Single-leg side hop test	4 times/Week, 8 weeks	E.G.,1 (HG): Single-leg side hop (L) ↑, Single-leg side hop (R) ↑ E.G.,2 (LG): Single-leg

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TABLE 3 (*Continued*) Participant, intervention, and main outcome for the 20 studies.

N	Study	Subjects	Intervention							Main outcome related to balance ability
			Type of athlete	Gender	Age	Type	Instability environment	Balance ability Measured index	Frequency and duration	
						E.G.,1 (LG): Integrative neuromuscular training (instability training is a part of the program) CG: No control group				side hop (L) ↑, Single-leg side hop (R) ↑
8	Negra et al. (2017)	33	Soccer player	Male	PTS: 12.1 ± 0.5 years PTC: 12.2 ± 0.6 years	E.G.,: Unstable performed combined plyometric training (PTC) CG: Stable performed plyometric training (PTS)	1) Airex balance pad 2) Thera-Band stability trainer	Static balance test: 1) SSBT, stable stork balance test 2) USBT, unstable stork balance test	3–5times/Week, 8 weeks	Between-group (post-test) SSBT↔, USBT ↑
9	Romero-Franco et al. (2012)	33	Sprinter	Male	21.82 ± 4.84 years	E.G.,: Proprioceptive training program on BOSU and Swiss ball CG: A shorter duration training	1) BOSU and Swiss ball	Reciprocal balance test: 1) Stability Test with Eyes Open and Closed; 2) Postural Stability; 3) Gravity Center Control	3 times/Week, 6 weeks	Between-group (post-test): XEO↑, Position of the gravity center in the posterior direction ↑, Position of the gravity center in the right direction ↑
10	Wee and Fatt (2019)	19	Soccer Player	Male	20 ± 1.73 years	E.G.,: Soccer program supplementary Swiss Ball Training (SBT) CG: Soccer program	1) Swiss Ball	Static balance test: 1) Standing Stork Test (SST)Dynamic balance test: 1) Four Step Square Test (FSST)	2 times/Week, 6 weeks	Between-group (post-test): SST↔, FSST↑
11	(M. Hammami et al., 2022)	42	Handball player	Male	E.G.,: 16.4 ± 0.4 years CG: 16.2 ± 0.4 years	E.G., (JSTG): Supplemental jump and sprint exercise training on sand CG: Standard in-season regimen	1) On sand	Static balance test: 1) Standing stork test Dynamic balance test: 2) Y balance test	3 times/Week, 7 weeks	E.G., (JSTG): Y balance test for the right leg and left leg↑, Stork balance (right leg) ↑
12	(R. Hammami et al., 2023)	32	Pre-pubertal weightlifter	Male	10.94 ± 0.47 years	E.G., (IRT1): Instability resistance training, 2 sets x 8, 20% (1RM) E.G., (IRT2): Instability resistance training, 2 sets x 4, 40% 1RM CG: No control group	1) Airex Balance Beam 2) Airex Balance Pad, 3) Thera-Band Stability Trainer 4) Togu Aero Step	Reciprocal balance test: 1) CoP displacements of the center of pressure oscillation test	5 times/Week, 8 weeks	E.G., (IRT1): CoP SA↑, CoP X↑, CoP Y↑, CoP V↑ E.G., (IRT2): CoP SA↑, CoP X↑, CoP Y↑, CoP V↔
13	Oliver and Brezzo (2009)	26	Volleyball and Soccer player	Female	Volleyball: 19.9 ± 1.8 years Soccer player: 18.5 ± 0.5 years	E.G.,: Functional balance training for volleyball player CG: No intervention for soccer player	1) The Indo Board 2) Flow cushion	Static balance test: 1) Biodex balance test	4times/Week, unknown weeks	E.G., (Volleyball player): Biodex (right) ↔, Biodex (left) ↔ CG (Soccer player): Biodex (right) ↔, Biodex (left) ↔

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TABLE 3 (*Continued*) Participant, intervention, and main outcome for the 20 studies.

N	Study	Subjects	Intervention							Main outcome related to balance ability
			Type of athlete	Gender	Age	Type	Instability environment	Balance ability Measured index	Frequency and duration	
14	Gönener and Gönener (2020)	40	Gymnast	Female	7 years old	E.G.,: Unstable surface training CG: Stable surface training	1) BOSU ball 2) Balance board 3) Sponge 4) Trampoline	Dynamic balance test: 1) Tecno-body ProKin PK200 model dynamic balance test	3times/Week, 8 weeks	E.G.,: PL↑, AGP↑, MS↑, AP↑, ML↔ CG: PL↔, AGP↔, MS↔, AP↔, ML↔
15	Zemková and Hamar (2010)	34	Basketball player	Female	E.G.,: 20.9 ± 2.4 years CG: 21.2 ± 2.8 years	E.G.,: Combined agility-balance training on wobble boards CG: Combined agility-balance training on stable surface	1) Wobble boards	Static balance test: 1) Eyes open and closed Bipedal stance on stable platform 2) Eyes open and closed Bipedal stance on wobble boards	4–5times/Week, 6 weeks	E.G.,: Bipedal stance on wobble board with eyes open and closed↓
16	Hammami et al. (2020)	31	Handball player PS:11 P:10 C:10	Male	PS: 16.2 ± 0.6 P: 16.4 ± 0.5 C: 16.5 ± 0.4	E.G., (PS): plyometrics training on sand surface CG (P): Standard plyometrics training on a stable surface CG (C): A standard in season regimen	1) On sand surface	Dynamic balance test: 1) Y Balance Test Static balance test: 2) Stork Balance Test	3 times/Week, 7 weeks	*Y Balance Test* E.G., (PS): right leg, RL/L↑, RL/B↑, RL/R↔; left leg, RL/L↔, RL/B↑, RL/R↔;CG (P): right leg, RL/L↑, RL/B↑, RL/R↔; left leg, RL/L↔, RL/B↑, RL/R↑;CG (C): right leg, RL/L↔, RL/B↑, RL/R↔; left leg, RL/L↔, RL/B↑, RL/R↔ *Stork Balance Test:* E.G., (PS): right leg↑; left leg↑ CG (P): right leg↑; left leg↑ CG (C): right leg↑; left leg↑
17	Eisen et al. (2010)	36	Volleyball and Soccer players	Mixed: Female and Male	18–22 years	E.G., (DD): Balance training with uniaxial on a rocker board E.G., (RB): Balance training with multiaxial on a dynadisc CG (CON): No training	1) Uniaxial on a rocker board [RB] 2) Multiaxial on a dynadisc [DD]	Dynamic balance test: 1) Star excursion balance test (SEBT)	3 times/Week, 4 weeks	Between-group E.G.,(DD), E.G., (RB) and CG (CON) differences at post-test: SEBT↑
18	Gidu et al. (2022)	96	Soccer player	Male	E.G.,: 14.2 ± 0.4 years CG: 14.0 ± 0.0 years	E.G.,: Proprioceptive training on Bosu ball CG: Normal program	1) BOSU ball	Static balance test: 1) Single-leg stance 2) Double-leg stance 3) Tandem stance 4) Total BESS score	4 times/Week, 8 weeks	E.G.,: 1) Single-leg stance↑ 2) Double-leg stance ↑ 3) Tandem stance↑ 4) Total BESS score↑
19		24	Soccer players	Male	15 ± 1 year					

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TABLE 3 (*Continued*) Participant, intervention, and main outcome for the 20 studies.

N	Study	Subjects	Intervention							Main outcome related to balance ability
			Type of athlete	Gender	Age	Type	Instability environment	Balance ability Measured index	Frequency and duration	
	Granacher et al. (2015)					E.G.,: Unstable plyometric training (IPT) CG: Stable plyometric training (SPT)	1)Balance beam, pad, Airex® 2)Stability trainer, Thera-Band® 3)Togu® Aero Step	Static balance test: 1) One-legged balance test Dynamic balance test: 1) Star excursion balance test (SEBT)	2 times/Week, 8 weeks	E.G.,: Star excursion balance test (SEBT) ↑
20	Chaouachi et al. (2017)	26	Soccer players	Male	13.9 ± 0.3 years	E.G., (ABPT): Alternated balance and plyometric exercises with unstable surface E.G., (BBPT): Balance and plyometric exercises with unstable surface	1) BOSU and Swiss ball 2) Inflated disc and foam surface	Static balance test: 1) Stork stands balance protocol Dynamic balance test: 1) Y balance test	2 times/Week, 8 weeks	E.G., (ABPT): Stork stand balance protocol↑, Y balance test ↑ E.G., (BBPT): Stork stand balance protocol↑, Y balance test ↑

Note: NR, not reported; yrs, years; Exp, sports experience; M, male; F, female; Freq, frequency; reps, repetitions; EG, experimental group; CG, control group; IRT, instability resistance training; ↑ significant within-group improvement; ↔ non-significant within-group.

3.3 Participant characteristics

Table 3 shows the characteristics of participants, intervention, and outcomes for the 20 studies. 1) Classification by athletes. 6 articles were on soccer players (Makhlouf et al., 2018; Negra et al., 2017; Wee and Fatt, 2019; Gidu et al., 2022; Granacher et al., 2015; Chaouachi et al., 2017); basketball players of 2 articles (Thielen et al., 2020; Zemková and Hamar, 2010); handball players of 2 articles (Hammami et al., 2022; Hammami et al., 2020); weightlifters of 2 articles (Kang et al., 2013; Hammami et al., 2023), volleyball combined soccer players of 2 articles (Oliver and Brezzo, 2009; Eisen et al., 2010), judo athletes of 1 article (Norambuena et al., 2021), archery athletes of 1 article (Prasetyo et al., 2023), rhythmic gymnasts of 1 article (Cabrejas Mata et al., 2022), badminton players of 1 article (Zhao et al., 2021), including sprinters of 1 article (Romero-Franco et al., 2012), gymnasts of 1 article (Gönener and Gönener, 2020). 2) Participant, gender, and age. The total number of athletic subjects was 664 (459 males, 157 females, and 48 no reported gender). Among the 20 studies, 18 articles reported the classification of age means, including below 10 years old in 1 article (Gönener and Gönener, 2020), 10–15 years old in 9 articles (Kang et al., 2013; Makhlouf et al., 2018; Cabrejas Mata et al., 2022; Negra et al., 2017; Hammami et al., 2023; Gidu et al., 2022; Granacher et al., 2015; Chaouachi et al., 2017; Norambuena et al., 2021), 16–20 years old of 7 articles (Zhao et al., 2021; Thielen et al., 2020; Wee and Fatt, 2019; Hammami et al., 2022; Oliver and Brezzo, 2009; Zemková and Hamar, 2010; Hammami et al., 2020), above 20 years old of 1 article (Romero-Franco et al., 2012). However, 20 articles have already covered the age of 7–20 for young athletes, and a few of the 20 studies reported under 10 years old and above 20 years old. The detail is shown in Table 3.

3.4 The type of instability intervention

Table 3 shows the type of instability intervention, unstable environment or surface, duration, and frequency for the 20 studies. These interventions of IRT included Instability suspension training of 3 articles (Norambuena et al., 2021; Thielen et al., 2020; Prasetyo et al., 2023), Instability balance training of 1 article (Kang et al., 2013), Combined balance and plyometric training (IRT is a part of the program) of 1 article (Makhlouf et al., 2018), Integrated functional core and plyometric training (IRT is a part of the program) of 1 article (Cabrejas Mata et al., 2022), Integrative neuromuscular training (IRT is a part of the program) of 1 article (Zhao et al., 2021), Unstable performed combined plyometric training (PTC) of 1 article (Negra et al., 2017), Proprioceptive training program on BOSU and Swiss ball of 2 article (Romero-Franco et al., 2012; Gidu et al., 2022), Soccer program supplementary Swiss Ball Training (SBT) of 1 article (Wee and Fatt, 2019), Supplemental jump and sprint exercise training on sand of 1 article (Hammami et al., 2022), Instability resistance training (2 sets x 8, 20% (1RM)) of 1 article (Hammami et al., 2023), Functional balance training for volleyball player of 1 article (Oliver and Brezzo, 2009), Unstable surface training of 1 article (Gönener and Gönener, 2020), Combined agility-balance training on wobble boards of 1 article (Zemková and Hamar, 2010),

Plyometrics training on sand surface of 1 article (Hammami et al., 2020), Balance training with uniaxial on a rocker board of 1 article (Eisen et al., 2010), Unstable plyometric training (IPT) of 1 article (Granacher et al., 2015), and Alternated balance and plyometric exercises with unstable surface of 1 article (Chaouachi et al., 2017).

In the type of unstable surface or environment, a common feature is that separating or integrating training with instability intervention used unstable surface or environment for each intervention or training activity. Among the 20 studies, 6 articles reported the unstable environments of Swiss ball, including only using Swiss ball of 2 articles (Kang et al., 2013; Wee and Fatt, 2019), combined using Swiss ball with other unstable environments of 4 articles (Makhlouf et al., 2018; Zhao et al., 2021; Romero-Franco et al., 2012; Chaouachi et al., 2017), also 6 articles reported the unstable environments of BOSU, including only using BOSU of 2 articles (Prasetyo et al., 2023; Gidu et al., 2022), combined using BOSU with other unstable environments of 4 article (Cabrejas Mata et al., 2022; Zhao et al., 2021; Gönener and Gönener, 2020; Chaouachi et al., 2017), 8 articles reported the unstable environments of Wobble boards, including only using Wobble boards of 2 article (Zemková and Hamar, 2010; Oliver and Brezzo, 2009), combined using Wobble boards with other unstable environments of 6 articles (Makhlouf et al., 2018; Zhao et al., 2021; Negra et al., 2017; Gönener and Gönener, 2020; Granacher et al., 2015; Chaouachi et al., 2017). Moreover, among the 20 studies, except for the Swiss ball, BOSU, and Wobble boards, two articles reported the unstable environments of the Suspension trainer (Norambuena et al., 2021; Thielen et al., 2020), the Elastic band strap of 1 article (Makhlouf et al., 2018), Thera-Band stability trainer and Togu® Aero Step of 3 articles (Negra et al., 2017; Hammami et al., 2023; Granacher et al., 2015), the Sand surface of 2 articles (Hammami et al., 2020; Hammami et al., 2022), Foam surface and Sponge of 2 articles (Gönener and Gönener, 2020; Chaouachi et al., 2017), Trampoline of 1 article (Gönener and Gönener, 2020), and Uniaxial on a rocker board and Multiaxial on a dyna-disc of 1 article (Eisen et al., 2010).

As for duration, 18 out of 20 articles reported the duration of IRT intervention, and only two articles did not report duration (Prasetyo et al., 2023; Oliver and Brezzo, 2009), including ten articles on 8 weeks (Kang et al., 2013; Makhlouf et al., 2018; Cabrejas Mata et al., 2022; Zhao et al., 2021; Negra et al., 2017; Hammami et al., 2023; Gönener and Gönener, 2020; Gidu et al., 2022; Granacher et al., 2015; Chaouachi et al., 2017), four articles on 6 weeks (Thielen et al., 2020; Romero-Franco et al., 2012; Wee and Fatt, 2019; Zemková and Hamar, 2010), two articles on 7 weeks (Hammami et al., 2022; Hammami et al., 2020), 1 article on 5 weeks (Norambuena et al., 2021), and 1 article on 4 weeks (Eisen et al., 2010). The above 20 references have shown that a 4–8 weeks short-term duration of IRT intervention could improve balance ability for different sports athletes.

Regarding frequency, the typical training frequency was 2–5 per week. Among these studies, six studies' training frequency was three times per week (Cabrejas Mata et al., 2022; Romero-Franco et al., 2012; Hammami et al., 2022; Gönener and Gönener, 2020; Hammami et al., 2020; Eisen et al., 2010); 4 studies' training frequency was two times per week (Makhlouf et al., 2018; Wee and Fatt, 2019; Granacher et al., 2015; Chaouachi et al., 2017); 4 studies' training frequency was four times per week (Thielen et al., 2020; Zhao et al., 2021; Oliver and Brezzo, 2009; Gidu et al., 2022); 2 studies' training frequency was five times per week (Norambuena et al., 2021; Hammami et al., 2023); 1 studies' training frequency was 3–5 times per week (Negra et al., 2017); 1 studies' training frequency was 4–5 times per week (Zemková and Hamar, 2010); and the remaining two studies' training frequency was unknow times per week (Kang et al., 2013; Prasetyo et al., 2023).

4 Outcome

The division of balance ability can be shown in Table 4. According to the balance ability classification theory in the field of sports training, there is one general category for balance ability (Tian, 2006; Michael, 2016; Deng et al., 2018). Among them, there are three subcategories in the balance ability type of general category: 1) Reciprocal balance ability, 2) Static balance ability, and 3) Dynamic balance ability. Therefore, this study systematically summarized and analyzed the results of 20 papers based on the general category and subcategories of balance ability mentioned above. The detail is shown in Table 4.

4.1 Effect of IRT on reciprocal balance ability

Table 3 shows that three studies have explored the effect of IRT intervention on reciprocal balance ability among ten judo athletes (Norambuena et al., 2021), 33 sprinters (Romero-Franco et al., 2012), and 32 pre-pubertal weightlifters (Hammami et al., 2023). One article showed t that there was no significant difference between the pre and post-test of the experimental group of judo athletes in the prone balance test for reciprocal balance ability (0.70 ± 0.48 vs. 0.40 ± 0.52, $p > 0.05$) (Norambuena et al., 2021). Meanwhile, in another study, the participants were track and field athletes. Between-group comparison, E.G., and C.G., the study results showed that it is significant differences in improved reciprocal balance ability in terms of XEO (E.G.,: −0.78 ± 4.31 vs. C.G.: 2.30 ± 2.75, $p < 0.01$), the position of the gravity center in the posterior (E.G., 69.75 ± 18.20 vs. C.G.: 54.71 ± 17.68, $p < 0.05$) and suitable (E.G.,: 63.31 ± 17.15 vs. C.G.: 49.71 ± 23,087, $p < 0.05$) direction test after proprioceptive training program on BOSU and Swiss ball (Romero-Franco et al., 2012). The result of the third study showed a statistically significant difference between the two experimental groups for pubertal weightlifters' reciprocal balance ability on CoP displacements of the center of pressure oscillation test: CoP S.A. (IRT1: 1940.17 vs. 548.21, $p > 0.01$; IRT2: 2,158.47 vs. 692.80, $p > 0.01$), CoP X (IRT1: 2,110.29 vs. 1,687.12, $p > 0.05$; IRT2: 2,134.54 vs. 1,690.68, $p > 0.05$), CoP Y (IRT1: 2,110.78 vs. 1728.89, $p > 0.05$; IRT2: 2,247.15 vs. 1936.52, $p > 0.05$), CoP V (IRT1: 63.61 vs. 50.76, $p > 0.05$) (Hammami et al., 2023).

4.2 Effect of IRT on static balance ability

Table 3 shows that IRT intervention impacts static balance ability: one-leg standing with open and closed eyes stable and unstable test, Biodex balance test (eyes open and closed Bipedal stance test), and the stork stand test. Three studies show that IRT intervention can provide instability resistance training, which can help improve static balance ability for weightlifters (Kang et al.,

TABLE 4 The general, subcategories, and test method of balance ability.

General Category	Subcategories	Main representative test methods
Type of balance ability	Reciprocal balance ability	(1) Postural stability balance (2) Center of gravity test (3) CoP displacements of the center of pressure oscillation test
	Static balance ability	(1) The stork stand test (2) One-leg standing with open or closed eyes balance test (3) Bipedal (double-leg) stance test
	Dynamic balance ability	(1) Star excursion balance test (SEBT) (2) Y Balance Test

2013), rhythmic gymnasts (Cabrejas Mata et al., 2022), soccer players (Gidu et al., 2022) in one-leg standing with open and closed eyes stable and unstable test. However, one article shows no significant difference in one-leg standing balance for soccer players after IRT training (Granacher et al., 2015). Similar to the one-leg standing balance test, three studies have explored the effect of the IRT program on the Bipedal (double-leg) stance test. Two studies found that IRT intervention can improve (double-leg) stance static balance ability for Basketball players (Zemková and Hamar, 2010) and soccer players (Gidu et al., 2022). However, after the IRT training, Oliver and Brezzo found no significant difference in the Biodex balance test for volleyball and soccer players (Oliver and Brezzo, 2009). Moreover, the stork stand test result is mostly for static balance ability. Six studies showed statistically significant within-group differences for the pre and post-test of the experimental group. Between-group were noted for the stork stand the test of static balance ability among archery athletes (Prasetyo et al., 2023), soccer players (Makhlouf et al., 2018; Negra et al., 2017; Chaouachi et al., 2017), handball player (Hammami et al., 2022; Hammami et al., 2020). Only two articles showed no significant difference for soccer players (Wee and Fatt, 2019; Negra et al., 2017) in the stork stand test of static balance ability between the experimental and control groups.

4.3 Effect of IRT on dynamic balance ability

Table 3 shows that IRT intervention has an impact on the following aspects of dynamic balance ability: Y balance test, Star excursion balance test (SEBT), single-leg side hop test, four-step square test (FSST), Tecno-body ProKin PK200 model dynamic balance test. In this study, five studies show that IRT intervention can provide instability resistance training, which can help improve dynamic balance ability in Y balance test for judo athletes (Norambuena et al., 2021), soccer player (E.G.,: $P < 0.01$, $d = 1.20$; C.G.: $P = 0.18$, $d = 0.28$) (Makhlouf et al., 2018), soccer player (both ABPT and BBPT experimental groups) (Chaouachi et al., 2017), handball player (Hammami et al., 2022), handball player (right leg, RL/L, RL/B; left leg, RL/B); (Hammami et al., 2020). A total of 2 articles showed a statistically significant difference in participants' dynamic balance ability in the Star excursion balance test (SEBT) for mixed volleyball and soccer players (Eisen et al., 2010) and soccer players (Granacher et al., 2015). However, 1 article showed no statistically significant difference in participants' dynamic balance ability in the Star excursion balance test (SEBT) for basketball players after the IRT training (Thielen et al., 2020). Other dynamic balance ability testing methods were used in the following two articles. One study examined the significant improvement impact of IRT for the dynamic balance ability of, E.G.,1 and, E.G.,2 with BOSU, Swiss ball, and Balance board for Single-leg side hop test (Left single-leg side hop, Right single-leg side hop) of 38 badminton players (17 ± 1.1 years) (Zhao et al., 2021). Another article revealed that the soccer program supplementary Swiss Ball Training (SBT) intervention did provide additional benefit to the dynamic balance ability for The step square test (FSST) of 19 soccer players (20 ± 1.73 years) (Wee and Fatt, 2019).

5 Discussion

The review included 20 studies involving diverse athletes and IRT interventions. The outcomes assessed in these studies varied for balance abilities. IRT is the process of creating an "unstable" platform by altering the stability of the support surface, imbalanced movement symmetry, and the occurrence of unexpected external forces that cause internal or external force imbalances in the body ((Behm et al., 2010). The findings of this systematic review provide robust evidence supporting the positive effects of IRT intervention on reciprocal, static, and dynamic balance ability among athletes. These findings are essential for developing targeted IRT programs to promote balance abilities.

5.1 Effect of IRT on reciprocal balance ability

Three studies empirically showed that IRT separately or integrating other training interventions could significantly improve judo athletes in prone balance test for reciprocal balance ability (Norambuena et al., 2021), track and field athletes' reciprocal balance ability in terms of position of the gravity center direction test after proprioceptive training program on BOSU and Swiss ball (Romero-Franco et al., 2012), and pubertal weightlifters' reciprocal balance ability on CoP displacements of the center of pressure oscillation test (Hammami et al., 2023).

The reasonable explanation for the results in which IRT intervention could significantly improve the reciprocal balance ability of the three studies is as follows. Firstly, the reciprocal balance ability refers to the kind of balance ability of the human body to evenly distribute the weight of the body to the fulcrums of the body, such as the force on both feet during standing time and whether the force on both buttocks is even during sitting position

(Evangelidis et al., 2016). The human body maintains balance through complex visual, vestibular, and proprioceptive systems (Bliss and Teeple, 2005). Reciprocal balance ability plays a crucial role in maintaining the stability of human posture and preventing falls. It especially maintains stability in the hip, knee, and ankle joints (Martino et al., 2023). Secondly, some research reports by scientists indicated that among subjects trained on unstable and stable surfaces, those trained on stable surfaces have poorer reciprocal balance abilities (Hirase et al., 2015). In addition, one of the essential interpretation criteria for reciprocal balance ability development is to activate visual and sensory-motor units by training on unstable surfaces and to adapt the body sway and body stability to these surfaces (Gönener and Gönener, 2020).

5.2 Effect of IRT on static balance ability

Eleven studies show that IRT can improve static balance ability for weightlifter (Kang et al., 2013), rhythmic gymnast (Cabrejas Mata et al., 2022), soccer player (Gidu et al., 2022) in one-leg standing with open and closed eyes stable and unstable test, Bipedal (double-leg) stance test of static balance ability for Basketball player (Zemková and Hamar, 2010), and soccer player (Gidu et al., 2022), and stork stand test of static balance ability about archery athletes (Prasetyo et al., 2023), soccer player (Makhlouf et al., 2018; Negra et al., 2017; Chaouachi et al., 2017), handball player (Hammami et al., 2022; Hammami et al., 2020).

The possible and reasonable explanations for IRT could significantly improve athletes' static balance ability of one-leg standing with open and closed eyes test, Bipedal (double-leg) stance test, and stork stand test are as follows. Firstly, the static balance ability refers to the ability of the human body to maintain a specific posture for a particular duration of time in a relatively static state, such as standing, standing upside down, archery, and other movements that are all static balance ability (Hrysomallis, 2007). In addition, the IRT training program consists of continuous unstable surface exercises in different unstable environments, improved static postural control, and hip, knee, and ankle joint strength production in athletes. The moderate instability of the unstable surface resulted in greater muscle activation than performing exercises on the floor (stable surface) (Gao et al., 2024). However, based on Table 3, four articles found that IRT has not improved static balance ability and no significant difference in one-leg standing balance for soccer players (Granacher et al., 2015; Wee and Fatt, 2019; Negra et al., 2017), and Biodex balance test for volleyball and soccer player (Oliver and Brezzo, 2009). The possible explanation is that the training duration and frequency were relatively short (only two times per week) or maybe that only a tiny portion of the training actions in the intervention used an unstable surface or environment, and a small amount of unstable intervention resulted in no significant difference in static balance ability between the, E.G., and C.G. groups.

5.3 Effect of IRT on dynamic balance ability

In this study, nine studies show that IRT can help improve dynamic balance ability in Y balance test for judo athletes (Norambuena et al., 2021), soccer player (Makhlouf et al., 2018; Chaouachi et al., 2017), handball player (Hammami et al., 2022; Hammami et al., 2020), star excursion balance test (SEBT) for mixed volleyball and soccer players (Eisen et al., 2010), soccer players (Granacher et al., 2015), single-leg side hop test for badminton players (Zhao et al., 2021), and four step square test (FSST) of soccer players (Wee and Fatt, 2019).

Perhaps the main reason for this result is that young athletes of different genders participating in IRT can affect their dynamic balance ability as follows. Research in biomedical fields highlights that hormonal differences significantly affect musculoskeletal structure and function, influencing dynamic balance and overall stability. For instance, conditions such as adolescent idiopathic scoliosis and osteoporosis, which occur more frequently in females, can impair postural control and balance due to altered spinal alignment and reduced bone density (Biz et al., 2006). Similarly, ligamentous injuries, such as ACL tears, are more prevalent in female athletes due to differences in ligament laxity and neuromuscular control, further affecting dynamic stability during high-intensity movements (Hewett et al., 2006).

Thus, firstly, the dynamic balance ability refers to the ability of the human body to control body posture during movements, such as Trampoline, Stunts, and Ice dance, all of which require athletes to have good dynamic balance ability (Chtara et al., 2016). Secondly, the possible reason is that to complete different IRT interventions (such as instability suspension training, balance training, combined balance, and plyometric training, unstable performed combined plyometric training, a proprioceptive training program on BOSU and Swiss ball, and supplemental jump and sprint exercise training on the sand and so on), the athlete needs not only the muscle strength of the core part to perform contraction but also the dynamic balance ability (depends on the comprehensive coordination ability of the human body to stimuli from vestibular organs, proprioceptive receptors composed of muscles, tendons, joints, and visual organs) to perform working together to complete the action above. Therefore, the influence of the dynamic balance ability of the athlete's body is that many complex factors work together that leads to this result (Wang et al., 2016). Last but not least, exercising on a relatively unstable surface increased the dynamic balance ability parameters of the experimental group, which may be explained by the fact that unstable training improved the supplementation patterns of deep and small muscle groups. Therefore, a high correlation coefficient exists between enhancing muscle activity and unstable environments (Lago-Fuentes et al., 2018; Gibbons and Bird, 2019). In addition, even though the, E.G., and C.G. groups performed similar exercises, those carried out on unstable surfaces can stimulate neural adaptation, improve neuro-muscular recruitment, enable the effective synchronization of motor units, lower neuro-inhibitory reflexes, and facilitate adequate proprioceptive feedback information for subjects' dynamic balance ability (Hirase et al., 2015). Moreover, the reasonable explanation of the only 1 article's results was not statistically significant in participants' dynamic balance ability in the Star excursion balance test (SEBT) for basketball players after instability suspended load training, and the possible explanation is that the training cycle is relatively short just 6 weeks.

6 Limitations

This review has a few limitations that need to be highlighted. 1) The current literature does not investigate the impact of the IRT program on other balance ability parameters such as the center of gravity balance, visual balance, and nervous system balance. Future research in this IRT intervention should address these aspects to acquire a deeper understanding. 2) The existing studies focus on the unstable surfaces of the environment or IRT, mainly using Swiss and BOSU. Therefore, future studies should develop other new unstable surfaces or environments, such as water, snow, sand surfaces, elastic bands, and suspension instability methods and environments. 3) Most interventions (80%–90%) in the included studies were unstable training interventions combined with other training methods, and there are not many IRT intervention methods in the literature for balance ability. Future studies should develop single IRT interventions for athletes in different events. 4) In the research results of the literature, there was a lack of analysis of covariance on the impact of IRT on balance ability for different athletes.

7 Conclusion

This systematic review of IRT on reciprocal, static, and dynamic balance ability among athletes provided evidence and materials that unstable surface training could improve the balance ability of judo athletes, basketball players, weightlifters, archery athletes, soccer players, rhythmic gymnasts, badminton Players, track and field athletes, handball players, volleyball players, and gymnasts using unstable surfaces or environments (i.e., BOSU, Swiss ball, Wobble boards, Suspension trainer, Sissel pillows, Inflated disc and foam surface, Airex balance pad, Togu power ball, Thera-Band, Elastic band strap, Sand surface and so on). Theoretically, this study indicated that IRT is an improvement training method for activating deep layers and small muscles of the human body, enhancing coordination between agonistic and antagonistic muscles, and improving nerve vestibule, proprioceptive sense, and visual sense for the Equilibrium Triad System of Balance Ability. Therefore, this review suggests that IRT should be considered in athletes' daily training routines for balance ability.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

JG: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. XF: Investigation, Methodology, Project administration, Resources, Writing–review and editing. HX: Software, Supervision, Validation, Visualization, Writing–original draft. QG: Software, Supervision, Validation, Visualization, Writing–review and editing. XW: Conceptualization, Data curation, Formal Analysis, Software, Writing–original draft.

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Conflict of interest

The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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The effects of 8 weeks of multi-directional movement training combined with balance training on the change of direction of young table tennis players

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Background: Change of direction (COD) skills are crucial for athletic performance in sports such as table tennis. Improving COD can enhance overall agility and responsiveness during competition.

Objective: To investigate the effects of an 8-week multi-directional movement training combined with balance training on the COD performance of young table tennis players.

Methods: Thirty young table tennis players from the same team were randomly assigned to two groups: the multi-directional movement training combined with the balance training group (MB, n = 15) and the control group (CON, n = 15). The MB group underwent balance training on unstable surfaces, while the CON group performed the same balance exercises on stable ground. Both groups participated in the same multi-directional movement training program, which was conducted three times a week with 24–48 h of recovery between sessions for a duration of 8 weeks.

Results: Significant group effects were observed in the modified agility test, non-dominant leg, dominant leg, and push block side lunge right test ($p < 0.05$). No significant group effects were found for the hexagon agility test, 3 m side slide test, A-movement test, or the whole table variable speed pendulum test ($p > 0.05$). Significant time-by-group interactions were noted for all variables ($p < 0.05$), indicating that improvements over time differed between the MB and CON groups. In the MB group, significant improvements were observed across all tests post-intervention, with high effect sizes (Partial η^2 values ranging from 0.361 to 0.815). In contrast, the CON group showed significant time effects in only a few tests, including the 3 m side slide test, A-movement test, modified agility test, and push block side lunge right test ($p < 0.05$), with no significant time effects for other variables.

Conclusion: This study aimed to explore whether multi-directional movement training, when combined with balance exercises, could improve COD skills in young table tennis players. The results will inform future training strategies for enhancing agility and movement efficiency in table tennis athletes.

KEYWORDS

change of direction, multi-directional movement training, balance training, young athletes, table tennis, agility

1 Introduction

Table tennis is a high-intensity, fast-paced sport that demands exceptional agility, balance, and change of direction (COD) abilities (Ozmen and Aydogmus, 2016). The game's dynamic nature demands rapid movements in multiple directions, quick reactions, and precise body control (Huang, 2022). Developing effective training strategies to enhance these physical attributes is crucial for improving performance and reducing injury risk in young table tennis players. Change of direction ability, in particular, is a fundamental skill in table tennis that allows players to quickly adjust their position and respond to opponents' shots (Dos' Santos et al., 2019). This skill involves a complex interaction of various physical components, including strength, power, balance, and coordination (Young and Rogers, 2014). While traditional training methods often focus on isolated aspects of physical fitness, such as strength or endurance, recent research suggests that an integrated approach, combining multiple physical components, may be more effective in improving sport-specific performance (Aloui et al., 2021).

Multi-directional movement training has gained attention recently as a potential method for enhancing COD ability in various sports (Jlid et al., 2020). For instance, short-term plyometric jump training has been shown to significantly improve physical fitness components such as strength, power, agility and repeated-sprint ability in young soccer players (Negra et al., 2020; Negra et al., 2017), These findings underscore the potential of targeted plyometric exercises to improve sport-specific performance in youth populations. This type of training involves exercises that challenge athletes to move quickly and efficiently in multiple planes of motion, mimicking the demands of their sport (Elgammal and Radwan, 2022). By incorporating multi-directional movements into training programs, athletes may develop improved neuromuscular control, proprioception, and overall movement efficiency (Guo et al., 2021). Balance training, on the other hand, has long been recognized as an essential component of athletic development and injury prevention programs. Improved balance can contribute to better postural control, stability during dynamic movements, and overall performance in sports that require quick changes in direction (Giboin et al., 2015). In table tennis, where players must maintain stability while executing fast and precise movements, balance training plays a crucial role in supporting the execution of high-intensity actions. In table tennis, where players must maintain stability while executing fast and precise movements, balance training is particularly important in supporting high-intensity actions.

The combination of multi-directional movement training and balance training has demonstrated promising results in improving athletic performance across various sports. For instance, Aloui et al. (2022) found that the integration of plyometric and short sprint training significantly enhanced measures of jump height, speed, COD, and balance in young soccer players. Similarly, Vuong et al. (2023) reported that combined change of direction and plyometric training on sand enhanced jumping, sprinting, and COD performance in professional basketball players. Combined balance and plyometric training has been shown to improve athletic performance metrics such as agility, jumping ability, and stability in female basketball players (Bouteraa et al., 2020). However, despite the growing body of evidence supporting the efficacy of multi-directional movement and balance training in other sports, there is a notable lack of research specifically addressing the needs of young table tennis players. Table tennis presents unique challenges due to its fast-paced nature and the need for precise movements within a confined space (Kaabi et al., 2022). As such, it is crucial to investigate whether the benefits observed in other sports can be translated to the specific demands of table tennis.

Given the potential benefits of combined multi-directional movement and balance training, and the absence of research targeting young table tennis players, there is a clear need for further investigation in this area. Understanding the effects of such a training program on COD ability in young table tennis players could provide valuable insights for coaches and practitioners seeking to optimize performance in this population. The present study aims to assess the effects of an 8-week multi-directional movement training program, coupled with balance training, on COD ability in young table tennis players. By focusing on this specific population and tailoring the intervention to the unique demands of table tennis, this study seeks to provide evidence-based recommendations for enhancing performance in this fast-paced, dynamic sport. It is hypothesized that 8 weeks multi-directional movement training combined with balance training can improve the COD performance of young table tennis players significantly.

2 Materials and methods

2.1 Participants

The study group consisted of 30 young Chinese table tennis players from a club in Zhejiang, born between 2007 and 2010, who were training in table tennis at the specialized sports training stage (Table 1), determined using G-Power (version 3.1.9.7; Franz Faul, University of Kiel, Kiel, Germany). These calculations were based on an α error probability of 0.05, a power (1-β error probability) of 0.8, an effect size (ES) of 0.4, and a test family encompassing F-tests and analysis of variance (ANOVA), specifically focusing on repeated measures and within-between interaction (Beck, 2013). The study

TABLE 1 Physical characteristics of participants in the MB and CON groups.

	Age (year)	Height (cm)	Mass (kg)	Training experience (years)
MB (n = 15)	15.63 ± 0.88	167.56 ± 2.83	56.75 ± 0.66	3.88 ± 0.66
CON (n = 15)	15.56 ± 0.81	167.44 ± 3.44	57.25 ± 3.34	3.94 ± 0.47

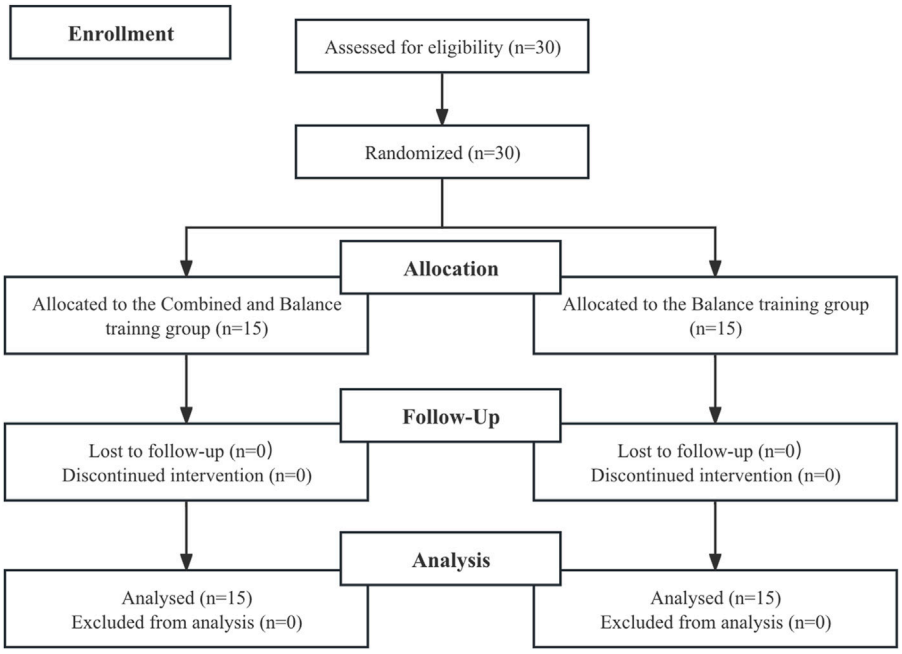


FIGURE 1
Flow chart of the progress through the phases of the study according to the consort statements.

group was selected arbitrarily using the following criteria: Written consent from parents and manager to participate in the research, membership in the province team, a minimum 3-year training period, health conditions, allowing all physical fitness tests to be carried out, the dominant arm is right side, have not suffered from any lower limb injury related to balance loss within the past 3 years, and playing style, requiring the use of rackets with a so-called smooth lining (excluding people using rackets with atypical cladding, such as anti-spin cladding, short pin, or long pin, where play is characterized by a different technique than topspin strokes used in a battery of special tests). The study was conducted in compliance with the Declaration of Helsinki and was approved by the local ethics committee (TJUS-2024-050). All data were analyzed confidentially.

2.2 Procedures

A total of 30 players volunteered for random allocation into two groups: the multi-directional movement training combined with balance training group (MB, n = 15) and a control group (CON, n = 15) according to a computer-generated randomization list (See Figure 1 for the recruitment process). Both groups performed the training program three times per week, with 24–48 h of recovery between sessions. The MB group engaged in a balance training program (Table 2), which was conducted under unstable conditions, while the CON group performed the same balance training program on a stable surface (floor). Following this, both the MB and CON groups participated in an identical multi-directional movement training program.

Before the official start of the training and testing, all participants underwent a 2-week familiarization phase, which involved training three times per week. During this period, participants were introduced to the balance exercises, multi-directional movement drills, and the test procedures. In addition, they received guidance on proper technique from a certified strength and conditioning coach. All training sessions and testing protocols were supervised by study personnel with expertise in strength and conditioning. Detailed descriptions of the balance training and multi-directional movement training protocols are provided in Tables 2, 3.

2.2.1 Hexagon agility test

The Hexagon Agility Test is a widely used assessment tool for evaluating players' COD ability and has been validated as an effective method for assessing on-court performance (Beekhuizen et al., 2009). For the test, participants began by standing 50 cm behind the No. 1 side of the hexagon (Figure 2). Upon hearing the

TABLE 2 The balance training program for multi-directional movement training combined balance training group and multi-directional movement training group.

Exercises	The first stage (1–2 weeks)	The second stage (3–5 weeks)	The third stage (6–8 weeks)
Stand on the balance board exercise	Static standing on the board with two legs 30 s/set*3 set	Static standing on the board with two legs and eyes closed 30 s/set*3 set	Squat on the plate with eyes closed (3 sets: 10 reps/set)
Supine straight leg bridge on Swiss Ball	Isometric supine straight leg bridge on Swiss Ball 30 s/set*3 set	Isometric supine single-leg bending bridge on Swiss Ball 30 s/set*3 set	Dynamic supine single-leg bending bridge on Swiss 10 reps/set*3 set
Side-plank with inflated balance disc	Side-plank with inflated balance disc with elbow 30 s/set*3 set	Side-plank with inflated balance disc and the non-supporting leg stretches backward 30 s/set*3 set	Side-plank with inflated balance disc and the non-supporting leg stretches backward with elastic band 10 reps/set*3 set
Lunge squat on BOSU ball	Lunge squat on BOSU ball 10 reps/leg/set*3 set	Lunge squat on BOSU ball and inflated balance disc 10 reps/leg/set*3 set	Lunge squat on BOSU ball and inflated balance disc with 5 kg dumbbells 10 reps/leg/set*3 set
Airex® Balance-pad Elite exercise	Single-leg squat with balance-pad 10 reps/leg/set*3 set	Single-leg standing with balance-pad and the non-supporting leg stretches backward 12 reps/leg/set*3 set	Single-leg support with balance-pad elite and the non-supporting leg stretches backward with elastic band 12 reps/leg/set*3 set
Rest	Between exercise: 60 s Between sets: 3 min		

Note: MB, group conducted training program on unstable support (e.g., BOSU, ball, Swiss ball, and Balance pad); and CON, group conducted training program on stable support (i.e., solid floor.

TABLE 3 The multi-directional movement training (MB) program for MB and CON group.

Exercises	The first stage (1–2 weeks)	The second stage (3–5 weeks)	The third stage (6–8 weeks)
Front barrier jump	Front high leg raise (15 cm) (15 hurdles/set*3 sets)	Front high leg raise (23 cm) (20 hurdles/set*3 sets)	Front high leg raise (30 cm) (25 hurdles/set*3 sets)
Quadrant jumps	Triangle jumps on both feet (4 round*3/set*3 sets)	Quadrilateral jumps on both feet (6 round *3/set*3 sets)	Hexagonal jumps (8 round *3/set*3 sets)
Cross jumps +10 m sprint	(4 round + sprints)/set * 3 sets	(6 round + sprints)/set * 3 sets	(8 round + sprints)/set * 3 sets
"Z" sprint	"Z" sprint + Forward rail jumps (15 cm) (2 reps/set*3 sets)	"Z" sprint + Forward rail jumps (23 cm) (3 reps/set*4 sets)	"Z" sprint + Forward rail jumps (30 cm) (4 reps/set*5 sets)
"M" sprint	"M" sprint + Lateral barrier jumps (15 cm) (2 reps/set*3 sets)	"M" sprint + Lateral barrier jumps (23 cm) (3 reps/set*4 sets)	"M" sprint + Lateral barrier jumps (30 cm) (3 reps/set*4 sets)
Lateral slide folding move + Sprint	(3 m return*4+5 m sprint)/set*3 sets	(3 m return*5+5 m sprint)/set*3 sets	(3 m return*6+5 m sprint)/set*3 sets
one-step lateral stomp	15 reps/set * 3 sets	20 reps/set * 3 sets	25 reps/set * 3 sets
In-situ crossover stomp swing	15 reps/set * 3 sets	20 reps/set * 3 sets	25 reps/set * 3 sets
Signal indeterminate movement	2-3 signal responses 20 s/set * 3 sets	4-5 signal responses 20 s/set * 3 sets	5-6 signal responses 20 s/set * 3 sets
Intensity	Low intensity	Middle intensity	High intensity
Rest	Between exercise: 60 s Between sets: 3 min	Between exercise: 60 s Between sets: 3 min	Between exercise: 60 s Between sets: 3 min

command "Ready, go," they were required to jump in and out of the lines in a clockwise direction, moving from 1 to 6. The test was timed using Smart Speed (Fusion Sport, Coopers Plains, Australia), which automatically recorded the start and end times. Each participant completed the test three times, and the shortest time recorded was used for analysis. A 2-min passive rest period was provided between each trial to ensure sufficient recovery.

2.2.2 T-half change of direction speed test

The T-half change of direction speed test was used to assess table tennis player's CODA ability (Picabea et al., 2021). Total distance of the test was 20 m. The participants' movements during the MAT were as follows (Figure 3): 1) A-B movements (5 m): Participants sprinted forward to cone B and touched the top of it with the right hand; 2) B-C movements (2.5 m): Moving laterally without crossing

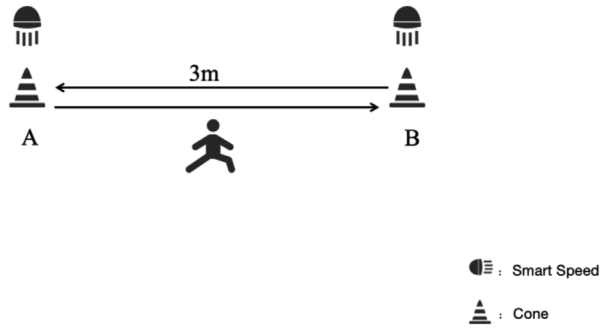


FIGURE 2
Hexagon agility test design.

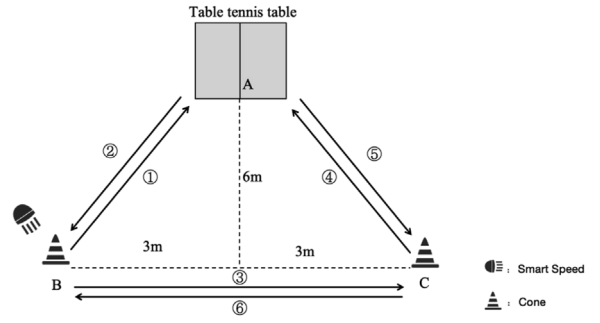


FIGURE 4
3 m side slide test design.

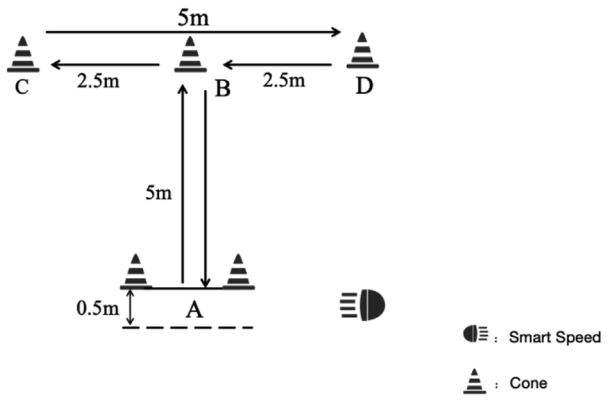


FIGURE 3
T-half change of direction speed test design.

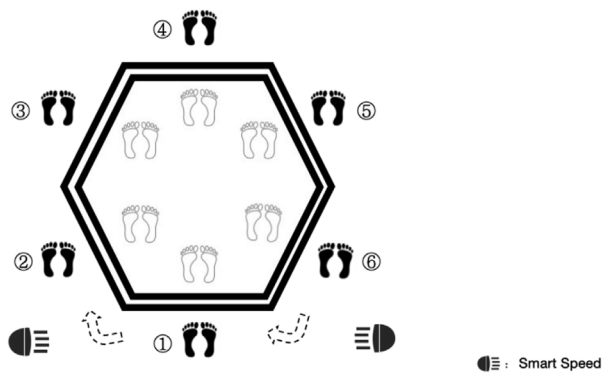


FIGURE 5
A-movement test design.

the feet, participants ran to cone C and touched its top with the left hand; 3) C-D movements (5 m): Participants ran laterally to cone D and touched its top with the right hand; 4) D-B movements (2.5 m): Participants moved back to cone B and touched its top with the left hand; 5) B-A movements (5 m): Participants ran backwards to line A. Trials where participants crossed their feet during B-C, C-D, and D-B movements, failed to touch the top of the cone, and/or failed to face forward throughout the tasks, were repeated. Each participant performed three trials interspersed with a 2 min rest period. One photocell gate was used to record the Smart Speed (Fusion Sport, Coopers Plains, Australia). The best value was selected for further analysis.

2.2.3 3 m side slide test

The 3 m side slide test is used to assess a table tennis player's change of direction ability. In a table tennis court, two cones (designated A and B) were positioned at a distance of 3 m apart (Figure 4). Smart Speed (Fusion Sport, Coopers Plains, Australia) was placed behind each of the cones. Prior to the commencement of the test, the participant was positioned between the two cones and contacted the upper edge of one side of the cones with their hand. Upon hearing the tester's "start" command, the subject was required to return to the two cones for five round trips, with each return necessitating contact with the upper edge of the baffle plate for the test to be considered valid. Each subject will complete a total of three maximal effort tests, with the highest score from the three tests being considered the final valid score. A recovery period of five to 10 minutes will be allowed between each test. The duration of the test was automatically recorded by the Smart Speed apparatus at the commencement and conclusion of the session.

2.2.4 A- movement test

The A-movement test is used to assess the ability of table tennis player's multi-directional change of direction and multi-directional sprint capability (Figure 5). In a table tennis court, the midpoint of the end line of the table tennis table is designated as point A. Perpendicular to the end line, parallel lines are established, extending outward for a distance of 6 m parallel to the end line. Point B is located 3 m on either side of the midpoint of the aforementioned parallel lines, and point C is similarly positioned 3 m from point B. Buckets are placed at points B and C to serve as markers. Prior to the commencement of the test, the athlete is required to assume a position at point B, with their back to the table tennis table. Once the command to commence has been given by the tester, the participants move with haste to the table and touches any

position before returning to point B. The athlete then proceeds to move around the barrels to point C and subsequently touches the table before returning to point C. At the conclusion of the test, the time taken to reach point A is recorded. The test is timed automatically by Smart Speed at both the start and the end of the test. The test is timed automatically by Smart Speed (Fusion Sport, Coopers Plains, Australia) at the beginning and end of the test. The entire test is performed around the marker barrels and cannot be touched, and there is no requirement for footwork throughout the test. Each participant performs a total of three Maximum Effort Tests, with the best of the three tests being the final valid score. A 5–10 min breaks between between each test.

2.2.5 Y-balance test

The lower-quarter Y-Balance dynamic test is a dynamic test that requires subjects to maintain single-leg stance while reaching as far as possible with the contralateral leg in 3 different movement directions (i.e., anterior, posteromedial, posterolateral) (Plisky et al., 2006; Hammami et al., 2016b), the assessment reflects the participant's lower extremity strength, flexibility, and balance ability (Cook et al., 2010). The Y-Balance balance test was performed using the FMS (Move2Perform, United States) standardized test suite.

Before the test started, participants' length of the right leg was assessed while in a supine lying position by measuring the distance from the anterior superior iliac spine to the most distal aspect of the medial malleolus. Further, participants practiced six trials per reach direction to get familiarized with the testing procedures. All trials were conducted barefooted. The protocol used for the completion of the YBT is similar to that described previously (Cook et al., 2010). Participants stood on the dominant leg, with the most distal aspect of their great toe on the center of the footplate from the YBT Kit. The participants were then asked to push the reach-indicator block with the free limb in the anterolateral, posteriormedial, and posteriorlateral directions in relation to the stance foot on the central footplate, while maintaining their single-limb stance. A test trial was classified invalid if the participants 1) did not touch the line with the reach foot while maintaining weight bearing on the stance leg, 2) lifted the stance foot from the footplate center, 3) lost balance at any point during the trial, 4) did not maintain start and return positions for one full second, or 5) touched down the reach foot to gain considerable support. The variables of interest for the study included the maximal reach for each direction. The average maximum normalized reach across the three directions was calculated in order to record a composite score for each subject. YBT measures were normalized by dividing each excursion distance by the participant's leg length, then multiplying by 100. Thus, normalized values can be viewed as a percentage of excursions distance in relation to the participant's leg length (Makhlouf et al., 2018). The test was demonstrated by a member of the research team prior to the participant completing three practice trials in each direction. Following the completion of the test trials, each participant was given a 1-min rest period and then conducted three test trials in each direction, and the maximum distance achieved in each direction (with a precision of 0.5 cm) was selected for the calculation of the total score. According to previous research (Filipa et al., 2010), a composite score (CS) was calculated and considered as the dependent variable using the following formula:

$$CS = \frac{Anterolateral\ Md + Posteromedial\ Md + Posterolateral\ Md}{leg\ length * 3} * 100\%$$

Md: maximum distance reached.

2.3 Push block side lunge right test

This test is used to measure the change of direction and dynamic balance control of table tennis players. Before the test, the participant stands in a ready-to-strike position on one side of the table tennis table and is served multiple balls by a server located on the opposite side of the table. First, two balls are served to the left side of the participant, and the participant completes a push and a block, and then one ball is served to the right side of the participant, and the participant moves to the right side and strikes the ball quickly. The number of successful shots was recorded by the recorder within 1 min. Each participant performed a total of 3 maximal effort tests, and the best of the 3 tests was taken as the final valid score, with a 5-min recovery period between each test. A 5–10 min breaks between each test.

2.4 Whole table variable speed pendulum test

The whole table variable speed pendulum test is used to assess a table tennis player's ability to observe and anticipate the direction of an opponent's movement on the court, the trajectory of the ball, the spin of the ball, the direction of the ball, and to rapidly change direction and adjust body position. Before the test commences, the participant will serve the ball with a combination of length and tempo changes. Participant is required to make a rapid judgement based on the trajectory, direction, speed and rotation of the ball, and subsequently adjust body posture and position in order to complete a forehand or backhand attack. The number of successful shots was recorded by the recorder within 1 minute. Each participant was given a total of 3 maximal effort tests, and the best score of the three tests was taken as the final valid score, with a 5-min recovery period between each test. The server for each test was selected at random.

2.5 Statistical analysis

Experimental data were processed by IBM SPSS statistical software package (version 26.0, Chicago, IL, United States). All data were presented as "mean ± standard deviation" (M±SD). All data were tested for normal distribution using Shapiro-Wilks test. Outliers, defined as studentized residuals greater than 3 standard deviations from zero, were identified and removed. To examine the effects of the MB on the performance, we firstly performed a two-way repeated-measure ANOVA (group × time). The dependent variable for each model was hexagon agility test, T-half change of direction speed test, 3 m side slide test, a-movement test, dominant leg, non-dominant leg, push block side lunge right test, and the whole table variable speed pendulum test. The model factors were group, time, and their interaction. When a significant interaction was observed, LSD *post hoc* correction was performed to identify the

TABLE 4 Descriptive statistics of results before and after the 8-week training intervention.

Variable	MB (N = 16)				CON (N = 16)				p-value		
	Pre	Post	Δ	Partial η^2	Pre	Post	Δ	Partial η^2	Time	Group	Time* group
Hexagon Agility Test (s)	4.43 ± 1.02	3.43 ± 0.87*	−1.0 ± 0.95	0.361	4.07 ± 0.75	3.87 ± 0.46	−0.2 ± 0.62	0.022	0.001*	0.083	0.027#
T-half change of direction speed test (s)	7.02 ± 0.30	6.47 ± 0.29*	−0.55 ± 0.3	0.739	6.98 ± 0.30	6.83 ± 0.31*	−0.15 ± 0.31	0.170	<0.001*	0.235	<0.001#
3 m Side Slide Test(s)	8.23 ± 0.41	7.38 ± 0.43*	−0.85 ± 0.42	0.725	8.14 ± 0.67	7.78 ± 0.60*	−0.36 ± 0.64	0.329	<0.001*	0.493	0.001#
A- Movement Test(s)	11.26 ± 0.56	10.37 ± 0.56*	−0.89 ± 0.56	0.791	11.16 ± 0.61	10.78 ± 0.51*	−0.38 ± 0.56	0.399	<0.001*	0.506	<0.001#
Dominant Leg	97.15 ± 2.33	106.53 ± 4.19*	9.38 ± 3.39	0.657	96.42 ± 3.95	97.31 ± 5.20	0.89 ± 4.62	0.017	<0.001*	0.005	<0.001#
Non-Dominant Leg	95.18 ± 2.31	102.04 ± 3.48*	6.86 ± 2.95	0.653	95.31 ± 3.35	95.52 ± 4.29	0.23 ± 3.85	0.002	<0.001*	0.028	<0.001#
Push Block Side Lunge Right Test	52.06 ± 3.44	55.50 ± 3.19*	3.44 ± 3.32	0.815	52.25 ± 2.84	54.19 ± 2.46*	1.94 ± 2.66	0.583	<0.001*	0.672	0.001#
Whole Table Variable Speed Pendulum Test	58.63 ± 3.28	63.00 ± 3.88*	4.37 ± 3.59	0.411	58.94 ± 3.55	57.69 ± 3.40	−1.25 ± 3.48	0.054	0.028*	0.079	<0.001#

* Statistically significant difference between pre-and post-test, $p < 0.05$.

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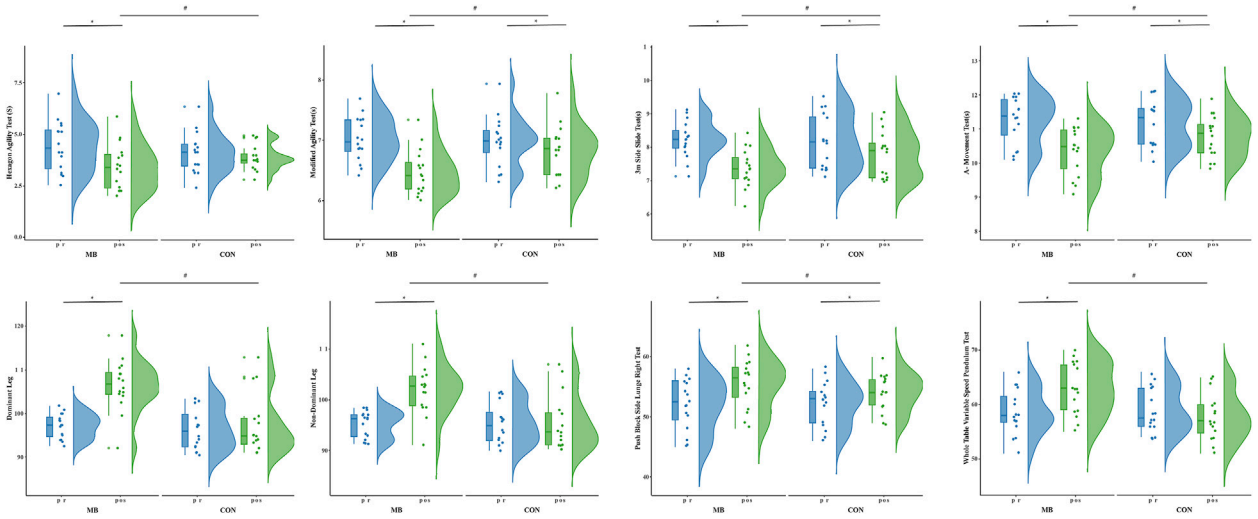


FIGURE 6
The task performance before and after Training. Note: *p < 0.05.

location of the significance. The model factor was time. *Partial* η^2 was used to assess the effect size (ES) where the significance was observed, with its strength being interpreted as the following: <0.06 as small, <0.14 as moderate, and ≥0.14 as large (Cohen, 1988). The level of significance was set at $p < 0.05$ for all tests.

3 Results

For group effects, significant differences ($p < 0.05$) were observed in the modified agility test, non-dominant leg, dominant leg, and push block side lunge right test. No significant group effects were found for the hexagon agility test ($p = 0.083$), 3 m side slide test ($p = 0.086$), a-movement test ($p = 0.084$), and the whole table variable speed pendulum test ($p = 0.079$) (Table 4).

Significant interactions between time and group were observed across all variables ($p < 0.05$), indicating that changes over time differed significantly between the MB group and CON group. In the MB, all tests showed significant improvements post-intervention compared to baseline, with the following Partial η^2 values: hexagon agility test (Partial $\eta^2 = 0.361$), T-half change of direction speed test (Partial $\eta^2 = 0.739$), 3 m side slide test (Partial $\eta^2 = 0.725$), A-Movement Test (Partial $\eta^2 = 0.791$), dominant leg (Partial $\eta^2 = 0.657$), non-dominant leg (Partial $\eta^2 = 0.653$), push block side lunge right test (Partial $\eta^2 = 0.815$), and the whole table variable speed pendulum test (Partial $\eta^2 = 0.411$), all with $p < 0.05$ (Figure 6).

In the CON, significant time effects ($p < 0.05$) were observed in the 3 m side slide test (Partial $\eta^2 = 0.329$), a-movement test (Partial $\eta^2 = 0.399$), T-half change of direction speed test (Partial $\eta^2 = 0.170$), and push block side lunge right test (Partial $\eta^2 = 0.583$). However, no significant time effects were found for the hexagon agility test ($p = 0.41$), dominant leg ($p = 0.48$), non-dominant leg ($p = 0.82$), or the whole table variable speed pendulum test ($p = 0.20$)

4 Discussion

The purpose of this study was to investigate the effects of 8 weeks of multi-directional movement training combined with balance training on the COD of young table tennis players. The results of our study demonstrated that the multi-directional movement combined with balance training (MB group) led to significantly greater improvements in COD ability and agility compared to the multi-directional movement-only group (CON group). The MB group showed significant improvements across all performance assessments, including the Hexagon Agility Test, T-half change of direction speed test, and the 3 m Side Slide Test. These findings suggest that integrating balance training into multi-directional movement training can effectively enhance performance in rapid directional changes, which is crucial for table tennis matches.

Due to the small size of the playing table and the high speed at which the game is played, a table tennis player has only a fraction of a second to simultaneously analyze the game, react, move and position properly to hit the ball in optimal conditions (Pradas et al., 2022). All these movement are performed in a limited space and require very fast movement, a high coordinating ability and appropriate strength. Hence the ability to change direction is a key skill required for success of table tennis. This study assessed the change of direction (COD) ability of the subjects during various movements by measuring their performance in the Hexagon Agility Test, T-half change of direction speed test, 3 m Side Slide Test, and A-Movement Test. The results indicate that both training methods effectively improved performance in the T-half change of direction speed test, 3 m Side Slide Test, and A-Movement Test. However, only the MB group showed significant improvement in the Hexagon Agility Test. Furthermore, detailed analysis revealed that the MB group demonstrated significantly greater improvements across all COD test metrics compared to the CON group. This is in line with our expected, and previous research findings in other sports

also supported our findings (Bouteraa et al., 2020; Makhlouf et al., 2018).Bouteraa et al. (2020) showed 8-week balance and plyometric training significantly enhanced agility for female adolescent basketball players. Makhlouf et al. (2018) compared that 8-week combination of agility and plyometric training with combination of balance and plyometric training on agility in young soccer players showed that combination of balance and plyometric training was an effective modality to develop agility in young soccer players. Theses research showed the effectiveness of balance training in improve agility. This might be due to the rapid change of direction that occur with agility maneuvers, challenge the ability to either maintain or return the center of gravity over the base of support and thus provide a stress to dynamic balance. Interestingly, this study found that the control group did not show significant improvement in the hexagon agility test, which further highlights the importance of balance in agility-based performance tests. Since the hexagon agility test does not involve long-distance movements and requires quicker footwork, it imposes greater requirements on balance for successful performance.

Additionally, the results of Y-balance test further support our hypothesis. The findings revealed that there was no improvement in the Y-Balance of both dominated and non-dominated leg for the CON group, while the MB group demonstrated significant improvements, and their performance was significantly better than that of the CON group. Zemková and Hamar (2010) demonstrated that after agility-balance training, a significant main effect of time for the dynamic balance in soccer players after 8 weeks of plyometric training on stable and unstable surfaces. Moreover, Bouteraa et al. (2020) also showed that combination of balance and plyometric could significantly improve the Y-balance test performance than regular training. These results were unsurprising, as according to the concept of training specificity (Behm et al., 2015), engaging in balance training is evidently more effective in improving dynamic balance compared to not incorporating balance training. As forementioned, the rapid change of direction movement challenges the ability to either maintain or return the centre of gravity over the base of support and thus provide a stress to dynamic balance. The improvement in dynamic balance observed in this study further supports the enhancement of COD performance. It provides additional evidence that the more effective improvement in COD performance seen in the MB group can be attributed to the enhancement of dynamic balance capabilities.

The results from the Whole Table Variable Speed Pendulum Test and the Push Block Side Lunge Right Test provide valuable insights into the impact of multi-directional movement combined with balance training on table tennis players' specific performance. The Whole Table Variable Speed Pendulum Test demonstrated a significant improvement in the MB group post-intervention, while the CON group did not show significant improvement. This suggests that the balance training incorporated in the MB group contributed to enhancing the players' ability to quickly adjust body posture and respond to changes in ball trajectory, speed, and spin. The MB group's superior performance likely stems from their enhanced neuromuscular control and core stability, developed through the multi-directional movement and balance training protocols. MB have been shown to improve proprioception and dynamic balance, which directly translate to better anticipation and quicker adjustments during gameplay (Hammami et al., 2016a; Bekris et al., 2012).

In the Push Block Side Lunge Right Test, the MB group also showed significant improvements post-intervention, outperforming the CON group, which had less pronounced improvements. The effectiveness of the MB training program is further supported by the specific nature of the exercises, which were designed to mimic the rapid lateral shifts required in table tennis, particularly in blocking and lunging scenarios. Previous studies have demonstrated that multi-directional training improves COD and lateral movements by targeting muscle groups and motor patterns involved in dynamic postural adjustments (Mohr et al., 2024). The program's focus on balance and lower-body strength likely contributed to the players' ability to better control their movement and recover more quickly, leading to superior performance in the test (Damian et al., 2024).

There are some limitations in this study. Firstly, although we successfully demonstrated improvements in dynamic balance and agility, it primarily relied on general performance-based tests such as the hexagon agility test and Y-balance test. These assessments, while useful, do not fully reflect the complexity and specificity of table tennis. In table tennis, change of direction involves multiple factors such as ball spin, speed, and placement, which are not adequately captured by the existing tests.Although table tennis-specific tests were incorporated, they were conducted with human-controlled ball serving, making the tests susceptible to variations in the skill level of the server and other human factors. This affects the repeatability and reliability of the tests. Therefore, future studies should focus on developing more precise and standardized table tennis-specific change of direction tests to reduce human interference and provide more reliable measurements. Additionally, another several limitations should be noted.The participant demographics were limited to male athletes from a specific region, which may restrict the generalizability of the findings to other populations, including female athletes or individuals from diverse geographic or athletic backgrounds. The study did not incorporate biomechanical analyses, such as force plate assessments or muscle activation studies, which could have provided a more comprehensive understanding of the underlying mechanisms influenced by the training intervention. The relatively short duration of the study (8 weeks) limits the ability to assess the long-term effects or sustainability of the training outcomes, warranting future longitudinal research. Addressing these limitations in future research could further enhance the understanding and applicability of the findings.

5 Conclusion

This study provides compelling evidence that an 8-week multi-directional movement combined with balance training program can significantly improve the COD ability and dynamic balance of young table tennis players. The MB group, which received balance training on unstable surfaces in addition to their regular multi-directional movement training, showed greater improvements across all COD tests compared to the CON group. These results highlight the

importance of integrating balance training into table tennis training programs to enhance agility and overall performance.

The findings of this study suggest that multi-directional movement training combined with balance exercises could be an effective method for enhancing the rapid directional changes required in table tennis. These insights provide practical implications for coaches and practitioners seeking to improve performance and reduce injury risk in young athletes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the ethics committee of Tianjing University of Sport (TJUS-2024-050). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

QC: Writing–original draft, Writing–review and editing. YL: Conceptualization, Investigation, Writing–original draft. XH: Data curation, Methodology, Writing–original draft. LZ: Data curation, Formal Analysis, Writing–original draft. BW: Supervision, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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It's time to re-evaluate the reporting of common measures from isokinetic dynamometers: isokinetic for torque, isotonic for power

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Isokinetic dynamometry is commonly used to provide an objective and reliable assessment of muscle function across a variety of clinical, athletic and research settings. Important muscle function variables that are commonly assessed are torque- and power- related measures. Isokinetic mode is overwhelmingly used to provide these variables, and has been so for decades; however, this mode may not be the best suited to examine power variables. The article aims to explore this issue through conceptual evaluation and empirical results using unpublished data. The implication is that due to the almost complete lack of unique information that power provides additional to torque in isokinetic mode, the isotonic mode is better suited to assess power for functional, operational, and methodological reasons. Thus, muscle function tests on an isokinetic dynamometer provide more fitting and useful data when isokinetic mode is used to determine torque measures, and isotonic mode is used to provide power measures.

KEYWORDS

strength testing, muscle function, biodex, muscle assessment, peak torque, mean torque

Introduction

Isokinetic dynamometry is commonly used as a muscle function assessment tool across a multitude of clinical, athletic, and research settings. It is generally considered as the gold standard for muscle function assessment due to its objective accuracy, reliability, and standardized controls (1–3). Other advantages of this form of muscle function testing include the capability of providing a multitude of parameters from even just a single repetition, such as peak torque (PT), mean torque, work, peak power (PP), mean power (MP), angle at PT, etc. Because of these features it is by a wide margin the most commonly employed test mode that is used when testing on isokinetic-capable dynamometers. To illustrate the mode reporting discrepancy, Figure 1 shows Pubmed search results comparing "isokinetic" vs. "isotonic" dynamometer power variable terminology, where isokinetic returned more than 10-fold the number of results (there were only 37 results for the "isotonic" dynamometer power phrase, since 1989).

Isokinetic dynamometers offer versatility beyond traditional isokinetic assessments, enabling various modes of muscle function evaluation including isometric, eccentric-only, and isotonic muscle actions. In isotonic mode, the dynamometer applies a

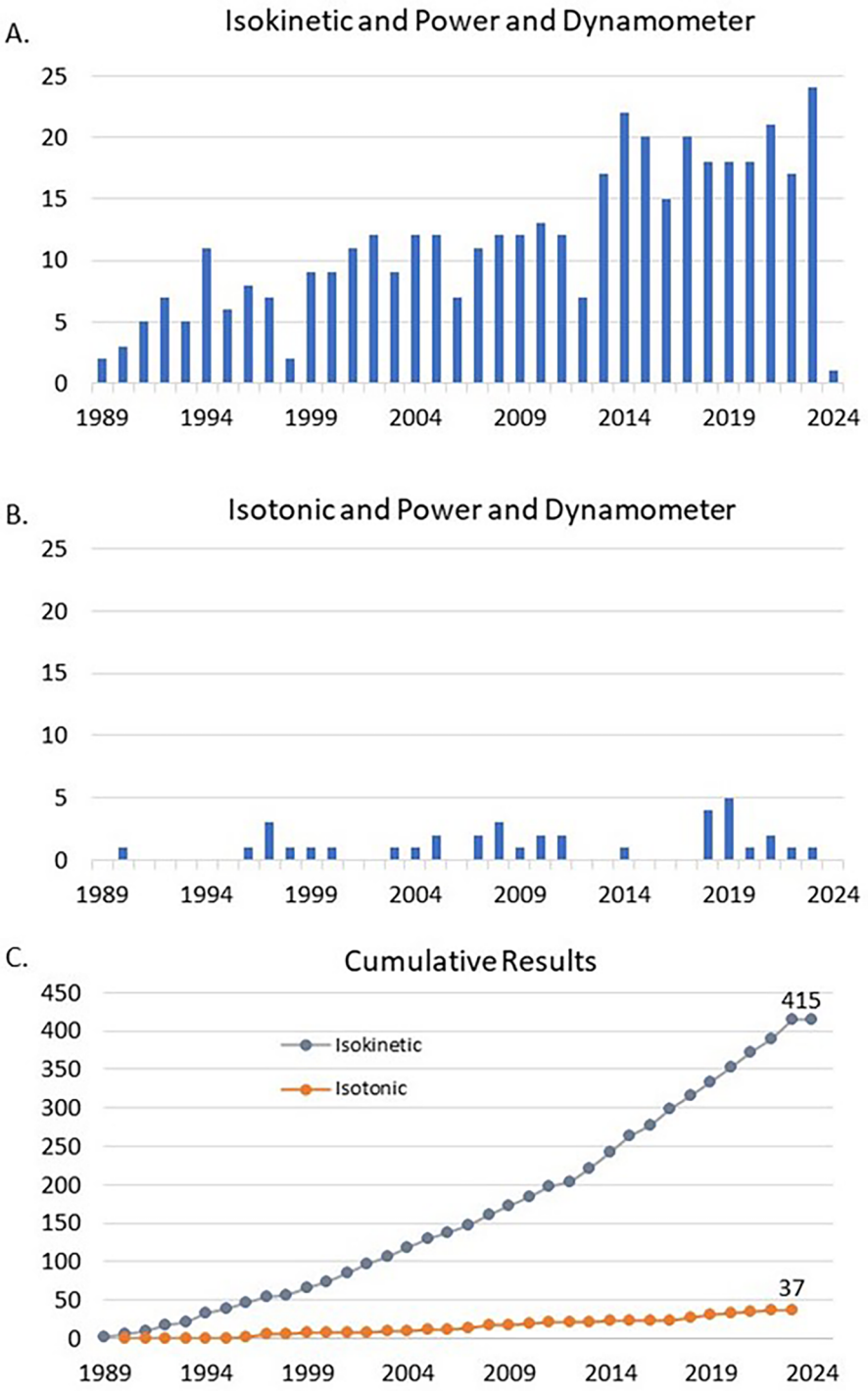


FIGURE 1
Presents the annualized search results from the Pubmed database for the search terms, (A) *"Isokinetic and Power and Dynamometer"* and (B) *"Isotonic and Power and Dynamometer"*. Panel C presents the cumulative search results for these terms to February of 2024.

"constant resistance," which is similar in resemblance to the loads encountered in traditional strength tests with free weights or machines. This mode more accurately (vs. isokinetic) reflects the load dynamics commonly experienced in daily activities, which typically involve both concentric and eccentric muscle actions in an environment where movement velocity is not constrained (3). Thus, the main difference between isokinetic and isotonic testing modes are that the former involves a constant velocity but variable resistance, whereas the latter is a constant load and variable velocity. The differences between these two concentric dynamometer-based test modes and how they interact with the most common output measures, namely torque and power, are

important; yet the implications of these differences has received relatively little attention in the context of isokinetic dynamometry assessments and the associated reported outcomes. Therefore, the purpose of this brief report is to employ conceptual principles and evidence-based data to highlight and compare the advantages and disadvantages of these two modes in regards to the torque and power output measures they each provide, and to describe how they may complement each other when integrated to provide more comprehensive evaluative muscle function assessment information.

Isokinetic vs. isotonic operational principles and physiological implications

Because of the dynamometer-imposed velocity control that characterizes the isokinetic mode, the velocity of the limb is of course constrained precisely to the predetermined velocity limit throughout a portion of the range of motion, with the portion of the set constant velocity being variable, depending on the velocity (i.e., isokinetic range excluding acceleration and deceleration phases, which are longer or shorter for faster or slower velocities). This constraining of the velocity is an important, and perhaps too often overlooked factor in regards to the effect that it has on the velocity dependent outcome measures, which primarily includes the commonly reported power measures from isokinetic mode tests. Indeed over 30 years ago observant investigators (4–6) well described how ultimately PT and PP were nearly perfectly associated when they were both derived from isokinetic assessments. This fact prompted one investigator (4) to suggest that measures of power may be "superfluous" when combined with PT, suggesting that practically no new meaningful information was provided by adding the second parameter (power).

Despite those early useful observations, it is rather remarkable that across the many decades and with the prolific research output involving these isokinetic-related measures, that the consideration of how this velocity constraining effect may impact the output variables has not been given as much consideration as perhaps it should. In fact, power is still a commonly reported outcome from isokinetic tests. The reasons for this are likely largely due to dynamometer research reporting conventions, along with the convenience of the software outputs. It is time to revisit the issue raised by early investigators and advocate for a more comprehensive approach to reporting key muscle function outcomes from dynamometer testing protocols. By adopting a more applicable and robust reporting framework, we can enhance the utility and relevance of these measures, maximizing the dynamometer's potential as a powerful tool for evaluating muscle function.

Power and torque parameters in isokinetic and isotonic contexts

The principle underlying the relationship between torque and velocity on power becomes disadvantageous in an isokinetic context, at least in terms of where the usefulness of power in a human performance domain is concerned. Because power is the product of force and velocity, constraining velocity to a set limit would then leave torque as the only factor that the resultant power is contingent upon. Put another way, if velocity is set the same for every contraction and/or across all participants, then the only factor that is varying power, is varying the torque output. This is the reason for why PT and power in an isokinetic movement are essentially almost perfectly related (Figure 2). This is problematic when it comes to muscle performance testing because, at best it wastes resources on unnecessary analyses and creates unnecessary "bulk" in numerical test reports (4), and at worst it may provide a false sense of what the true power capabilities really are, thereby providing an erroneous profile of one's true muscle function status. The latter is a counterproductive consequence to the point of the test in the first place, due to its misleading potential, and it is what particularly needs to be avoided.

It may be argued that if PT and power move in near-perfect alignment during isokinetic tests, reporting PT alone could suffice. This rationale, presented in earlier studies, was considered a practical and non-redundant approach to reporting data derived from isokinetic assessments (4). However, this approach raises a critical limitation when aiming for a comprehensive evaluation of muscle performance.

Power is a highly significant attribute in sports, daily functional activities, and health-related outcomes (7–10). In fact, extensive evidence suggests that power may surpass strength in its relevance to athletic performance, functional status, and the detection of clinical impairments (3, 7, 9, 10). Simply disregarding power in reporting, on the basis that it overlaps with PT during isokinetic tests, would undermine its unmatched utility. Such a practice fails to leverage the unique and essential information that power can provide.

To illustrate this point, data (unpublished) were analyzed from 52 adult male and female participants who performed isokinetic tests at 60°/s and 240°/s, as well as an isotonic test at 25% of maximum isometric strength. Figure 2 presents the coefficients of determination (r^2) for the relationships among PT, PP, and MP across different velocities and testing modes. The data demonstrate the near-complete variance explained by PT on PP for isokinetic conditions, but this relationship is markedly reduced in the isotonic mode. This indicates that while PT and PP offer no unique information during isokinetic tests, isotonic power measures provide distinct data and variance from PT. This distinction is of course highly desirable, as it highlights the value of isotonic power measures in muscle function assessments, providing critical insights that are not captured by isokinetic PT alone.

Power is unquestionably a critical and worthwhile metric for evaluating one's muscle performance. To maximize its functional relevance, power should be assessed in a velocity-unconstrained manner. Indeed, in addition to its functional relevance, assessing power is desirable precisely because it does not represent the exact same characteristics as PT as per its unique sensitivity to a number of health, sport performance, and functional aspects (as

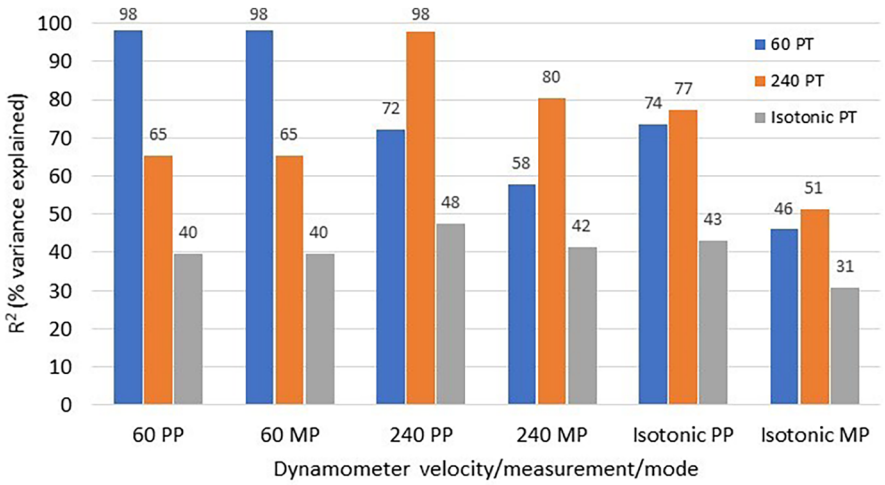


FIGURE 2
Presents the coefficient of determination (r^2) values for the relationships between the peak torque (PT), peak power (PP) and mean power (MP) dynamometer output measures across separate isokinetic tests at 60 and 240 deg/s and isotonic muscle action modes. Data is from 52 adult participants that performed all muscle contraction modes, in random order, with a 2-min rest period between conditions, and following a familiarization session on a Biodex dynamometer (unpublished data). The coefficients are represented in three series (blue is 60 deg/s PT, orange is 240 deg/s PT and gray is isotonic PT set at 25% of maximum isometric strength) and these series data show the relationships that correspond to the respective *x*-axis titled variable. Note how the PT isokinetic measures nearly perfectly explain the variance in their respective isokinetic PP measures, and how these relationships are markedly diminished when examining them for all of the isotonic mode variables. All correlations were statistically significant at the $P < 0.001$ level.

described above). The issue, therefore, lies in determining how to measure power using an isokinetic dynamometer without allowing it to be limited or overly influenced by its correlation with PT.

The isotonic mode of dynamometry provides a convenient solution by better decoupling torque and power measurements, allowing each metric to best occupy its specific domain in accordance to its likely dynamometer-based assessment purpose (e.g., isokinetic for standardizing velocity-specific strength, and power for its functional implications).

Although it should be noted that there may be cases where reporting both PT and power from isokinetic assessments is warranted—such as when the need arises to directly compare with studies that have exclusively reported the power measure with isokinetic mode. For instance, the two measures are expressed in different units (Nm for PT and Watts for power), making direct comparisons with studies reporting only power values challenging. Nevertheless, this paper contends that the most effective way to utilize power as a complementary measure is through isotonic mode assessments. Even when isokinetic power is reported, including isotonic power alongside it ensures that power retains its unique functional utility, avoiding redundancy with PT and enhancing the depth and applicability of muscle function evaluations.

That said, isotonic mode on an isokinetic dynamometer is not without limitations. In particular, PT as measured in isotonic mode may not provide highly meaningful information for certain comparative purposes. This limitation arises because isotonic PT values are constrained by the constant external load; in other words, PT mostly reflects the fixed external load of the system and does not vary significantly within a constant load system when using a submaximal load. Instead, it is the velocity that varies with changes in applied force.

An illustrative example comes from the dataset discussed earlier, where young and older participants demonstrated a 28% difference in isometric strength, as expected. Yet, their isotonic PT values were nearly identical (64.2 vs. 63.6 Nm), highlighting the limitation of isotonic PT for discriminating between groups with significant strength differences. Consequently, while isotonic mode is well-suited for assessing power and velocity, it appears less useful for evaluating PT as a discriminating variable when assessed at relatively low submaximal loads.

The influence of higher submaximal relative isotonic loads on the utility and discriminative ability of PT remains poorly understood. Future studies should investigate whether PT serves as a more effective discriminative measure when evaluated under these less-explored isotonic dynamometer conditions. Additionally, more studies are required to investigate the practical aspects of how best to incorporate an isotonic muscle assessment protocol alongside an isokinetic protocol. Key factors such as specific methods (sets, reps, rest periods), reliability factors, and fatigue effects should be thoroughly explored to develop an optimized and time-effective protocol that maximizes data usefulness, accuracy, and practicality.

Discussion

The solution to this mode by measure dilemma is to use both isokinetic and isotonic modes when aiming to comprehensively describe muscle function capabilities. Rather than report all

metrics solely from the isokinetic mode, it would be more prudent to use isokinetic for the advantages it provides in giving a suitable PT measure (i.e., to independently and reliably provide PT capacities without the confounding influence of velocity), but incorporate isotonic contractions for the express purpose of providing the power measures. Such a protocol would yield more fruitful and relevant comprehensive muscle performance data sets whereby both PT and power would be suited to their distinct purposes, and each would give some unique information on muscle function. The combination of these modes is therefore an optimal way to capture the best of each, and would not require more than a few extra sets of testing (requiring < 5 min of time to add 2–3 isotonic sets to the isokinetic testing). Hence, isokinetic mode should be used primarily for PT measures and isotonic for power.

Data availability statement

The data analyzed in this study is subject to the following licenses/restrictions: just reported as aggregate values. Requests to access these datasets should be directed to brennan.thompson@usu.edu.

Ethics statement

The studies involving humans were approved by Utah State University Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was obtained from the participants or the participants' legal guardians/next of kin.

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Action over anthropometrics: an action-scaled framework for youth sports modifications

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KEYWORDS

modified sport, body-scaling, action-scaling, gender, collective behavior

Introduction

In junior sports, equipment, pitch dimensions, and team sizes are typically modified to better suit the action system of younger athletes (for a review, see Buszard et al., 2016). These modifications are aimed to attain the same dynamics and task constraints in youth games as in adult games (Limpens et al., 2018). For example, the Dutch Football Association (KNVB) recommends that children under 10 years of age play soccer in a 6 v 6 format on a reduced pitch measuring 42.5 by 30 meters, about half the size of an adult pitch, and with goals sized at 5 by 2 meters. According to sports organizations like FIFA, these adjustments benefit both stakeholders and players. For stakeholders, smaller pitches are more economical to build and maintain, while for players, the smaller format encourages frequent ball touches and greater involvement, enhancing enjoyment, skill development, and overall engagement with the sport (FIFA, 2013). As a result, sports programs increasingly use these modifications to support participation and talent development (Buszard et al., 2022).

However, the guidelines for (re-)designing youth sport environments remain unclear and often are arbitrary (Buszard et al., 2016), raising significant issues. For instance, the absence of a conceptually coherent and standardized framework for these modifications has created inconsistencies, with sports organizations varying in their guidelines and frequently updating their standards (FIFA, 2013). To address these issues, Broadbent et al. (2021) recently proposed a body-scaled approach for sports modification, suggesting that adjustments to pitches or equipment should reflect the anthropometric relationship between children and adults (see also Limpens et al., 2018; Azmi et al., 2024; for a review, see Buszard et al., 2016). In this opinion paper, we first discuss the advantages and limitations of the body-scaled approach in youth sports modifications and then propose an action-scaled approach. Additionally, we highlight two often-overlooked aspects of youth sports that are also brought into focus by the action-scaled approach and warrant further attention.

Body-scaled vs. action-scaled framework

Body-scaled approach

The concept of body-scaling was first introduced by Warren (1984) in his seminal study on stair climbing. He investigated how people's perception of whether stairs were climbable was related to their body measurements. Warren observed considerable

variation among young adults in the step heights they perceived as climbable. However, he found that, regardless of individual differences in body height, stairs were consistently perceived as climbable when the step height was <0.88 times the individual's leg length. When step heights exceeded this ratio, stairs were perceived as unclimbable. From this, Warren concluded that individuals perceive affordances (i.e., possibilities for action, Gibson, 1979) by scaling environmental properties to their body measures. Since then, this body-scaled approach has been validated across various tasks, including sitting (Mark et al., 1990), reaching and grasping (van der Kamp et al., 1998), and walking through narrow openings (Warren and Whang, 1987).

Building on this foundation, the body-scaled approach has recently been applied to youth sports, where researchers and practitioners adapt equipment and field dimensions to fit young athletes' body measurements (e.g., Limpens et al., 2018; Gorman et al., 2021; Broadbent et al., 2021; Azmi et al., 2024). These modifications aim to maintain similar proportions or ratios between the size of equipment or fields' and players' body measurements, replicating the ratios typically found in adult sports (Limpens et al., 2018). Research has shown that such adjustments benefit young players by improving accuracy and technique (Timmerman et al., 2015) and encouraging greater functional variability (Buszard et al., 2020). Furthermore, these changes enhance young players' self-efficacy, leading to more positive and enjoyable experiences in sports (Gimenez-Egido et al., 2023).

Action-scaled approach

Despite its widespread popularity and application, the body-scaled framework has not been without its critics. One of the earliest critiques came from Konczak et al. (1992), who noted that stair climbing involves two key tasks: first, placing one foot on an elevated surface, and second, shifting the center of mass over the newly positioned foot to establish it as the new base of support while extending the weight-bearing leg. They argued that additional biomechanical factors, such as muscle strength and joint flexibility, could influence the perception of climbability beyond leg length alone. Their experimental findings supported this argument, showing that both perceived and actual climbing ability among older adults were influenced not only by body anthropometrics but also by muscle strength and joint flexibility.

These findings underscore a key limitation of the body-scaled approach: affordance perception is not solely determined by body dimensions. Instead, it is shaped by a broader range of factors, including coordination, agility, and strength, which evolve throughout development. This insight has significant implications for fields such as youth sports, where these additional factors play a crucial role in shaping how individuals perceive affordances. Rooted in ecological psychology, affordances reflect the relationship between an individual's action capabilities and relevant environmental properties (Gibson, 1979; Fajen, 2007). Therefore, action capabilities are a multidimensional concept, influenced by a range of human characteristics, such as body anthropometrics, coordination, agility, and strength. However, they cannot be fully captured or defined by any single factor.

Movement control is guided by the perception of affordances, with performers moving in ways that sustain affordance perception (Fajen, 2007). As a result, variations in action capabilities among individuals lead to different perceived possibilities for action (Vauclin et al., 2024). For instance, faster goalkeepers may perceive some penalties as stoppable, while slower goalkeepers may not (Zheng et al., 2021, 2022). Similarly, modifications to environmental properties—such as adjusting equipment or pitch dimensions—can create new affordances. For example, reducing the ball's weight enables children to shoot more accurately and pass farther than they could with a standard-weight ball during a basketball game (Arias et al., 2012).

Building on this understanding, while modifications based on the body-scaled approach simplify the task, they do not maintain the same dynamics as the adult game. This is because body measurements alone may not fully account for a performer's action capabilities (Konczak et al., 1992). Although younger players often demonstrate improved performance in body-scaled sports settings compared to unmodified ones, these skills may develop exclusively within the context of the body-scaled game and not transfer effectively to adult games. To address this limitation, scaling based on task-specific action capabilities is recommended. This approach considers the ratio between the task-specific action capabilities of children at different developmental stages and those of adults, as expressed in the following Equation 1:

$$\frac{\text{Task constraints for adults}}{\text{Task} - \text{specific action capabilities of adults}} = \frac{\text{Task constraints for youth}}{\text{Task} - \text{specific action capabilities for youth}} \quad (1)$$

For instance, in tennis, the primary task-specific action capability is ball-striking speed, which directly influences time pressure (Buszard, 2022). If the ball speed in adult games is twice as fast as in U10 children's games, the length of the modified court for U10 children should be half that of the adult court to maintain comparable task demands. By aligning task constraints with players' action capabilities, the action-scaled approach creates an environment for youth that offers a similar set of affordances as the adult game. This alignment enhances skill development and increases the likelihood of a smoother transition from children's games to adult-level performance.

Gender differences

A significant yet often overlooked aspect of modifying youth sport programs is the consideration of gender differences. Research has traditionally focused on male youth athletes, leaving female participants underrepresented. This creates a knowledge gap in understanding how gender shapes the design of enriching sports and learning environments. Before puberty, boys and girls typically exhibit similar anthropometric characteristics and action abilities (e.g., De Ste Croix et al., 2002; Broadbent et al., 2021). However, as they mature, their developmental trajectories diverge. Adult

men generally become larger, faster, and stronger than women, leading to notable differences in maximum action capabilities (Broadbent et al., 2021). Consequently, the same environment can offer different affordances to men and women.

For example, Zheng et al. (2022) compared the penalty goalkeeping behaviors of adult male and female goalkeepers that compete at similar skill levels. Female goalkeepers required more time to defend a regular sized goal. Additionally, female kickers produced less powerful shots, resulting in longer ball flight times when kicking the ball from the regular distanced penalty spot. Together, these factors create stricter constraints for female goalkeepers, as their action capabilities differ more markedly from men than those of the kickers. Consequently, the possibilities for action vary between male and female goalkeepers during a soccer penalty kick. Specifically, female goalkeepers are constrained to start their dives early and thus are more susceptible to deceptive actions of the kicker compared to their male counterparts (Zheng et al., 2022).

Gender differences in action capabilities underscore the need for thoughtful design in modified sports. Before puberty, using identical equipment and playing fields for boys and girls may result in undersized setups for girls (Broadbent et al., 2021). After puberty, as boys grow faster and stronger, these same fields and equipment may become oversized for girls, making tasks more challenging and potentially reducing their engagement. This challenge is evident in reports of many secondary school-aged girls (12–18 years old) avoiding physical education classes due to feelings of incompetence (Hortigüela-Alcalá et al., 2021). Addressing these issues requires accounting for gender differences in action capabilities when designing youth sports guidelines. The action-scaled approach can ensure sports environments are tailored to the distinct action capabilities of boys and girls, promoting inclusivity and engagement.

Collective behavior

Most research on modified sports has concentrated on individual sports (e.g., Limpens et al., 2018) or specific technical skills within team sports (e.g., Arias et al., 2012). However, the influence of modified sports on the collective behavior of young players remains largely unexplored. From an ecological psychology perspective, collective behavior in sports is guided by shared team affordances, or the opportunities for action perceived collectively by a group of players (Silva et al., 2013). Perceiving these shared affordances requires players to perceive not only their own maximum action capabilities but also that of their teammates and opponents (Silva et al., 2013). Consequently, action capabilities play a more important role than body anthropometrics in perceiving shared affordances. The action-scaled approach is thus more suitable than the body-scaled approach for supporting the development of shared affordances in modified sports.

The primary task constraint influencing the perception of shared team affordances is the distance between players, which is shaped by sport modifications such as pitch dimensions and player numbers (Clemente et al., 2020). This distance is closely tied to players' maximum action capabilities, such as how far they can kick the ball or how quickly they can intercept it (Travassos et al., 2012). Smaller pitches with more players reduce player distances, limiting exploration and decreasing variability in collective behaviors (Olthof et al., 2018). Additionally, player distances influence the attunement to shared team affordances: shorter distances encourage verbal communication, while longer distances promote reliance on non-verbal communication, such as eye contact (Caso and van der Kamp, under review).[1]

These shifts in communication indicate that players adapt to different information sources as distances change, resulting in distinct patterns of collective behavior.

Building on the role of action capabilities and player distances in shaping shared team affordances, we propose the action-scaled approach as a framework to support the development of collective behavior in modified youth sports. This approach aims to provide youth players with a set of affordances comparable to those in adult games, ensuring that representative team affordances are effectively integrated into their environment. However, further research is needed to identify the specific shared affordances and the underlying team-action capabilities in which they are grounded.

Conclusion

This opinion paper evaluated the strength and limitations of the body-scaled approach in youth sports modifications and advocates for the action-scaled approach as a more effective alternative. By aligning task constraints with players' action capabilities, the action-scaled approach ensures that the collection of affordances available closely mirror those in adult games, fostering skill development that transitions smoothly to adult performance. Additionally, the paper highlights the importance of addressing gender differences and collective player behavior, filling critical gaps in current practices and paving the way for more inclusive and effective youth sports frameworks. For practical implementation, sports organizations should collaborate with sport scientists and experienced practitioners to identify the task-specific action capabilities required in each sport. They should then assess how current youth modifications align with adult games using the action-scaled approach. For example, they should determine whether these modifications are oversized or undersized and adjust them accordingly. Furthermore, future research should empirically evaluate the effects of these action-scaled modifications on youth performance across different sports and developmental stages. Such studies would offer essential evidence to support the broader adoption of this innovative framework and further enhance its application in youth sports settings.

1 Caso, S., and van der Kamp, J. (under review). An ecological perspective on intra-team communication in elite football. *Int. Rev. Sport Exerc. Psychol.*

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Reviewing the association between motor competence and physical activity from a behavioral genetic perspective

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A much-cited model by Stodden and colleagues has proposed motor competence to be a 17 promising target for intervention to increase childhood physical activity. Motor competence is thought to influence future physical activity through bidirectional causal effects that are partly direct, and partly mediated by perceived motor competence and physical fitness. Here, we argue that the model is incomplete by ignoring potential confounding effects of age-specific and age-invariant factors related to genetics and the shared family environment. We examined 106 systematic reviews and/or meta-analyses on the Stodden model for the mention of familial confounding. These reviews summarized data from 1,344 primary studies on children in the age range 0–18 on the associations in five bidirectional pathways: motor competence—physical activity, motor competence—perceived motor competence, perceived motor competence—physical activity, motor competence—physical fitness, and physical fitness—physical activity. We show that a behavioral genetic perspective has been completely lacking from this vast literature, despite repeated evidence for a substantial contribution of genetic and shared environmental factors to motor competence (h^2 = ♂55%—♀58%; c^2 = ♂31%—♀29%), physical fitness (h^2 = ♂65%—♀67%; c^2 = ♂3%—♀2%), and physical activity (h^2 = ♂37%—♀29%; c^2 = ♂33%—♀49%). Focusing on the alleged causal path from motor competence to physical activity, we find that the systematic reviews provide strong evidence for an association in cross-sectional studies, but weak evidence of prediction of physical activity by motor competence in longitudinal studies, and indeterminate effects of interventions on motor competence. Reviews on interventions on physical activity, in contrast, provide strong evidence for an effect on motor competence. We conclude that reverse causality with familial confounding are the main sources of the observed association between motor competence and physical activity in youth. There is an unabated need studies on the interplay between motor competence, perceived motor competence, physical fitness, and physical activity across early childhood and into adolescence, but such studies need to be done in genetically informative samples.

KEYWORDS

motor development, Stodden model, twin studies, perceived motor competence, cardiorespiratory fitness, muscular fitness

1 Introduction

1.1 The importance of physical activity in children and adolescents

The paramount importance of regular physical activity (PA) to enhance children's health has been extensively documented (Elhakeem et al., 2018; Janssen and Leblanc, 2010; Jose et al., 2011; Kaplan et al., 1996; Leskinen et al., 2009; Wendel-Vos et al., 2004). The well-established effects of physical activity have led to the development of physical activity guidelines for youth, widely adopted across the globe (World Health Organization, 2020). Despite this, and the many active policies supporting an increase in physical activity in various settings, the majority of children and adolescents does not meet recommended physical activity levels (Guthold et al., 2020). Furthermore, as children move through childhood and adolescence towards adulthood, physical activity participation rates tend to further decline (Conger et al., 2022).

Of note, these general epidemiological trends describe what happens to the average child but fail to address the large individual differences in physical activity behaviors. These individual differences have been shown to be remarkably stable throughout the lifespan (Breau et al., 2022; Telama et al., 2005; van der Zee et al., 2019) such that children who start out to be more physically active in childhood tend to remain more active later in life. This 'tracking' of physical activity suggests that it would pay off to increase the number of active children to arrive at larger numbers of adolescents and adults meeting the recommended physical activity levels. Not surprisingly therefore, much effort has been spent on identifying modifiable determinants of childhood physical activity. One of the more promising traits investigated is motor competence (Øglund et al., 2015; Øglund et al., 2014). Globally, children (3–10 years) demonstrate "below average" to "average" motor competence levels (Bolger et al., 2021), suggesting that there is room for improvement of this trait by targeted intervention. However, such intervention is only meaningful to increase youth physical activity levels to the extent that motor competence has a causal effect on physical activity.

1.2 The role of motor competence in physical activity: the 2008 Stodden model

Motor competence can be defined as the full complement of a person's motor abilities needed to execute all forms of goal-directed motor acts necessary to manage everyday tasks (Bolger et al., 2021; Henderson and Sugden, 1992). The potential role of motor competence for physical activity received a large boost with the development of the "Stodden model" by Stodden et al. (2008). The Stodden model identifies motor competence as a main determinant of youth and adolescent physical activity, a basic idea foreshadowed by the earlier work of Hands and Larkin (2002). To be physically active as they grow older, children need fundamental motor skills like running, jumping, catching, and throwing. Children that start out with low actual and perceived motor competence may not engage in sufficient physical activity to develop the motor competence and physical fitness needed to engage in the required level of physical activity during middle and late childhood. This will draw them into a negative spiral of disengagement in which the lower levels of physical activity in turn will amplify their motor skill deficits compared to their more active peers. "This will ultimately result in high levels of physical inactivity and will place these individuals at risk for being obese during later childhood, adolescence, and adulthood. "(Stodden et al., 2008, p. 297).

Three characteristics of the Stodden model turn it into a dynamic but complex model that make it difficult to predict the development of stable physical activity habits as well as moments that would be optimal for change by intervention. First, it adds two mediational pathways, acting through physical fitness and through perceived motor competence, to the direct pathways between motor competence and physical activity. Second, it suggests non-recursive, reciprocal effects in the direct and mediated pathways. Third, the model allows changes in the direction of effects in the pathways as a function of age. While being very complete by incorporating age-moderation, bidirectionality, and mediation, the Stodden model at the same time is undercomplete by solely focusing on the possibility that these pathways reflect *causal* effects.

1.3 The potential confounding by familial factors in pathways of the Stodden model

In its essence, the Stodden model revolves around a set of five associations between motor competence and physical activity, between motor competence and perceived motor competence, between perceived motor competence and physical activity, between motor competence and physical fitness, and between physical fitness and physical activity (MC-PA, MC-PMC, PMC-PA, MC-Fitness, Fitness-PA). These associations can arise through fundamentally different mechanisms governing the development and the ensuing stability of the associations between the traits as well as the changes in these associations over time. Figure 1 depicts potential sources of the association between motor competence and physical activity at each of three different ages, and how these sources can impact on the stability of these associations across developmental time. To maintain intelligibility, the Figure greatly simplifies the continuous nature of development by using discrete ages 2, 7, and 13, rather than a more fine-grained model that uses steps of, e.g., 2 months. It's aim is merely to provide an illustration of the complexity of interpreting (longitudinal) associations.

As a major innovation to the Stodden model, Figure 1 adds latent determinants that may act as confounders of the associations between motor competence and physical activity, or its putative mediators, perceived motor competence and physical fitness. Two sets of latent determinants have been repeatedly nominated by the field of behavior genetics to play a role in many developmental traits. The first set of determinants consists of the common or shared environment that contains all factors shared by family members living in the same household, including the physical home environment, family warmth and mutual support, parenting style and example setting, neighborhood characteristics, and socioeconomic status (including education level of the parents). The second set consists of the genetic variance shared by family members which may reflect additive trait effects of the two parental alleles in a gene, or non-additive trait effects due to allelic dominance or allelic interaction (epistasis).

Starting at the top of the model shown in Figure 1, we see that motor competence at age 2 ("MC age 2") is considered to be influenced by latent determinants ("Det MC2"). These may involve genetic

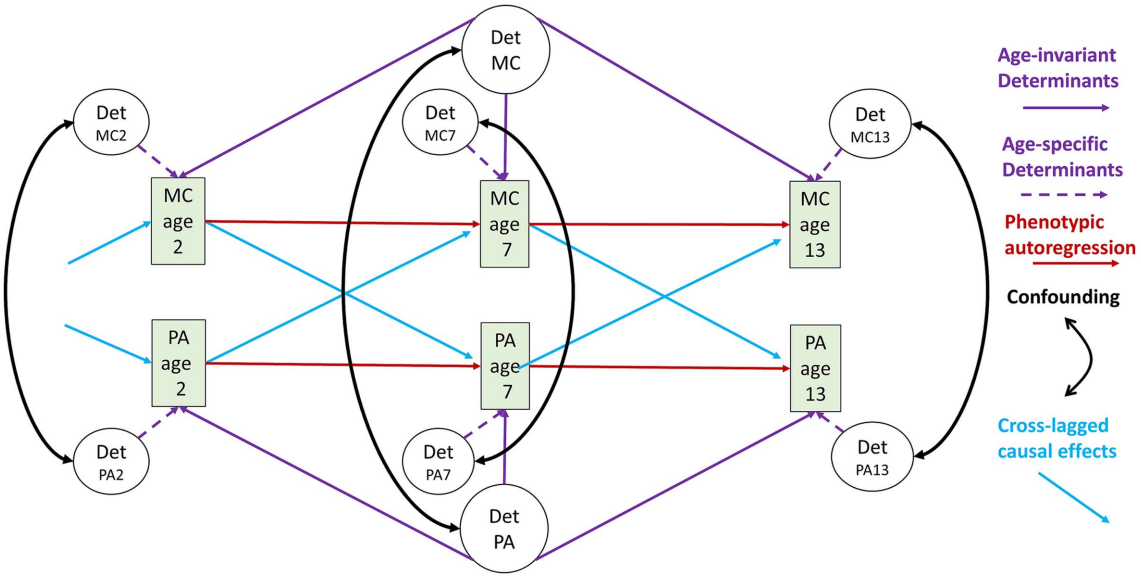


FIGURE 1
Sources of the association between motor competence and physical activity and its stability over time. Rectangles contain the observed values of the motor competence (MC) and physical activity (PA) traits at the three example ages (2, 7, 13). Ovals contain the set of latent determinants of these traits (DetMC, DetMC2, DetMC7, DetMC13 and DetPA, DetPA2, DetPA7, DetPA13) which may be genetic or environmental determinants. DetMC2, DetMC7, DetMC13 contain the age-specific latent genetic/environmental determinants of motor competence operating on MC at age 2, 7 and 13, respectively. DetMC contains the age-invariant latent genetic/environmental determinants that operate on the traits at all ages. Similar applies to DetPA, DetPA2, DetPA7, DetPA13. Dotted purple arrows from DetMC2, DetMC7, DetMC13 and DetPA2, DetPA7, DetPA13 reflect age-specific effects of these determinants, whereas the solid purple arrows from DetMC and DetPA reflect age-invariant effects of these determinants. Double-headed black arrows indicate correlation of the underlying determinants, which leads to confounding in the MC-PA associations. Red continuous lines indicate the autoregression of the motor competence and physical activity traits across time. Blue arrows indicate true causal effects of motor competence on physical activity, or in reverse, physical activity on motor competence. Blue arrows pointing into age 2 reflect causal effects from earlier ages.

variants that influence sensorimotor brain functioning and neuromuscular control, or differences in motor skill challenges related to the family that children grow up in or other environmental factors such as climate or exposure to structured physical education in school or childcare settings. The influence of these genetic and environmental determinants of motor competence can show substantial stability over time (reflected in the purple arrows emanating from the latent "Det MC" factor that influences motor competence at *all* ages) because the genetic code does not noticeably change after conception, and influences related to parental rearing styles, and neighborhood or household characteristics can also be stable. However, the influence of some of the latent determinants may be confined to specific ages (reflected in the latent "Det MC2 … Det MC13" factors). For example, parental social support effects may be strong at ages 2 and 7 but become more diluted when children enter secondary school. While some genetic variants may be expressed at all ages, other variants may show age-specific (suppression of) gene-expression as part of maturation. At the bottom of the figure, we see a parallel situation for physical activity, again with both age-invariant and age-specific latent factors influencing physical activity behaviors at the three ages depicted.

At each age, an association between motor competence and physical activity may arise entirely through the correlation of the age-invariant and/or age-specific factors, without the need for a direct causal path between the two traits. For example, part of the many genetic variants that influence motor competence may overlap with those influencing physical activity, creating horizontal genetic pleiotropy when they influence these traits through *independent* routes (Minica et al., 2020; Minica et al., 2018; Solovieff et al., 2013; Verbanck et al., 2018). Likewise, environmental risk factors like household poverty and parental rearing styles may independently restrict motor competence development and reduce opportunities for regular physical activity. If the effects of genetic or environmental factors change in strength from childhood to adolescence, they may also cause a strengthening or weakening of the associations over time. Such a confounder-induced age-related change in the association would not be discriminable from an age-moderation effect on the putative causal pathway between motor competence and physical activity.

The confounding genetic or environmental effects may work directly on the two traits themselves, but also make use of an intermediate trait that itself exerts a causal effect on both traits. A first example would be that the same genetic variants that influence motor competence also influence physical activity through their effects on the dopaminergic brain systems that influence motor control as well as exercise reward pathways. A second example of such confounding would be that an obesogenic family environment would increase body mass index (BMI), with BMI having effects on both motor competence and physical activity. In short, cross-sectional associations between motor competence and physical activity at each age can reflect confounding by correlated determinants, which may be genetic or environmental in nature.

However, the effect of the latent underlying factors does not rule out the additional existence of causal effects of motor competence at an earlier age on current physical activity. These causal effects are reflected in the cross-lagged paths of Figure 1. For

example, physical activity at age 7 may, in part, depend on the ability to perform basic motor actions at a sufficient level to engage in active play with parents, siblings, or peers at school from age 2 to 7. Conversely, the lagged causal effect may also work in the other direction. Daily engagement in physical activity from age 2 to 7, i.e., playing regular ball games in preschool, may actively contribute to building up motor competence, i.e., lead to increased kicking/throwing skills, at age 7. Such bidirectional causal mechanisms are suggested by the Stodden model as the main cause of the association between motor competence and physical activity in middle and late childhood.

Apart from the mechanisms inducing cross-sectional associations at each age, Figure 1 also depicts the mechanisms that lead to stability of the association of motor competence and physical activity over developmental time. A first mechanism causing stability of the associations between motor competence and physical activity is the autoregression of each of the traits separately. Substantial evidence shows that, even if absolute levels show large maturational changes, the individual differences in both motor competence and physical activity are stable across time (Barnett et al., 2010; Branta et al., 1984; Farooq et al., 2020; Malina, 1990; McKenzie et al., 2002; Pereira et al., 2022; Schmutz et al., 2020). This 'tracking' of motor competence and physical activity may arise from direct causal influences of the trait level at a starting age on the trait level at a later age. For example, once a neuromotor skill has been mastered (running, balancing on a beam) it will not be easily lost, and habit formation may solidify physical activity behaviors once these have been taken up in an initial period (Rebar et al., 2024).

Autoregression can be a first source of stability of the association of motor competence and physical activity over time. Once an association has come into existence, e.g., is bootstrapped at age 2 by correlated underlying determinants, it will be propagated across time sheerly by the stability in each of the two traits. A second mechanism that leads to stability of the association of motor competence and physical activity over time are the causal effects of motor competence on physical activity and the reverse causal effects of physical activity on motor competence. Finally, a third mechanism causing stability of the association is a correlation of the age-invariant genetic or environmental determinants of motor competence and physical activity ("Det PA" and "Det MC" in Figure 1). These will not just induce cross-sectional association but also longitudinal associations between motor competence and physical activity.

The Stodden model was created when the associations between the traits in the five pathways (MC-PA, MC-PMC, PMC-PA, MC-Fitness, Fitness-PA) were mostly observed in cross-sectional studies. Cross-sectional studies cannot discriminate between the mechanisms outlined in Figure 1 and outlined above. Nonetheless, if one of the hypothesized associations in the Stodden model is found to be absent, it would at once tell us that no causal effect is likely to exist. In that sense, cross-sectional studies are vital in first demonstrating the primary possibility of a causal association. Longitudinal studies are a step up from cross-sectional studies in that they establish the presence of cross-time (lagged) associations between the traits and can rule out reversed causation. If the assumed causal trait (e.g., motor competence at an early age) is seen to predict the assumed caused trait (e.g., physical activity in adolescence) in the future but in parallel, the association is not seen to hold in the opposite direction this would falsify reverse causation of motor competence by physical activity.

The strongest design to show true causality in the pathways of the Stodden model is the intervention design, where either motor competence or physical activity are manipulated, and it is tested whether the induced changes in one trait led to changes in the other trait. Well-conducted RCTs remain the highest level of evidence for a true causal effect. However, large individual differences can be seen in the response to intervention and it is not always clear what is driving these differences (Kennedy et al., 2021; Liu et al., 2024; Ma et al., 2021; Prochaska et al., 2008). Again familial factors are a potential source of the heterogeneity in responding to intervention. Attempts to increase motor competence and physical activity may fall on more fertile ground in some children compared to others, simply based on their genetic abilities and/or more supportive family environment. So, to further add to complexity, the underlying determinants of motor competence and physical activity in Figure 1 may partly act through their moderating effects of (parental or school-based) attempts to change these traits.

If the genetic and shared environmental determinants independently influence motor competence and physical activity behavior, the size of the causal effects hypothesized to underlie the observed association between motor competence and physical activity behavior would be incorrectly estimated from the size of the association when this confounding is not taken into account. Since the publication of the Stodden model, a very large amount of systematic reviews with or without meta-analyses have been published on one or more of the Stodden pathways. A reasonable expectation, therefore, is that this large volume of work has duly taken the potential of familial confounding into account. Cursory inspection of some highly cited reviews (Barnett et al., 2022; De Meester et al., 2020; Engel et al., 2018; Figueroa and An, 2017) suggested that this might not be the case, but more systematic inspection of the large volume of systematic reviews is needed. In addition, for familial confounding to be a potential issue, it is required that the traits in the Stodden model show substantial variance caused by shared environmental or genetic factors. This requires a review of studies on these traits in the behavioral genetics literature.

1.4 The aims of this narrative review

The first aim of this narrative review is to examine whether and how shared environmental or genetic confounding had been considered, and possibly ruled out, in the large body of literature on the five pathways in the Stodden model. To do so, we inspected all systematic reviews and meta-analysis of primary studies published after 2008 and searched for discussions on potential confounding by genetic and shared environmental factors.

As our second aim, we compare the strength of the evidence and effect sizes obtained for the effect of motor competence on physical activity in cross-sectional and longitudinal designs. This path of the Stodden model is important for intervention studies aiming to increase middle and late childhood physical activity. If familial confounding is present in this main Stodden pathway, we expect

cross-sectional associations to be stronger than longitudinal associations. In addition, we expect that interventions on motor competence would not increase physical activity to the degree predicted from the cross-sectional effect sizes.

As a third aim, we explicitly test the potential for familial confounding in the five bidirectional pathways of the Stodden model. This requires that the variance in the traits in the Stodden model in childhood and adolescence are caused by genetic and shared environmental factors. This can be tested in a nuclear family design (e.g., parental, spousal and sibling correlations) or in a wider pedigrees (correlations between, e.g., self-aunt/uncle, self-niece/nephew, etc.), but the strongest design focuses on the comparison of MZ and DZ twin correlations (Knopik et al., 2017; Polderman et al., 2015). We, therefore, review the existing twin studies on the contribution of genetic and shared environmental factors to each of the traits in the Stodden model. Furthermore, we review direct tests of familial confounding that estimate the overlap in genetic and shared environmental factors influencing multiple traits, e.g., between motor competence and physical activity.

In short, our research questions are:

1 To what extent have past systematic reviews and meta-analyses on the pathways of the Stodden model considered unmeasured confounding, in by particular genetic and shared environmental factors?
2 In the main pathway between motor competence and physical activity, are the reported cross-sectional associations stronger than longitudinal associations that in turn are stronger than the effects seen in intervention studies?
3 Do twin studies show that, during childhood and adolescence, genetic and shared environmental factors contribute to individual differences in the traits used in the Stodden model?

2 Method

2.1 Search and selection of systematic reviews and meta-analyses on the Stodden model

To address research question 1, a literature search was performed for systematic reviews and/or meta-analyses of the relationships between motor competence, physical activity, perceived motor competence, and physical fitness. Definitions and assessment strategies for these traits can be found in the Supplementary Sections 1, 2. We searched the Pubmed, Web of Science, and EMBASE databases for reviews published after January 1, 2009 (i.e., after the publication of the Stodden model) and before January 15, 2025 (date of final search). The detailed search strategy is shown in Supplementary Methods Section 3'. Of note, for physical activity traits we only extracted results on total physical activity (TPA), moderate-to-vigorous physical activity (MVPA) or leisure time physical activities (LTPA, including exercise and sports) but discarded light physical activity and sedentary behavior.

The extracted titles and abstracts were initially screened by YZ to identify reports fulfilling the inclusion criteria. Articles were stored in the Endnote citation manager. Full-text reading of selected systematic reviews and meta-analyses was performed independently by YZ and EdG. Discrepancies in article selection were discussed and resolved. References were checked to identify additional systematic reviews and meta-analyses on the traits in the Stodden model.

2.1.1 Inclusion and exclusion criteria

We included peer-reviewed systematic reviews or meta-analyses of observational or interventional studies in humans that assessed the association between any two of the four traits. Only reviews published in English with a focus on participants younger than 18 years old were included. We excluded reviews where the traits from the Stodden model were not among the primary outcomes, or were no association statistics or intervention effects were reported. We excluded reviews on special populations such as youth athletes, children with medical problems or psychiatric conditions. Figure 2 provides a flow diagram describing the selection of the reviews included in the data extraction and analysis step.

2.1.2 Data extraction

We extracted the authors of the systematic reviews, year of publication, presence of a meta-analysis, period covered by the search used, age range of the target population, number of primary studies included in the review, and the study design of the primary studies, i.e., (cluster) randomized controlled trial, non-randomized interventional studies, longitudinal, or cross-sectional studies (see Table 1). We then scrutinized the text of the discussion and conclusion sections of the reviews for mention of concerns about unmeasured confounding in general, and more specifically about genetic and shared environmental confounding. This process was repeated by both authors, and an automated text search for the keywords 'risk of bias', 'confound*', 'familial', 'environment*', 'genetic*' and 'heritab*' was used to verify our manual inspection. All information was extracted separately for all pathways (e.g., motor competence and physical activity, perceived motor competence and actual motor competence, motor competence and fitness, etc.) and ordered by age within each pathway.

2.1.3 Strength of evidence and effect sizes in the motor competence—physical activity pathway

To address research question 2, we extracted additional data on the overall strength of evidence and average effect sizes reported by the included reviews on the main bidirectional pathway of the Sodden model between motor competence and physical activity (see Table 2). The information was separately provided per study design, ordered by age groups (early childhood ~2–5 years of age; middle childhood ~6–12 years of age; and adolescence ~13–18 years of age), and further by the subdomains of the traits (e.g., for motor competence, subdomains like object control skills or balancing skills).

The rating for the level of evidence in support of a pathway was based on an adaptation of the methodology developed by Sallis et al. (2000) and later revised by Barnett et al. (2022). Based on the percentage of findings in the primary studies supporting the association according to the systematic review, a pathway was classified as a non-significant (coded as "0") when only 0 to 33% of studies reported a significant association, or when no significant meta-analytic effects across four or more studies were found. A pathway was classified as an inconsistent or indeterminate (coded as "?") association when between 34 and 59% of the primary studies reported a significant association or when less than four primary studies in total reported a

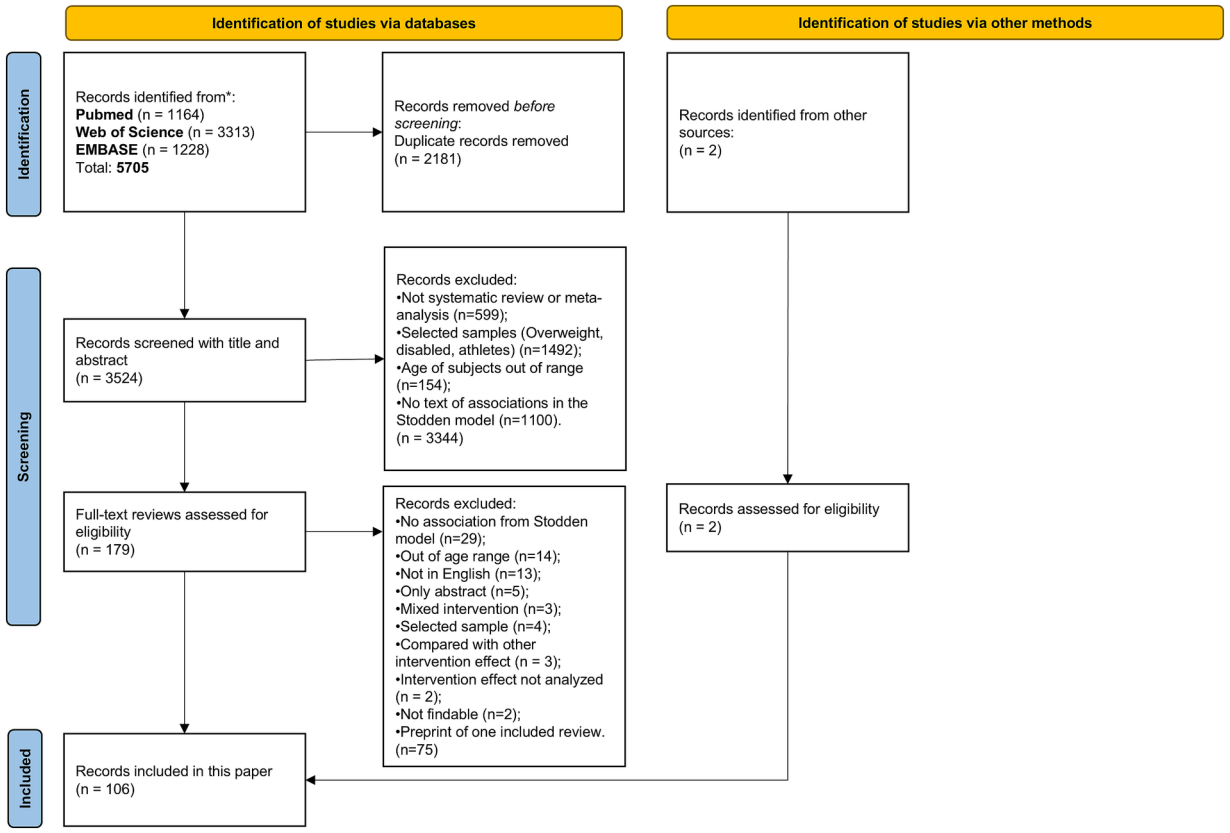


FIGURE 2
Flow diagram describing the selection of the systematic reviews and meta-analyses on the core pathways of the Stodden model.

significant association. Also, a significant meta-analytic effect across less than four primary studies was considered indeterminate. A pathway was classified as strong (coded as "+" or "-", depending on the direction of the association) when ≥60% of four or more primary studies supporting a significant association, or a significant meta-analytic effect across four or more primary studies was found. The ≥60% criterion to consider evidence "strong" may appear strict but takes into account that there is considerable concern about publication bias towards significant results in sports science in general (Pesce, 2012) and in the specific domain of motor development/physical activity studies (Barnett et al., 2022).

For the effect sizes for the associations/effects reported we used the meta-analytic estimates when a meta-analysis was present. For systematic reviews without meta-analysis, the average value reported in the review was used, or when no average was reported, we computed the median across reported results for the primary studies. The effect sizes were categorized into three types. Following Cohen (1988) and Peterson and Brown (2005) the effect was considered small if the pooled correlation was between $0.10 < r < 0.30$, the meta-analytic estimate (Hedges *g*, Cohen's *d*, or standardized mean difference (SMD)) was between 0.2 to 0.5, or the standardized regression β was between 0.05 and 0.25. The effect size was considered moderate if the pooled correlation was between $0.30 < r < 0.50$, the meta-analytic estimate (Hedges *g*, Cohen's *d*, or SMD) was between 0.5 to 0.8, or the standardized β was between 0.25–0.45. The effect was large if the pooled correlation was >0.50, the meta-analytic estimate (Hedges' *g*, Cohen's d or SMD) was >0.8, or the standardized β was ≥0.45.

2.2 Twin studies on the traits in the Stodden model

To address research question 3 on the potential for familial confounding, we retrieved all twin studies on the four traits of the Stodden model. The twin design compares the intra-pair resemblance between two types of sibling relationships; genetically identical twins or monozygotic (MZ) twins, a result of division of a single fertilized egg during an early stage in embryonic development, and non-identical twins or dizygotic (DZ) twins, resulting from two separate fertilized eggs (de Geus, 2023). Consequently, MZ twins are genetically identical and the difference between the twins is due to person-specific environmental factors, i.e., experiences that one of the twins has and the co-twin does not. Dizygotic twins shared on average 50% of their genetic make-up. In contrast to familial aggregation studies, that cannot separate genetic and familial environmental sources of covariance, twin studies can decompose all phenotypic variance of the trait of interest into sources of additive ('A') and non-additive ('D') genetic influences shared environmental influences (influences shared with other family members, e.g., upbringing; referred to as 'C') and person-specific environmental influences (influences unique to the individual; referred to as 'E').

TABLE 1 Systematic reviews and meta-analyses on the core pathways in the Stodden model (2008).

No.	Review	Type of review	Age range (years)	Trait 1	Trait 2	Primary studies on trait 1 and 2 (RCT/ INT/ LON/ CSS)	Confounding mentioned		
							General	Environ mental effects	Genetic effects
MC and PA (44 reviews included)									
1	Øglund et al. (2015)	Systematic review and meta-analysis	0–2	Motor development	PA	3 (0/0/2/1) *N* = 13,534	√	√	X
2	Santos et al. (2023)	Systematic review	0–3	MC	PA (aquatic activities)	6 (0/3/2/3) *N* = 215	√	X	X
3	Carson et al. (2017)	Systematic review	0–4	PA	Motor development	22 (6/6/1/10) *N* = 5,380	√	X	X
4	Timmons et al. (2012)	Systematic review	0–4	PA	MC	4 (3/1/0/0) *N* = 802	√	X	X
5	Bingham et al. (2016)	Systematic review	0–6	MC	TPA	11 (0/0/1/10) *N* = 12,338	√	X	X
6	Hesketh et al. (2017)	Systematic review	0–6	Motor skills	PA	10 (7/3/0/0) *N* = 3,204	X	X	X
7	Grady et al. (2025)	Systematic review and meta-analysis	0–6	PA (school and care-based PA)	FMS	16 (16/0/0/0) *N* = 4,905	√	X	X
8	Behringer et al. (2011)	Meta-analysis	0–18	PA (strength training)	Jump, run, throw	34 (0/34/0/0) *N* = 1,432	X	X	X
9	Chen et al. (2024)	Meta-analysis	2–6	PA	FMS	23 (22/1/0/0) *N* = 4,068	√	X	X
10	Barnett et al. (2022)	Systematic review	2–18	MC	PA	30 (2/0/26/3) *N* = 15,900	√	√	√
11	Figueroa and An (2017)	Systematic review	3–5	Motor skills	PA	11 (6/0//5) *N* = 2,157	√	X	X
12	Engel et al. (2018)	Systematic review and meta-analysis	3–5	FMS	TPA	11 (8/3/0/0) *N* = 3,023	√	X	X
13	Barnett et al. (2016)	Systematic review and meta-analysis	3–5	Locomotor skills	PA	13 (1/0/4/8) *N* = 6,556	√	√	X
14	Van Capelle et al. (2017)	Systematic review and meta-analysis	3–5	PA	MC	20 (11/9/0/0) *N* = 4,245	√	X	X
15	Veldman et al. (2021)	Systematic review	3–5	MVPA	Motor development	11 (4/6/1/1) *N* = 1,341	√	X	X
16	Xin et al. (2020)	Systematic review	3–6	FMS	PA	26 (0/0/2/24) *N* = 4,851	√	√	X
17	Xu et al. (2024)	Systematic review	3–6	FMS	MVPA	21 (0/0/4/18) *N* = 26,275	X	X	X

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TABLE 1 (Continued)

No.	Review	Type of review	Age range (years)	Trait 1	Trait 2	Primary studies on trait 1 and 2 (RCT/ INT/ LON/ CSS)	Confounding mentioned		
							General	Environ mental effects	Genetic effects
18	Jones et al. (2020)	Systematic review and meta-analysis	3–6	FMS	MVPA	19 (0/0/5/15) *N* = 3,690	X	X	X
19	Liu Y. et al. (2023)	Systematic review and meta-analysis	3–6	FMS	MVPA	11 (0/0/3/8) *N* = 2,514	√	X	X
20	Wang and Zhou (2024)	Meta-analysis	3–6	PA (MC-focused)	Gross motor skills	23 (23/0/0/0) *N* = 2070	√	X	X
21	Li et al. (2022)	Systematic review and meta-analysis	3–7	PA (extra PE)	FMS	23 (17/6/0/0) *N* = 2,258	√	X	X
22	Sinclair and Roscoe (2023)	Systematic review	3–11	PA (swimming)	FMS	10 (3/7/0/0) *N* = 611	√	X	X
23	Johnstone et al. (2018)	Systematic review and meta-analysis	3–12	PA (active play)	FMS	2 (2/0/0/0) *N* = 193	√	X	X
24	Liu et al. (2020)	Systematic review	3–12	PA (active video games)	FMS	9 (6/3/0/0) *N* = 478	√	X	X
25	Hassan et al. (2022)	Systematic review and network meta-analysis	3–12	PA (aerobic exercise)	Gross motor skills	13 (13/0/0/0) *N* = 1,109	√	X	X
26	Oppici et al. (2022)	Systematic review and meta-analysis	3–12	PA (exergame)	FMS	9 (6/3/0/0) *N* = 783	√	X	X
27	Sun and Chen (2024)	Systematic review and meta-analysis	3–12	PA (sports)	FMS	12 (12/0/0/0) *N* = 1701	√	X	X
28	Zhang et al. (2024)	Systematic review	8–17	PA	FMS	26 (11/15/0/0) *N* = 1,133	X	X	X
29	Lorås (2020)	Systematic review and meta-analysis	3–13	PA (extra PE)	MC	20 (10/10/0/0) *N* = 4,190	√	X	X
30	Holfelder and Schott (2014)	Systematic review	3–18	FMS	PA	22 (0/0/4/18) *N* = 10,107	√	X	X
31	Logan et al. (2015)	Systematic review	3–18	FMS	PA	13 (0/0/1/12) *N* = 10,534	X	X	X
32	Lubans et al. (2010)	Systematic review	3–18	FMS	PA	18 (0/0/4/14) *N* = 8,981	X	X	X
33	García-Hermoso et al. (2020)	Systematic review and meta-analysis	3–18	PA (extra PE)	FMS	15 (11/4/0/0) *N* = 7,177	√	X	X
34	Zeng et al. (2017)	Systematic review	4–6	PA	Motor skills	10 (10/0/0/0) *N* = 1,602	√	X	X
35	Comeras-Chueca et al. (2021)	Systematic review and meta-analysis	4–15	PA (active video game)	Motor competence	10 (8/2/0/0) *N* = 979	√	X	X

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TABLE 1 (Continued)

No.	Review	Type of review	Age range (years)	Trait 1	Trait 2	Primary studies on trait 1 and 2 (RCT/ INT/ LON/ CSS)	Confounding mentioned		
							General	Environ mental effects	Genetic effects
36	Graham et al. (2022)	Systematic review and meta-analysis	5–11	FMS	MVPA	19 (15/4/0/0) *N* = 10,412	√	X	X
37	Moon et al. (2024)	Systematic review and meta-analysis	5–12	PA (extra PE)	MC	27 (10/17/0/0) *N* = 13,281	√	X	X
38	Norris et al. (2016)	Systematic review	5–15	PA (active video game)	Motor skills	8 (4/4/0/0) *N* = 1,063	√	X	X
39	Dudley et al. (2011)	Systematic review	5–18	PA (extra PE and school sport)	MC	4 (3/1/0/0) *N* = 3,196	√	X	X
40	Collins et al. (2019a)	Meta-analysis	5–18	Strength training	Throw, sprint, squat, and jump	20 (0/20/0/0) *N* = 1,028	√	X	X
41	McDonough et al. (2020)	Systematic review	6–12	PA (active video games)	Motor skills	25 (25/0/0/0) *N* = 4,325	√	X	X
42	Rico-González (2023)	Systematic review	6–12	PA (extra PE)	FMS	4 (4/0/0/0) *N* = 1,235	√	√	X
43	Poitras et al. (2016)	Systematic review	7–15	Motor skills	TPA	9 (1/1/1/6) *N* = 5,013	√	X	X
44	Burton et al. (2023)	Systematic review and meta-analysis	11–17	MC	PA	30 (1/0/10/19) *N* = 17,702	√	X	X
MC and PMC (4 reviews included)									
10	Barnett et al. (2022)	Systematic review	2–18	MC	PMC	11 (0/2/3/6) *N* = 3,187	√	√	√
32	Lubans et al. (2010)	Systematic review	3–18	FMS	PMC	3 (3/0/0/0) *N* = 1,288	X	X	X
45	De Meester et al. (2020)	Systematic review and meta-analysis	3–24	MC	PMC	32 (1/0/3/29) *N* = 7,959	√	X	X
44	Burton et al. (2023)	Systematic review and meta-analysis	11–17	MC	PMC	58 (3/0/10/45) *N* = 22,256	√	X	X
PMC and PA (5 reviews included)									
46	Wang and Zhou (2023)	Systematic review	4–12	PA (MVPA)	PMC	3 (0/0/1/2) *N* = 1,464	X	X	X
47	Craggs et al. (2011)	Systematic review	4–18	PMC	PA	8 (0/0/8/0) *N* = 2,768	X	X	X
48	Babic et al. (2014)	Systematic review and meta-analysis	5–20	PMC	PA	46 (0/2/12/34) *N* = 32,438	√	X	X
49	Zamorano-Garcia et al. (2023)	Meta-analysis	7–18	PA	Perceived sport competence	10 (1/9/0/0) *N* = 3,626	√	√	X

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TABLE 1 (Continued)

No.	Review	Type of review	Age range (years)	Trait 1	Trait 2	Primary studies on trait 1 and 2 (RCT/ INT/ LON/ CSS)	Confounding mentioned		
							General	Environ mental effects	Genetic effects
50	Collins et al. (2019a)	Systematic review and meta-analysis	10–16	Resistance training	Perceived sport competence	7 (2/5/0/0) $N = 460$	√	√	X
MC and Physical fitness (10 reviews included)									
10	Barnett et al. (2022)	Systematic review and meta-analysis	2–18	MC	Physical fitness	16 (2/0/13/1) $N = 6,039$	√	√	√
51	Hui et al. (2024)	Systematic review and meta-analysis	3–10	MC	Physical fitness	23 (0/23/0/0) $N = 2007$	√	√	X
52	Liu C. et al. (2023)	Systematic review	3–16	FMS	CRF	16 (0/0/1/15) $N = 14,336$	X	X	X
32	Lubans et al. (2010)	Systematic review	3–18	FMS	Physical fitness	18 (0/0/4/14) $N = 8,981$	X	X	X
53	Cattuzzo et al. (2016)	Systematic review	3–18	MC	CRF	38 (0/0/7/31) $N = 35,189$	X	√	X
54	Utesch et al. (2019)	Meta-analysis	4–20	MC	CRF	19 (0/0/0/19) $N = 15,984$	X	X	X
55	Lang et al. (2018)	Systematic review	5–17	MC	CRF	4 (0/0/0/4) $N = 2,670$	√	√	X
56	Lin et al. (2022)	Systematic review	6–10	Neuromuscular training	Physical fitness	4 (0/4/0/0) $N = 346$	X	X	X
57	Jiang et al. (2024)	Systematic review and meta-analysis	7–14	MC	CRF	2 (0/0/0/2) $N = 4,932$	√	√	X
44	Burton et al. (2023)	Systematic review and meta-analysis	11–17	MC	Physical fitness	7 (1/0/1/5) $N = 1,146$	√	X	X
Physical fitness and PA (54 reviews included)									
58	Henriques-Neto et al. (2020)	Systematic review	0–18	Commuting PA	CRF and muscular strength	11 (1/1/1/8) $N = 18,592$	√	√	X
59	Smith et al. (2019)	Systematic review and meta-analysis	1–25	PA (extra PE)	Muscular fitness	17 (16/1/0/0) $N = 1,653$	√	X	X
60	Garcia-Hermoso et al. (2020)	Systematic review and meta-analysis	3–6	PA	CRF	9 (9/0/0/0) $N = 4,006$	√	X	X
61	Szeszulski et al. (2019)	Systematic review and meta-analysis	3–7	PA (school and care-based PA)	CRF	10 (8/2/0/0) $N = 3,061$	X	√	X
24	Liu et al. (2020)	Systematic review	3–12	PA (active video games)	Physical fitness	5 (5/0/0/0) $N = 304$	√	X	X
62	Pozuelo-Carrascosa et al. (2018)	Meta-analysis	3–12	PA (extra PE)	CRF	20 (20/0/0/0) $N = 7,287$	√	X	X

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TABLE 1 (Continued)

No.	Review	Type of review	Age range (years)	Trait 1	Trait 2	Primary studies on trait 1 and 2 (RCT/ INT/ LON/ CSS)	Confounding mentioned		
							General	Environ mental effects	Genetic effects
63	Stojanović et al. (2024)	Systematic review and meta-analysis	3–18	PA	CRF	3 (0/0/0/3) *N* = 605	X	X	X
64	Garcia-Hermoso et al. (2021)	Systematic review and meta-analysis	3–18	VPA	CRF	4 (0/0/4/0) *N* = 565	√	X	X
33	García-Hermoso et al. (2020)	Systematic review and meta-analysis	3–18	PA (extra PE)	CRF	20 (17/3/0/0) *N* = 4,485	√	X	X
65	Breslin et al. (2023)	Systematic review	4–12	PA (The Daily Mile)	Physical fitness	9 (1/8/0/0) *N* = 5,581	X	X	X
66	Anico et al. (2022)	Systematic review	4–12	School-based run/walk	CRF	7 (0/5/2/0) *N* = 5,024	√	√	X
67	Gutierrez-Garcia et al. (2018)	Systematic review	4–14	PA (Judo)	Physical fitness	4 (0/4/0/0) *N* = 403	X	X	X
35	Comeras-Chueca et al. (2021)	Systematic review and meta-analysis	4–15	Active video game	CRF	6 (3/3/0/0) *N* = 1,005	√	X	X
68	Villa-González et al. (2023)	Systematic review and meta-analysis	5–13	PA (extra PE)	Muscular fitness	17 (16/1/0/0) *N* = 1,653	√	√	X
69	Duncombe et al. (2022)	Systematic review and meta-analysis	5–17	HIIT	CRF	30 (24/6/0/0) *N* = 3,026	√	X	X
70	Larouche et al. (2014)	Systematic review	5–17	Commuting PA	CRF	10 (0/0/2/8) *N* = 26,948	√	X	X
71	Wu et al. (2023)	Systematic review and network meta-analysis	5–18	PA (extra PE)	Physical fitness	63 (48/15/0/0) *N* = 7,226	X	√	X
72	Zhou et al. (2024)	Systematic review	5–18	PA	Physical fitness	30 (24/7/0/0) *N* = 6,494	X	X	X
73	Bauer et al. (2022)	Systematic review and meta-analysis	5–18	HIIT	CRF	8 (0/8/0/0) *N* = 867	X	X	X
74	Eather et al. (2022)	Systematic review and meta-analysis	5–18	HIIT	CRF and muscular fitness	11 (3/8/0/0) *N* = 1,011	X	X	X
75	Lubans et al. (2011)	Systematic review	5–18	Commuting PA	CRF	5 (0/0/1/4) *N* = 13,604	√	√	X
76	Sun et al. (2013)	Systematic review	5–18	PA (extra PE)	CRF	11 (11/0/0/0) *N* = 2,694	√	√	X
77	Wu et al. (2021)	Meta-analysis	5–18	Resistance training	Muscle strength	42 (42/0/0/0) *N* = 1728	X	X	X
78	Moran et al. (2018)	Systematic review and meta-analysis	5–18	PA	Muscular fitness	21 (21/0/0/0) *N* = 2,267	X	X	X

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TABLE 1 (Continued)

No.	Review	Type of review	Age range (years)	Trait 1	Trait 2	Primary studies on trait 1 and 2 (RCT/ INT/ LON/ CSS)	Confounding mentioned		
							General	Environ mental effects	Genetic effects
79	Hanna et al. (2023)	Systematic review	6–11	PA (The Daily Mile)	Physical fitness	5 (0/5/0/0) *N* = 2,700	X	√	X
80	Errisuriz et al. (2018)	Systematic review	6–11	PA (extra PE)	CRF	8 (4/4/0/0) *N* = 12,977	X	X	X
42	Rico-González (2023)	Systematic review	6–12	PA (extra PE)	Physical fitness	8 (8/0/0/0) *N* = 5,710	√	√	X
81	Beets et al. (2009)	Meta-analysis	6–12	PA (after-school program)	Physical fitness	6 (6/1/0/0) *N* = 4,686	X	X	X
82	Burns et al. (2018)	Meta-analysis	6–12	PA	CRF	20 (13/10/0) *N* = 10,779	X	X	X
83	Braaksma et al. (2018)	Systematic review	6–12	PA	CRF	23 (23/0/0/0) *N* = 7,071	X	X	X
84	Reyes-Amigo et al. (2017)	Systematic review	6–12	HIIT	CRF	10 (6/4/0/0) *N* = 330	X	X	X
85	Gäbler et al. (2018)	Systematic review and meta-analysis	6–18	PA	Physical fitness	15 (0/15/0/0) *N* = 595	X	X	X
86	Neil-Sztramko et al. (2021)	Systematic review and meta-analysis	6–18	PA (extra PE)	Physical fitness	41 (41/0/0/0) *N* = NR	X	√	X
87	Li et al. (2024)	Multivariate and Network Meta-analysis	6–18	PA	Physical fitness	36 (0/0/NR/NR) *N* = 2,658	√	X	X
88	Gralla et al. (2019)	Systematic review	6–18	VPA	CRF	16 (0/0/0/16) *N* = 8,041	X	X	X
89	Cibinello et al. (2023)	Systematic review and meta-analysis	6–18	Pilates	Flexibility and muscle strength	10 (0/0/NR/NR) *N* = 804	√	√	X
90	Behringer et al. (2010)	Systematic review	6–18	PA	Muscular fitness	77 (1/1/12/63) *N* = 1728	X	X	X
43	Poitras et al. (2016)	Systematic review	7–16	PA	CRF	38 (6/3/1/28) *N* = 26,865	√	X	X
91	Lei and Jun (2022)	Systematic review	7–17	PA (Taekwondo Poomsae training)	Physical fitness	15 (0/15/0/0) *N* = 536	X	X	X
92	Pinho et al. (2024)	Meta-analysis	7–17	PA	Physical fitness	80 (0/0/NR/NR) *N* = 5,769	X	X	X
93	Clemente et al. (2022)	Systematic review	7–18	PA (soccer training)	Physical fitness	13 (0/13/0/0) *N* = 2,794	√	X	X
94	Woodforde et al. (2022)	Systematic review	7–18	PA (extra PE)	Physical fitness	4 (2/2/0/0) *N* = 444	X	X	X

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TABLE 1 (Continued)

No.	Review	Type of review	Age range (years)	Trait 1	Trait 2	Primary studies on trait 1 and 2 (RCT/ INT/ LON/ CSS)	Confounding mentioned		
							General	Environ mental effects	Genetic effects
95	Cox et al. (2020)	Meta-analysis	8–18	Resistance training	Muscle strength	11 (0/0/NR/NR) *N* = 253	√	√	X
96	Peralta et al. (2020)	Systematic review	8–19	PA (extra PE)	CRF	24 (0/15/2/7) *N* = 15,159	X	X	X
97	Zhao et al. (2023)	Meta-analysis	10–12	PA (jumping rope)	Physical fitness	15 (15/0/0/0) *N* = 1,048	√	√	X
98	Ferreira et al. (2024)	Systematic review	10–15	PA (swim exercise)	Physical fitness	5 (0/5/0/0) *N* = 459	√	X	X
99	Ramirez-Campillo et al. (2023)	Systematic review and meta-analysis	10–16	PA (Plyometric training)	Physical fitness	11 (0/0/??/??) *N*=NR	X	X	X
100	Garcia-Banos et al. (2020)	Systematic review and meta-analysis	10–18	PA (extra PE)	Muscular fitness	11 (3/8/0/0) *N* = 1,161	X	X	X
101	Minatto et al. (2016)	Systematic review and meta-analysis	10–19	PA (extra PE)	CRF	40 (23/17/0/0) *N* = 19,970	√	√	X
102	da Silva Bento et al. (2022)	Systematic review	10–19	HIIT	CRF	14 (14/0/0/0) *N* = 664	X	X	X
103	de Andrade Gonçalves et al. (2015)	Systematic review	11–19	PA	Physical fitness	6 (0/0/1/5) *N* = 7,599	X	√	X
104	Singh et al. (2022)	Systematic and meta-analysis	11–19	PA (jump rope training)	CRF	13 (2/11/0/0) *N* = 538	X	X	X
105	Costigan et al. (2015)	Systematic review and meta-analysis	13–18	HIIT	CRF	15 (9/6/0/0) *N* = 1,110	X	X	X
106	Behm et al. (2017)	Systematic review	13–18	PA (extra PE)	Muscular strength	8 (0/0/NR/NR) *N* = 3,297	X	X	X

CRF = Cardiorespiratory fitness; CSS = Cross-sectional Studies; FMS = Fundamental Movement Skills; HIIT = High-intensity interval training; INT = Non-randomized intervention studies; LON = Longitudinal studies; MC = Motor competence; MVPA = Moderate-to-vigorous physical activity; NR = Not reported; PA = Physical activity; PE = Physical Education; RCT = (Clustered) Randomized Controlled Trials studies; PMC = Perceived motor competence; RCT = (Clustered) Randomized Controlled Trial studies; TPA = total physical activity; VPA = Vigorous physical activity.

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TABLE 2 Design characteristics and main findings from the reviews on the association between motor competence and physical activity.

Review	Type of review	Publication year (search period)	Age range (years)	Trait 1 (MC domain)	Trait 2 (PA domain)	# of studies on trait 1 and 2 (RCT/ INT/LON/ CSS)	Overall findings	Strength of evidence*	Effect size **
Cross-sectional–early childhood									
Santos et al. (2023)	Systematic review	2023 (until 2022.12.22)	0–3	MC	PA (aquatic activities)	6 (0/3/2/3) N = 215	All six studies (100%) found a significant association between swimming activities and motor development.	+	Not specified
Bingham et al. (2016)	Systematic review	2016 (until 2016.09)	0–6	MC	TPA	9 (0/0/1/8) N = 1,202	Nine out of 23 analyses (37%) identified motor competence as associated with total physical activity.	?	Not specified
Bingham et al. (2016)	Systematic review	2016 (until 2016.09)	0–6	MC	MVPA	10 (0/0/1/9) N = 1809	Eleven out of 26 analyses (42%) identified motor competence as associated with moderate-to-vigorous physical activity.	?	Not specified
Figueroa and An (2017)	Systematic review	2017 (until 2015.03.31)	3–5	MC (Motor skill competence)	PA	11 (6/0/0/5) N = 2,157	Eight out of 11 studies (72.7%) reported a significant association. The effect size was not specified but noted to differ by gender, physical activity intensity, motor skill type, and day of the week (weekdays versus weekends).	+	Not specified
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	MC (fundamental movement skills)	PA	26 (0/0/2/24) N = 4,851	Sixteen out of 26 studies (61.5%) reported a significant association between MC and any PA trait (r = 0.10–0.46).	+	Small to moderate
Xu et al. (2024)	Systematic review	2024 (until 2022.07)	3–6	MC (fundamental movement skills)	MVPA	19 (0/0/4/18) N = 26,275	Across 19 studies, fifteen out of 23 (82.6%) analyses found a significant association between FMS and MVPA (r = 0.25, 95%CI: 0.22 ~ 0.27).	+	Small
Xu et al. (2024)	Systematic review	2024 (until 2022.07)	3–6	MC (fundamental movement skills)	MVPA	12 (0/0/2/11) N = 6,561	Across 12 studies, seven out of 14 (50%) analyses found a significant association between FMS and TPA (r = 0.23, 95%CI: 0.19 ~ 0.27).	?	Small
Jones et al. (2020)	Systematic review and meta-analysis	2020 (until 2019.04)	3–6	MC (fundamental motor skills)	MVPA	12 (0/0/0/12) N = 2,578	Eight of 12 analyses (67%) reported a significant association. Meta-analysis showed a small effect (r = 0.20, 95%CI: 0.13–0.26). Heterogeneity: τ value of ±0.089 from a random effect model.	+	Small
Liu Y. et al. (2023)	Systematic review and meta-analysis	2023 (until 2023.08)	3–6	MC (fundamental motor skills)	MVPA	3 (0/0/1/2) N = 260	Three datasets examined the association between total MC and MVPA. Meta-analysis showed a large effect (β = 0.56, 95% CI: 0.38–0.75, p = 0.001). No heterogeneity (I^2 = 0%, p = 0.99) from a random effect test.	?	Large
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	MC (fundamental movement skills)	MVPA	16 (0/0/1/16) N = 2,617	Eleven out of 16 studies (69%) found a significant association between MC and MVPA.	+	Small to moderate
Jones et al. (2020)	Systematic review and meta-analysis	2020 (until 2019.04)	3–6	MC (fundamental motor skills)	TPA	12 (0/0/0/12) N = 1903	Ten out of 12 analyses (83%) found a significant association. Meta-analysis showed a small effect (r = 0.20, 95%CI: 0.12–0.28). Heterogeneity: τ value of ±0.113 from a random effect model.	+	Small

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TABLE 2 (Continued)

Review	Type of review	Publication year (search period)	Age range (years)	Trait 1 (MC domain)	Trait 2 (PA domain)	# of studies on trait 1 and 2 (RCT/INT/LON/CSS)	Overall findings	Strength of evidence*	Effect size **
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	MC (fundamental movement skills)	TPA	12 (0/0/0/12) N = 2,152	Nine out of 12 studies (75%) supported small to moderate associations between MC and TPA.	+	Small to moderate
Barnett et al. (2016)	Systematic review and meta-analysis	2016 (1995–2014)	3–5	Locomotor skills	PA/Sports	7 (1/0/0/6) N = 963	Five out of 11 analyses (45%) found a significant association between PA/sports and locomotor skills. Heterogeneity was not reported on this association.	?	Not specified
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	Locomotor skills	TPA	10 (0/0/0/10) N = 2,144	Six out of 10 studies (60%) found a significant association between locomotor skills and TPA.	+	Small to moderate
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	Locomotor skills	MVPA	16 (0/0/2/15) N = 3,024	Nine out of 16 studies (56%) found a significant association between locomotor skills and MVPA.	?	Small to moderate
Liu Y. et al. (2023)	Systematic review and meta-analysis	2023 (until 2023.08)	3–6	Locomotor skills	MVPA	5 (0/0/1/4) N = 981	Six datasets examined the association between locomotor skill and MVPA Meta-analysis showed no association (β = 0.06, 95% CI: −0.35- 0.47, p = 0.79). Heterogeneity: I^2 = 90.26%, (p = 0.001) from a random effect test.	0	No association
Barnett et al. (2016)	Systematic review and meta-analysis	2016 (1995–2014)	3–5	Object control skills	PA/Sports	6 (1/0/0/5) N = 863	Five out of 11 analyses (45%) found a significant association between PA/sports and object control skills. Heterogeneity was not reported on this association.	?	Not specified
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	Object control skills	TPA	11 (0/0/0/11) N = 2,190	Nine out of 11 studies (82%) found a significant association between objective control skills and total physical activity.	+	Small to moderate
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	Object control skills	MVPA	17 (0/0/1/16) N = 3,024	Twelve out of 17 studies (71%) found a significant association between object control skills and MVPA.	+	Small to moderate
Liu Y. et al. (2023)	Systematic review and meta-analysis	2023 (until 2023.08)	3–6	Object control skills	MVPA	4 (0/0/1/3) N = 855	Four datasets examined the association between object control skill and MVPA. Meta-analysis showed a significant, small effect (β = 0.15, 95% CI: 0.02, 0.27, p = 0.02). No heterogeneity (p = 0.15) from a random effect test.	+	Small
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	Stability	TPA	4 (0/0/0/4) N = 1,424	Two out of four studies (50%) found a significant association between stability skills and TPA.	?	Small to moderate
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	Stability	MVPA	3 (0/0/1/2) N = 1,410	One out of three studies reported a significant association between stability skills and MVPA.	?	Small to moderate
Cross-sectional–middle/late childhood									
Holfelder and Schott (2014)	Systematic review	2014 (2000–2013.06)	3–18	MC (fundamental movement skills)	PA	12 (0/0/2/10) N = 6,071	Ten out of 12 studies (83.3%) found a significant association between MC and PA, with r ranging from 0.17 to 0.47.	+	Small to moderate

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TABLE 2 (Continued)

Review	Type of review	Publication year (search period)	Age range (years)	Trait 1 (MC domain)	Trait 2 (PA domain)	# of studies on trait 1 and 2 (RCT/ INT/LON/ CSS)	Overall findings	Strength of evidence*	Effect size **
Barnett et al. (2016)	Systematic review and meta-analysis	2016 (1995–2014)	3–18	MC (skill composite)	PA/ sports	3 (1/0/1/1) $N = 913$	Three out of four analyses (75%) found a significant association between PA and motor skill composite score. Heterogeneity was not reported for the random effect test on this association.	+	Not specified
Logan et al. (2015)	Systematic review	2015 (until 2013.11)	3–18	MC (fundamental movement skills)	PA	13 (0/0/1/12) $N = 10,534$	All studies found at least one significant association between FMS and physical activity. Effect sizes differed across age: small to moderate in early childhood and adolescence and small to large in middle to late childhood.	+	Small to moderate Small to large
Lubans et al. (2010)	Systematic review	2010 (until 2009.06)	3–18	MC (fundamental movement skills)	PA	13 (0/0/2/11) $N = 5,187$	Twelve out of 13 studies (92.3%) found a significant association between MC and at least one domain of PA.	+	Not specified
Poitras et al. (2016)	Systematic review	2016 (until 2015.01)	7–15	MC (motor skill development)	TPA	6 (0/0/1/5) $N = 5,179$	Three out of five (60%) cross-sectional studies found a significant association.	+	Not specified
Burton et al. (2023)	Systematic review and meta-analysis	2023 (until 2022.08.05)	11–17	MC (motor competence)	PA	8 (1/0/0/7) $N = 5,224$	Eight out of 13 analyses (61%) found a significant association. Meta-analysis showed a small effect (r = 0.21, 95%CI: 0.12–0.30). Very high heterogeneity ($I^2 = 90.64$) from a random effect test.	+	Small
Holfelder and Schott (2014)	Systematic review	2014 (2000–2013.06)	3–18	Locomotor skills	PA	5 (0/0/1/4) $N = 744$	All five studies (100%) found a significant, small to moderate association between object control and PA, with r ranging from 0.14 to 0.46.	+	Small to moderate
Burton et al. (2023)	Systematic review and meta-analysis	2023 (until 2022.08.05)	11–17	Locomotor skills	PA	5 (0/0/2/3) $N = 1,443$	Five out of six analyses (80%) found a significant association. Meta-analysis showed a small effect (r = 0.21, 95% CI: 0.12–0.30). High heterogeneity ($I^2 = 62.94$) from a random effect test.	+	Small
Holfelder and Schott (2014)	Systematic review	2014 (2000–2013.06)	3–18	Object control Skills	PA	6 (0/0/2/4) $N = 1824$	All six studies (100%) found a significant, association between object control and PA.	+	Small to moderate
Burton et al. (2023)	Systematic review and meta-analysis	2023 (until 2022.08.05)	11–17	Object control skills	PA	6 (0/0/2/4) $N = 5,081$	Eight out of 12 analyses (67%) found a significant association. Meta-analysis showed a small effect (r = 0.26, 95% CI: 0.18–0.33). Moderate heterogeneity ($I^2 = 38.58$) from a random effect test.	+	Moderate
Burton et al. (2023)	Systematic review and meta-analysis	2023 (until 2022.08.05)	11–17	Stability/ balance	PA	5 (0/0/1/4) $N = 6,369$	Eight out of 11 analyses (72.7%) found a significant association. Meta-analysis showed a small effect (r = 0.20,95%CI: 0.13–0.27). Very high heterogeneity ($I^2 = 86.22$) from a random effect test.	+	Small

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TABLE 2 (Continued)

Review	Type of review	Publication year (search period)	Age range (years)	Exposure	Outcome	# of studies using LON	Overall findings	Strength of evidence*	Effect size **
Longitudinal–early childhood—MC - > PA									
Øglund et al. (2015)	Systematic review and meta-analysis	2015 (until 2014.09)	0–2	MC (motor development)	PA	3 *N* = 4,951	Two of three studies (66.7%) found that motor development before age 2 predicted physical activity and sport participation in youth with a small effect size. Heterogeneity was not reported for the random effect test on this association.	+	Small
Jones et al. (2020)	Systematic review and meta-analysis	2020 (until 2019.04)	3–6	MC (fundamental motor skills)	PA	5 *N* = 1,112	Three out of five longitudinal studies (60%) showed that MC predicts PA with a small effect size ($0.21 < r < 0.28$). Heterogeneity was not reported for the random effect test on this association.	+	Small
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	MC (fundamental movement skills)	PA	2 *N* = 357	Two longitudinal studies found that MC did not predict PA.	0	No prediction
Longitudinal–middle/late childhood–MC - > PA									
Graham et al. (2022)	Systematic review and meta-analysis	2021 (until 2017.05)	5–11	MC (fundamental movement skills)	MVPA	19 *N* = 10,412	Only six out of 19 studies showing significant prediction (31.5%). Fourteen of the 19 studies were pooled into a meta-analysis. FMS had a large effect on daily MVPA (13.3 min/day, 95% CI 8.0–18.6; $R^2 = 0.89$). Heterogeneity: τ value of ±7.6 (95%CI: −13 to 21) from a random effect model.	?	Large
Holfelder and Schott (2014)	Systematic review	2014 (2000–2013.06)	3–18	MC (fundamental movement skills)	PA	7 *N* = 1936	Motor skill competence at baseline significantly explained 5–18% of variance in PA at follow-up in 5 out of 7 studies (71.4%).	+	Small
Barnett et al. (2022)	Systematic review	2022 (until 2019.11.08)	2–18	MC (skill composite)	PA	7 *N* = 4,167	Across seven studies, 71% of the analyses reported a significant prediction of PA by total MC (PA ranging from LPA to VPA, with most studies using MVPA).	+	Small
Barnett et al. (2022)	Systematic review	2022 (until 2019.11.08)	2–18	Locomotor, Coordination, Stability skills	PA	15 *N* = 6,331	Across 15 studies, 42% of the analyses showed locomotor and coordination/ stability skills to predict PA (PA ranging from LPA to VPA, with most studies using MVPA).	?	Small to moderate
Longitudinal–early childhood–PA- > MC									
Jones et al. (2020)	Systematic review and meta-analysis	2020 (until 2019.04)	3–6	PA	MC (fundamental motor skills)	2 *N* = 344	Only two studies explored the longitudinal prediction of MC by PA, showing PA to predict balance and locomotor, but not (or a negative effect) for agility and object control. Heterogeneity was not reported on this association.	?	Small

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TABLE 2 (Continued)

Review	Type of review	Publication year (search period)	Age range (years)	Exposure	Outcome	# of studies using LON	Overall findings	Strength of evidence*	Effect size **
Xin et al. (2020)	Systematic review	2020 (2000.01–2020.04)	3–6	PA	MC (fundamental movement skills)	2 *N* = 357	Two longitudinal studies found that PA was a significant predictor for MC (β = 0.07–0.26).	?	Small
Longitudinal–middle/late childhood–PA- > MC									
Barnett et al. (2022)	Systematic review	2022 (until 2019.11.08)	2–18	PA	MC (Motor competence)	11 *N* = 5,528 (2 trials were included)	Eleven longitudinal studies investigated the pathway from PA to any form of MC, with no evidence to support an association, with only 8% analyses significant. Both interventions did not show a significant effect.	0	No effect
Barnett et al. (2022)	Systematic review	2022 (until 2019.11.08)	2–18	PA	Locomotor, Coordination, Stability skills	11 *N* = 4,586	Across 11 studies, 24% of the analyses supported a pathway from locomotor/ coordination/ stability skills to PA (ranging from LPA to VPA, with most studies using MVPA).	0	No effect
Barnett et al. (2022)	Systematic review	2022 (until 2019.11.08)	2–18	PA	Object control skills	5 *N* = 2,200	Across five studies, 38% analyses supported a pathway from object control skills to PA (ranging from LPA to VPA, with most studies using MVPA).	?	Small

Review	Type of review	Publication year (search period)	Age range (years)	Intervention	Outcome	# of RCT/ INT studies	Overall findings	Strength of evidence*	Effect size **
Intervention–early childhood–MC - > PA									
Hesketh et al. (2017)	Systematic review	2017 (until 2015.10)	0–6	MC (motor skills)	PA	10 (7/3) *N* = 3,204	Out of 10 RCT/INT studies, five (50%) reported motor skills training had a positive effect on time spent on PA.	?	Not specified
Engel et al. (2018)	Systematic review and meta-analysis	2018 (until 2017.7.20)	3–5	MC (fundamental motor skills)	TPA	7 (6/1) *N* = 1,623	Three out of seven (42.9%) studies found a significant effect of MC intervention on the total amount of PA. Meta-analyses showed a small improvement in total PA (SMD = 0.32; 95% CI: 0.09–0.54; $p = 0.006$). Very high heterogeneity ($I^2 = 76\%$, Chi^2 $p = 0.0004$) from a random effect test.	?	Small
Engel et al. (2018)	Systematic review and meta-analysis	2018 (until 2017.7.20)	3–5	MC (fundamental motor skills)	MVPA	7 (7/0) *N* = 1,531	One out of seven (14.3%) studies found a significant effect of MC intervention on MVPA. Meta-analyses showed a small improvement in MVPA (SMD = 0.21; 95% CI: 0.01–0.40; $p = 0.03$). High heterogeneity ($I^2 = 63\%$, Chi^2 $p = 0.01$) from a random effect test.	0	Small

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TABLE 2 (Continued)

Review	Type of review	Publication year (search period)	Age range (years)	Intervention	Outcome	# of RCT/ INT studies	Overall findings	Strength of evidence*	Effect size **
Intervention–middle/late childhood–MC - > PA									
Engel et al. (2018)	Systematic review and meta-analysis	2018 (until 2017.7.20)	5–12	MC (fundamental motor skills)	TPA	3 (2/1) $N = 414$	None of three studies (0%) found a significant effect of MC intervention on the total amount of PA, while meta-analysis showed a small significant improvement in total PA (SMD = 0.23; 95% CI: 0.03–0.42; $p = 0.02$). No heterogeneity ($I^2 = 0\%$, Chi^2 $p = 1$) from a random effect test.	0	Small
Engel et al. (2018)	Systematic review and meta-analysis	2018 (until 2017.7.20)	5–12	MC (fundamental motor skills)	MVPA	3 (0/3) $N = 348$	One out of three (33.3%) studies found a significant effect of MC intervention on MVPA. Meta-analysis showed a small significant improvement in MVPA (SMD = 0.29 95% CI: 0.08–0.51; $p = 0.007$). High heterogeneity ($I^2 = 63\%$, Chi^2 $p = 0.01$) from a random effect test.	?	Small
Intervention–early childhood–PA - > MC									
Timmons et al. (2012)	Systematic review	2012 (until 2011.03)	0–4	PA	MC	4 (3/1) $N = 802$	All four intervention studies found that PA significantly improved MC.	+	Not specified
Carson et al. (2017)	Systematic review	2017 (until 2016.4.14)	0–4	PA	MC (motor development)	12 (6/6) $N = 5,245$	Ten out of 12 intervention studies (83.3%) found that PA improved MC.	+	Not specified
Grady et al. (2025)	Systematic review and meta-analysis	2025 (2014.09–2022.10)	0–6	PA (early childhood education and care-based PA)	MC (fundamental movement skills)	16 (16/0) $N = 4,905$	Early childhood education and care-based PA was found to significantly improve FMS (SMD = 0.544, 95%CI: 0.1–0.98, $p = 0.015$). Very high heterogeneity ($I^2 = 95.8\%$) from a random effect test.	+	Moderate
Chen et al. (2024)	Meta-analysis	2024 (until 2023.11.01)	2–6	PA (MC-focused exercise training)	MC (fundamental motor skills)	23 (22/1) $N = 4,068$	All 23 intervention studies (22 RCT) found that motor skills-focused exercise training significantly improved FMS compared to the control group, with structured intervention the most effective (Hedge's $g = 1.29$, $p < 0.001$). No heterogeneity ($I^2 < 25\%$) from a random effect test.	+	Large
Wang and Zhou (2024)	Meta-analysis	2024 (until 2024.03)	3–6	PA (MC-focused exercise training)	MC (gross motor skills)	23 (23/0/0/0) $N = 2070$	Twenty out of 23 studies were included in the meta-analysis. Of these, 17 (85%) showed significant improvement by motor skills-focused exercise training on gross motor skills as compared to active control (Cohen's d = 1.53). Very high heterogeneity ($I^2 = 93\%$, $p < 0.01$) from a random effect test.	+	Large
Veldman et al. (2021)	Systematic review	2021 (until 2019.11.21)	3–5	MVPA	MC (motor development)	11 (4/6) $N = 1,281$	All ten intervention studies (100%) found a positive effect of MVPA on motor development (either total score, a specific component, or an individual skill).	+	Not specified

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TABLE 2 (Continued)

Review	Type of review	Publication year (search period)	Age range (years)	Intervention	Outcome	# of RCT/ INT studies	Overall findings	Strength of evidence*	Effect size **
Van Capelle et al. (2017)	Systematic review and meta-analysis	2017 (until 2016.03.30)	3–5	PA	MC (fundamental motor skills)	21 (6/15) $N = 4,245$	Restricting to teacher-led interventions, the meta-analysis across 13 analyses indicated that PA intervention led to a trivial but significant improvement in MC (SMD = 0.13, 95%CI: 0.03–0.22, $p = 0.008$) in only 4 analyses (30.7%). Very high heterogeneity ($I^2 = 84\%$, $p < 0.00001$) from a random effect test.	?	Small
Zeng et al. (2017)	Systematic review	2017 (2000.01–2017.07)	4–6	PA	MC (motor skills)	10 (10/0) $N = 1,602$	Eight out of 10 RCTs (80%) reported that increasing PA led to significant improvements in motor performance.	+	Not specified
Van Capelle et al. (2017)	Systematic review and meta-analysis	2017 (until 2016.03.30)	3–5	PA	Object control skills	7 (5/2) $N = 558$	Restricting to teacher led interventions the meta-analysis across eight analyses indicated a small but significant improvement in object control skills (SMD = 0.47, 95%CI: 0.15–0.80, $p = 0.004$) in 6 analyses (75%). Very high heterogeneity ($I^2 = 89\%$, p < 0.00001) from a random effect test.	+	Small
Van Capelle et al. (2017)	Systematic review and meta-analysis	2017 (until 2016.03.30)	3–5	PA	Locomotor skills	5 (4/1) $N = 602$	Restricting to teacher led interventions the meta-analysis across seven analyses indicated a small significant improvement in locomotor skills (SMD = 0.44, 95%CI: 0.16–0.73, $p = 0.002$). High heterogeneity ($I^2 = 57\%$, $p = 0.06$) from a random effect test.	+	Small
Li et al. (2022)	Systematic review and meta-analysis	2021	3–7	PA (physical education)	MC (fundamental movement skills)	23 (17/6) $N = 2,258$	Meta-analysis showed a significant improvement of extra physical education on any form of MC (SMD range:1.38–1.56, $I^2 = 59.2$–93.8%). Very high heterogeneity ($I^2 = 89.7\%$, $p = 0.0000$) from a random effect test.	+	Large
Johnstone et al. (2018)	Systematic review and meta-analysis	2018 (until 2016.12)	3–12	PA (active play)	MC (fundamental movement skills)	2 (2/0) $N = 193$	Both studies showed a significant effect of active play interventions on children's FMS quotient score and one-leg balance. Meta-analysis could not be conducted with two studies.	?	Not specified
Liu et al. (2020)	Systematic review	2020 (until 2020.10)	3–12	PA (active video games)	MC (fundamental movement skills)	5 (3/2) $N = 340$	Across five studies, two (40%) reported that active video games significantly improved FMS compared to a control manipulation.	?	Not specified
Zhang et al. (2024)	Systematic review	2024 (2000–2023)	8–17	PA	MC (fundamental motor skills)	26 (11/15) $N = 1,133$	Across 26 studies, 16 out of 17 (94.1%), ten out of ten (100%), and two out of two studies (100%) found significant effect of PA on locomotor, balance, and object control skills, respectively.	+	Not specified
Oppici et al. (2022)	Systematic review and meta-analysis	2022 (2007–2022)	3–12	PA (exergaming)	MC (fundamental movement skills)	9 (6/3) $N = 783$	Across nine studies, seven out of 14 analyses (50%) found that exergaming had significant improvements in MC as compared to the control (r = 0.24, 95%CI: 0.11–0.36). Heterogeneity from a random effect test was not reported.	?	Small

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TABLE 2 (Continued)

Review	Type of review	Publication year (search period)	Age range (years)	Intervention	Outcome	# of RCT/ INT studies	Overall findings	Strength of evidence*	Effect size **
Sun and Chen (2024)	Systematic review and meta-analysis	2024 (2001–2022)	3–12	PA (sports game)	MC (fundamental motor skills)	12 (12/0) $N = 1701$	All 12 studies (100%) found that sports game interventions had a significant effect on MC (SMD = 0.30, $p < 0.0001$). No details on the meta-analytic test approach were reported.	+	Small
Intervention–Middle/Late Childhood–PA - > MC									
Moon et al. (2024)	Systematic review and meta-analysis	2024 (until 2021.11)	5–12	PA (physical education)	MC	27 (10/17) $N = 13,281$	Twenty-six studies were included in meta-analyses with 22 (84.6%) showing statistically significant effect on MC (Hedges' g = 0.71; 95% CI = 0.60–0.81; $p < 0.001$). Very high heterogeneity ($I^2 = 78.4\%$) from a random effect test.	+	Large
Rico-González (2023)	Systematic review	2023 (until 2022.02)	4–12	PA (school-based physical education)	FMS	4 (4/0)	Across four studies, three (75%) showed significant effects of PA (school-based physical education) on FMS.	+	Not specified
Norris et al. (2016)	Systematic review	2016 (until 2015.05)	5–15	PA (active video game)	MC (motor skills)	3 (2/1) $N = 805$	Across three studies, two (66.7%) showed significant effects of PA (active video game) on MC as compared to control.	+	Not specified
García-Hermoso et al. (2020)	Systematic review and meta-analysis	2020 (until 2019.10)	3–18	PA (physical education)	FMS	7 (5/2) $N = 3,870$	All seven studies (100%) showed significant effects of PE-based PA interventions on FMS (Hedges g = 0.38; 95% CI, 0.27–0.49). High heterogeneity ($I^2 = 73.4\%$, $p = 0.02$) from a random effect test.	+	Small
Dudley et al. (2011)	Systematic review	2011 (1990.01–2010.06)	5–18	PE and school sport	MC	4 (3/1) $N = 3,196$	Across four studies, all analyses supported an effect of school sports on MC.	+	Not specified
Sinclair and Roscoe (2023)	Systematic review	2023 (until 2023.02)	3–11	PA (swimming)	MC (fundamental movement skills)	10 (3/7/0/0) $N = 611$	All ten studies found that swimming significantly improved at least one domain of MC.	+	Not specified
Hassan et al. (2022)	Systematic review and network meta-analysis	2022 (Until 2022.05)	3–12	Aerobic exercise	MC (gross motor skills)	13 (13/0) $N = 1,109$	Network meta-analysis showed that aerobic exercise training was an effective treatment for the total gross motor skills (ES: 7.49, 95% Cl: 0.1 to 15.7). Bayesian random-effects modeling was used and no heterogeneity was found.	+	Large
Hassan et al. (2022)	Systematic review and network meta-analysis	2022 (Until 2022.05)	3–12	PA (exergaming)	MC (gross motor skills)	13 (13/0) $N = 1,109$	Network meta-analysis showed that exergaming was not an effective treatment for the total gross motor skills (ES: −0.17, 95% Cl: −12.8 to 12.4). Bayesian random-effects modeling was used and no heterogeneity was found.	0	No effect

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TABLE 2 (Continued)

Review	Type of review	Publication year (search period)	Age range (years)	Intervention	Outcome	# of RCT/ INT studies	Overall findings	Strength of evidence*	Effect size **
Hassan et al. (2022)	Systematic review and network meta-analysis	2022 (Until 2022.05)	3–12	Aerobic exercise training	Locomotor skills	11 (11/0) $N = 1,021$	Network meta-analysis showed that aerobic exercise training was not an effective treatment for locomotor skills (ES: 4.12, 95% Cl: −1.4 to 9.4). Bayesian random-effects modeling was used and no heterogeneity was found.	0	No effect
Hassan et al. (2022)	Systematic review and network meta-analysis	2022 (Until 2022.05)	3–12	PA (exergaming)	Locomotor skills	11 (11/0) $N = 1,021$	Network meta-analysis showed that exergaming was an effective treatment for locomotor skills (ES: 12.50, 95% Crl: 0.28 to 24.50). Bayesian random-effects modeling was used and no heterogeneity was found.	+	Large
Hassan et al. (2022)	Systematic review and network meta-analysis	2022 (Until 2022.05)	3–12	Aerobic exercise training	Object control skills	16 (16/0) $N = 1,515$	Network meta-analysis showed that aerobic exercise training was an effective treatment for object control skills (SMD: 6.90, 95% Cl: 1.39 to 13.50). Bayesian random-effects modeling was used and no heterogeneity was found.	+	Large
Hassan et al. (2022)	Systematic review and network meta-analysis	2022 (Until 2022.05)	3–12	PA (exergaming)	Object control skills	16 (16/0) $N = 1,515$	Network meta-analysis showed that exergaming was not an effective treatment for object control skills (SMD: −0.4, 95% Cl: −10.2 to 8.9). Bayesian random-effects modeling was used and no heterogeneity was found.	0	No effect
McDonough et al. (2020)	Systematic review	2020 (2000–2020)	6–12	PA (18), exergaming (7)	MC (motor skill development)	25 (25/0) $N = 4,325$	Out of 25 RCTs, 20 (80%) that used various PA interventions led to significant improvements children's motor skill development.	+	Not specified
Lorås (2020)	Systematic review and meta-analysis	2020 (2002–2020)	3–13	PA (physical education)	MC	20 (10/10/0/0) $N = 4,190$	Sixteen out of 23 analyses (69.6%) found that physical education intervention had significant effect on overall motor competence ($g = -0.69$, 95%CI: −0.91 to-0.46, $p < 0.001$). Very high heterogeneity ($I^2 = 92.74\%$) from a random effect test.	+	Moderate
Carson et al. (2017)	Systematic review	2016 (until 2015.01)	7–15	PA	MC (motor skill development)	2 (1/1) $N = 203$	Neither of the two intervention studies found effects on motor skill development.	?	No effect
Behringer et al. (2011)	Meta-analysis	2011 (until 2009.08)	0–18	Strength training	Jump, run, throw	34 (0/34) $N = 1,432$	Meta-analysis indicated that strength training led to a significant improvement in combination of jumping, running, and throwing ES = 0.52 (95%CI: 0.33–0.71). No heterogeneity ($I^2 = 0\%$) from a fixed effects model.	+	Moderate to large

(Continued)

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TABLE 2 (Continued)

Review	Type of review	Publication year (search period)	Age range (years)	Intervention	Outcome	# of RCT/ INT studies	Overall findings	Strength of evidence*	Effect size **
Comeras-Chueca et al. (2021)	Systematic review and meta-analysis	2021 (until 2021.03)	4–15	Active video game	Motor competence	10 (8/2) $N = 979$	Seven out of 10 (70%) studies found that active video game had a significant improvement on motor competence. Heterogeneity wasn't reported for the random effect test on the PA-MC association.	+	Not specified
Collins et al. (2019a)	Meta-analysis	2019 (until 2017.06)	5–18	Strength training	Throw, sprint, squat-, standing-long-, and vertical jump	22 (0/22) $N = 943$	Significant intervention effects were identified in 33 analyses on sprint (Hedges' $g = 0.292$,95% CI: 0.017 to 0.567, $p = 0.038$), squat jump (Hedges' $g = 0.730$, 95% CI: 0.374 to 1.085, $p = < 0.001$), standing long jump (Hedges' $g = 0.298$, 95% CI 0.096 to 0.499, $p = 0.004$), throw (Hedges' $g = 0.405$, 95% CI 0.094 to 0.717, $p = 0.011$) and vertical jump (Hedges' $g = 0.407$, 95% CI 0.251 to 0.564, $p = < 0.001$) ability. High heterogeneity for squat jump ($I^2 = 59\%$), and noor moderate heterogeneity for other outcomes ($I^2 = 0–35\%$).	+	Moderate to large

* Strength of evidence was categorized into three types: "0," no association (0–33% of studies supporting a significant association, or no significant meta-analytic effects across four or more studies). "?," indeterminate/inconsistent association (34–59% of studies and less than four studies supporting a significant association, or a non-significant meta-analytic effect or a significant meta-analytic effect across less than four studies). "– "or "+" strong association (≥ 60% of studies and four or more studies supporting a significant association, or a significant meta-analytic effect across four or more studies). ** Effect size was categorized into three types: Small, Correlation: $0.10 < r < 0.30$; Hedges'*g*, or Cohen's d/SMD values of 0.2 to 0.5; standardized β 0.10–0.19. Moderate, Correlation: $0.30 < r < 0.50$; Hedges'*g*, or Cohen's *d*/SMD values of 0.5 to 0.8; standardized β 0.20–0.29. Large, Correlation: $r > 0.50$; Hedges'*g*, or Cohen's *d* or SMD values > 0.8; standardized $\beta > = 0.30$. Heterogeneity classification based on I^2: No: 0–25%; moderate 26–20%; high 51–75%; very high 76–100%. CI = Confidence interval; Crl = Credible intervals; CSS = Cross-sectional studies; ES = effect size; FMS = Fundamental Movement Skills; INT = Non-randomized intervention studies; LPA = Light physical activity; LON = Longitudinal studies; MC = Motor competence; MVPA = Moderate-to-vigorous physical activity; PA = Physical activity; RCT = (Clustered) Randomized Controlled Trial studies; SMD = Standardized mean differences; TPA = Total physical activity; VPA = Vigorous Physical activity.

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2.2.1 Search and selection of behavioral genetics studies

We built on the multiple recent reviews conducted by our group (de Geus, 2023; van der Zee and de Geus, 2019; Zi et al., 2023a; Zi et al., 2023b), but additionally added publications from 2023 and 2024. We searched PubMed and Web-of-Science from January 1980 to December 2024 using the keywords ('Physical Activity' OR Exercise OR Sports OR Lifestyle OR Fitness OR Endurance OR Strength OR VO2*) AND (Gene* OR Twin OR Family OR Familial OR Heritability) AND "Humans" [MeSH terms]. Reference sections of selected papers were used to identify additional papers missed by these search terms. We included all studies addressing univariate or multivariate genetic and environmental contributions to one or more of the four traits of the Stodden model using a twin design. Studies with less than 50 complete twin pairs were excluded. We also removed studies reporting on twins with a mean age higher than 18 and. In some studies, the same twin sample was re-used for slightly different research questions. For example, two studies (Huppertz et al., 2017; van der Aa et al., 2010) used overlapping samples with three other studies (Aaltonen et al., 2020; Aaltonen et al., 2013; Huppertz et al., 2016). If the exact same PA trait was used, we only extracted data from the study using the largest sample size. For the studies conducted by Maia and colleagues we used data presented in their 2013 summary (Maia et al., 2013). Finally, we discarded results on light physical activity or sedentary behavior and limited inclusion to total PA, moderate-to-vigorous PA, and leisure time PA including structured sports and exercise participation.

2.2.2 Data extraction

We extracted the authors, year of publication, country, mean age and range of the target population, the Stodden trait(s) examined, the number of MZ and DZ twin pairs, the measurement strategy used for the trait examined, and the estimates of genetic and shared environmental contributions to the traits. Non-additivity (D) was generally not found (or modeled) by the twin studies, so we extracted only the A and C parameters. We preferentially used the A and C parameters estimates from full ACE models; when only reduced AE models were reported we followed the authors in their assumption that C was zero, but note that a small effect of C in these studies may have been undetected due to low power. When sex differences in the A or C parameters were tested, the differential male and female results are reported. When they were not tested or explicitly found to be absent, the same estimates are reported for males and females. When multiple models with different covariates were tested, we selected those that only corrected for age and sex.

3 Results

3.1 Reporting of confounding by genetic and shared environmental factors

Our search detected 106 systematic reviews, of which 67 added a meta-analysis, on a total of 1,344 unique primary studies that examined one or more of the associations implied by the Stodden model. Table 1 lists all systematic reviews and meta-analyses and Supplementary Table 1 reports on the primary studies, their study design, sample size, and in which systematic reviews and meta-analyses they had been included.

There were 44 systematic reviews addressing the bidirectional MC-PA pathway, 4 systematic reviews on the bidirectional MC-PMC pathway, 5 systematic reviews on the bidirectional PMC-PA pathway and 10 systematic reviews on the path from MC to Fitness. By far the largest amounts of systematic reviews ($n = 54$) were done on the path from physical activity to muscular or cardiorespiratory fitness (PA-Fitness) which is a major area of interest in pediatric exercise science. No reviews included primary studies on the path from fitness to MC or fitness to PA, as manipulation of fitness without also manipulating PA is not feasible in children. Many of the systematic reviews on a specific pathway used overlapping sets of the primary studies, and the more recent reviews generally used the largest number of primary studies.

The patterns in the numbers of the primary studies largely followed that of the systematic reviews (see Supplementary Table 1). There were 426 primary studies reporting on the MC-PA pathway, 102 primary studies on the MC-PMC pathway, 74 primary studies reporting on the PMC-PA pathway, and 100 studies reporting on the MC-fitness pathway. Again, the vast majority of primary studies ($n = 937$) reported on the PA-fitness pathway. As expected, the PA-fitness and MC-fitness studies exclusively tested the effect of MC/PA on fitness traits (not the reverse path). The total number of children and adolescents that have participate in the primary studies testing the Stodden design is over 1.2 million participants.

The very large amount of primary studies described by the systematic reviews should allow us to uncover whether and how past studies on the Stodden model have taken confounding by genetic and shared environmental factors into account. We rely on the authors of the systematic reviews and meta-analyses to have explicitly reported on this. Table 1 reports on our inspection of the discussion sections of the systematic reviews and meta-analyses on text related to potential familial confounding. Our inspection revealed that almost all reviews have taken the potential of unmeasured confounding into account as part of the quality rating the primary studies as prescribed by various guidelines for systematic reviews and meta-analyses, e.g., STROBE, PRISMA, and GRADE (Balshem et al., 2011; Page et al., 2021; von Elm et al., 2007). The quality of the primary studies was often judged to be low to moderate, and it was rarely rated good (see Supplementary Methods Table 4.1). These low scores might in principle have been caused by the majority of primary studies not taking into account potential confounder effects on the associations obtained in the study. We, therefore, considered studies reporting risk of bias as having mentioned 'general confounding' (marked by $\surd$ in the column of Table 1).

Despite this guideline-enforced attention to the risk of bias, as expressed in study quality scores, explicit mention and discussion of (sources of) familial confounding was very rare. For example, in the main MC-PA pathway, aspects of the family environment were explicitly mentioned as a potential source of confounding in only 5 out of the 44 systematic reviews on this pathway. Most cited shared environmental confounders were parental socioeconomic status and parental social support which may influence both motor competence and physical activity (Barnett et al., 2016; Øglund et al., 2015; Xin et al., 2020). Strikingly, clear mention or discussion of genetic confounding was absent. Only Barnett and colleagues, in their authoritative review of 2022, wrote: "The broad scope of this review meant that we could not assess how other relevant variables (e.g., diet, *genetics*, cultural settings, growth and maturation, cognition, motivation) related to the core variables in the model." This indirect allusion is the only reference to genetics in the context of confounding in 106 systematic reviews and meta-analyses.

3.2 Strength of evidence and effect sizes in the association between motor competence and physical activity by study design

Forty-four systematic reviews ($n = 22$) and meta-analyses ($n = 22$) specifically investigated the direct or mediated paths between motor competence and physical activity in both directions (see Table 2 for details). Of the reviews, 25% reported on a cross-sectional design, 12% on a longitudinal, 32% on an intervention design and 31% were (cluster) RCTs. Many reviews reported on multiple analyses of the MC-PA association from the same primary studies. Separate results were given for the total score for motor competence, and/or scores for all or one of the specific domains of locomotor, object, and stability skills. Separate results were also given for different types of physical activity, including either TPA or MVPA and cardiorespiratory as well as strength training activities.

3.2.1 Cross-sectional studies

Thirteen systematic reviews ($n = 8$) or meta-analyses ($n = 5$) investigated the association between motor competence and physical activity mostly based on primary studies using a cross-sectional design (Barnett et al., 2016; Bingham et al., 2016; Burton et al., 2023; Figueroa and An, 2017; Holfelder and Schott, 2014; Jones et al., 2020; Liu et al., 2023; Logan et al., 2015; Lubans et al., 2010; Poitras et al., 2016; Santos et al., 2023; Xin et al., 2020; Xu et al., 2024). In early childhood, strong evidence for an association between motor competence and TPA or MVPA was found in 12 out of the 22 analyses but indeterminate or no evidence was detected in 10 analyses (Bingham et al., 2016; Figueroa and An, 2017; Jones et al., 2020; Liu et al., 2023; Logan et al., 2015; Santos et al., 2023; Xin et al., 2020; Xu et al., 2024) (see Table 2). The association was much more robust in middle to late childhood, as well as in samples with larger age ranges that included adolescence, with the evidence unanimously strong in all 11 analyses (Barnett et al., 2016; Burton et al., 2023; Holfelder and Schott, 2014; Logan et al., 2015; Lubans et al., 2010; Poitras et al., 2016). Averaged (and meta-analytic) effect sizes were between small and moderate, corresponding to a correlation coefficient of ~0.25. The analyses using the separate fundamental motor skills yielded a very comparable pattern.

3.2.2 Longitudinal studies

Six systematic reviews ($n = 2$) or meta-analyses ($n = 4$) evaluated longitudinal studies in which motor competence was used as the predictor of future physical activity (Barnett et al., 2022; Graham et al., 2022; Holfelder and Schott, 2014; Jones et al., 2020; Øglund et al., 2015; Xin et al., 2020) or in which physical activity was used as the predictor of future motor competence (Barnett et al., 2022; Jones et al., 2020; Xin et al., 2020). Strong evidence for predictive effect of motor competence on physical activity was found in only 3 out of the 7 analyses and indeterminate evidence in 4 analyses (see Table 2). The predictive effects of motor competence seemed to hinge mostly on locomotor and stability skills, with no prediction of future physical activity by object skills (Barnett et al., 2022). No different pattern was seen in early versus middle/late childhood, and the effect sizes were typically small.

When a reverse relationship was examined, indeterminate (3 analyses) or no evidence (2 analyses) was found for a predictive effect of physical activity on future motor competence (Barnett et al., 2022; Jones et al., 2020; Xin et al., 2020).

3.3 Intervention studies

Twenty-nine systematic reviews ($n = 10$) or meta-analyses ($n = 19$) (Behringer et al., 2011; Carson et al., 2017; Chen et al., 2024; Collins et al., 2019b; Comeras-Chueca et al., 2021; Dudley et al., 2011; Engel et al., 2018; García-Hermoso et al., 2020; Grady et al., 2025; Hassan et al., 2022; Hesketh et al., 2017; Johnstone et al., 2018; Li et al., 2022; Liu et al., 2020; Lorås, 2020; McDonough et al., 2020; Moon et al., 2024; Norris et al., 2016; Oppici et al., 2022; Poitras et al., 2016; Rico-González, 2023; Sinclair and Roscoe, 2023; Sun and Chen, 2024; Timmons et al., 2012; Van Capelle et al., 2017; Veldman et al., 2021; Wang and Zhou, 2024; Zeng et al., 2017; Zhang et al., 2024) directly addressed the causality in the association between motor competence and physical activity by including intervention studies only. Of these, only two reviews focused on the crucial path of the Stodden model where an increase in motor development would lead to an increase in physical activity levels (Engel et al., 2018; Hesketh et al., 2017). Indeterminate evidence at best was found that intervention on motor competence increases physical activity levels, either in early or in middle childhood samples.

All other 27 reviews included primary studies that tested the reverse effects of physical activity interventions on motor competence, the majority using RCTs. Fifteen of these reviews focused on early childhood. Thirteen of these (12 out of 16 analyses) reported strong evidence for a causal effect of physical activity on motor competence, whether expressed in a total score or in separate scores for locomotor and object control skills. Three reviews (4 out of 16 analyses) reported indeterminate evidence (Johnstone et al., 2018; Liu et al., 2020; Oppici et al., 2022). When reported, the average effect sizes of the PA interventions in early childhood varied from small to large, with larger effect sizes seen when PA was mixed with a deliberate motor skills training component (Chen et al., 2024; Wang and Zhou, 2024). Twelve reviews focused on middle-childhood reporting on RCTs using physical activity intervention to improve motor competence in. Strong evidence (13 out of the 17 analyses) was found that increasing physical activity improved a trait in the MC domain, in all but one review. No, or indeterminate, evidence was found in only 4 of the analyses (see Table 2).

3.4 Potential confounding by familial factors

The systematic search for twin studies on the four Stodden traits uncovered only five studies for motor competence (Goetghebuer et al., 2003; Peter et al., 1999; Smith et al., 2017; Zi et al., 2024; Zi et al., 2023b) and none for perceived motor competence. In contrast, very many twin studies were found that reported on cardiorespiratory or muscular fitness and physical activity traits (see Table 3).

3.4.1 Genetic and shared environmental effects on motor competence

The top part of Table 3 lists the twin studies on motor competence. High heritability (~55%) and substantial effects of the shared family environment on explained variance (~35%) were found for early motor development in boys and girls as reflected in the timing of early motor milestones development (Goetghebuer et al., 2003; Peter et al., 1999; Smith et al., 2017; Zi et al., 2023b). Shared environmental factors still played a major role in gross motor competence at age 5, but the relative contribution to the total variance was only half to one-third

(23% vs. 48% for boys, 16% vs. 48% for girls) of that for motor milestone achievement at age 2 (Zi et al., 2024). At age 5, the individual differences in the mother-reported mastery of seven gross motor skills were even more heritable than age-2 motor milestones attainment in both boys (57% vs. 43%) and girls (65% vs. 44%).

3.4.2 Genetic and shared environmental effects on physical activity

The bottom part of Table 3 lists the twin studies that tested the heritability of physical activity traits. A variety of methods were used, and physical activity was measured either as a total weekly activity score or a score reflecting moderate-to-vigorous activity, often restricted to leisure time activities in particular structured sports and exercise activities. The latter have the advantage of being more reliably assessed by self-report (van der Zee et al., 2020). While the different instruments and traits used induced some heterogeneity in the estimates for heritability and shared environmental influences, this heterogeneity strongly attenuates when only the larger samples are considered. These mostly converge on the sample-size weighted averages across all detected twin studies. On average, 29% of the variance in physical activity in girls was caused by genetic factors and 49% was caused by shared environmental factors. In boys, on average 37% of the variance in physical activity in boys was caused by genetic factors and 33% was caused by shared environmental factors. Heritability estimates from device-based measures of physical activity were very comparable to those from survey-based measures.

3.4.3 Genetic and shared environmental effects on physical fitness

The middle part of Table 3 lists the twin studies that tested the genetic contribution to individual differences in physical fitness in childhood and adolescence, a main mediator in the Stodden model. Three studies reported on the heritability of $\dot{V}O_{2max}$, an index of cardiorespiratory fitness. Heritability estimates varied between 60 and 69% (Maes et al., 1996; Schutte et al., 2019; Schutte et al., 2016b; Sundet et al., 1994). The other twin studies focused on explosive power, muscular strength, muscular endurance, flexibility, and balance. For example, muscular strength measured by the handgrip test was assessed in four large studies with an average heritability of 70% (Isen et al., 2014; Okuda et al., 2005; Schutte et al., 2016b; Silventoinen et al., 2008). A number of studies also measured balancing skills often using tests that strongly overlap with tests used in the motor competence domain. Heritability estimates for balance ability ranged from 27 to 48%.(Maes et al., 1996; Schutte et al., 2019; Schutte et al., 2016b; Vandenberg, 1962; Williams and Gross, 1980).

Averaging across the various fitness measures, the sample-size weighted averages for heritability was 65% for boys and 67% for girls. Of note is that the shared environmental factors were not seen to meaningfully contribute to the variance in physical fitness in youth. Any confounding of pathways in the Stodden model relying on fitness, therefore, would be restricted to genetic confounding.

4 Discussion

The potential role of motor competence for physical activity received a large boost with the development of the "Stodden model" by Stodden and coworkers in 2008. The Stodden model has inspired a large volume of work, with 106 systematic reviews and/or meta-analyses detected by our literature search reporting on 1,344 primary papers. Many of the systematic reviews and meta-analyses end by a plea for interventions on motor competence in order to ensure future mental and physical health. This enigmatic call-to-intervention reflects the laudable desire to provide societally useful knowledge. This desire does not, however, absolve us form the obligation to provide a strong evidence base that intervention on motor competence is directly causal to increases in youth physical activity levels. Such causality is implied by the original Stodden model.

From a behavioral genetic perspective, we suggested that shared environmental and genetic confounders should be added to the model (see Figure 1). We then examined the systematic reviews and meta-analyses on the Stodden model to see if, and to what extent, this potential familial confounding, and in particular genetic confounding had already been taken into account. We find that confounding by shared environmental factors, which include household/neighborhood/parental rearing style characteristics, did receive cursory attention. However, essentially none of the past systematic reviews or meta-analyses of the cross-sectional or longitudinal observational studies on the Stodden model had considered, let alone ruled out, genetic confounding. We identify the lack of attention to familial confounding, specifically genetic confounding, as a huge knowledge gap in the fields of motor development and youth public health.

In contrast to cross-sectional or longitudinal observational studies, studies using experimental interventions on traits of the Stodden model rule out familial confounding by design. Particularly, in the form of RCTs, they remain the preferred method of assessing causal effects. However, not all paths of the Stodden model are amenable to intervention testing. Changing fitness other than by manipulating physical activity levels is near impossible, as it would require giving, e.g., blood doping to young children. This rules out an experimental test of an effect of fitness on physical activity, an effect hypothesized by one of the mediating pathways of the Stodden model. Likewise, manipulating perceived motor competence without changing actual motor competence is hard, if not unfeasible, which complicates experimental testing of the other mediating pathway in the Stodden model.

Manipulating motor competence by specific motor skill training without overly increasing physical activity levels is feasible in principle, although we note that most interventions on motor competence also increase the amount of physical activity as part of the motor skills training. Nonetheless, these intervention on fundamental motor skills are closest to an experimental test of a causal effect of motor competence on future physical activity in the core pathway of the Stodden model. Strikingly, the only two reviews focused such interventions found indeterminate evidence at best that intervention on motor competence increases physical activity levels, either in early or in middle childhood samples (Engel et al., 2018; Hesketh et al., 2017). This suggests that the hypothesized causal path from motor competence to physical activity does not contribute to the observed association between these two traits.

The most feasible intervention to test a number of the hypothesized paths in the Stodden model are those involving a direct increase in physical activity itself. Indeed, the majority of interventions studies on the Stodden model have focused on the effects of extra physical education lessons, and post-school sports and exercise activities. The systematic reviews on intervention studies provide strong evidence for an effect of physical activity on increased motor competence and fitness, even unanimously so in middle and late childhood. This is in keeping

TABLE 3 Twin studies on the genetic and shared environmental contribution to the variance in motor competence, physical fitness and physical activity.

Reference	Age Mean	Country	Trait	Instrument	Measurement details	N MZ pairs	N DZ pairs	Heritability males	Heritability females	Shared env. males	Shared env. females
Motor competence											
Peter et al. (1999)	0.5	Israel	Motor milestones	Turn over	The age of first-time being able to fully turn over	30	68	34%	34%	50%	50%
Peter et al. (1999)	0.65	Israel	Motor milestones	Sit up	The age of first-time being able to sit up for a few seconds without support	30	68	31%	31%	56%	56%
Peter et al. (1999)	0.73	Israel	Motor milestones	Stand up	The age of first-time being able to pull up to a standing position without support	30	68	0%	0%	33%	33%
Peter et al. (1999)	1.1	Israel	Motor milestones	Walks (5 s)	The age of first-time being able to walk five steps without support	30	68	22%	22%	67%	67%
Goetghebuer et al. (2003)	0.5	UK	Motor milestones	Roll over	The age of first-time being able to fully turn over	22	62	0%	0%	--	--
Goetghebuer et al. (2003)	0.6	UK	Motor milestones	Crawl	The age of first-time being able to move forwards or backwards either on stomach or on hands and knees	22	62	93%	93%	--	--
Goetghebuer et al. (2003)	0.6	UK	Motor milestones	Sit without support	The age of first-time being able to sit up and maintain the head without rear support	22	62	0%	0%	--	--
Goetghebuer et al. (2003)	0.7	UK	Motor milestones	Stand with support	The age of first-time being able to maintain a standing position by holding on to one's hand	22	62	72%	72%	--	--
Goetghebuer et al. (2003)	0.8	UK	Motor milestones	Walk with support	The age of first-time being able to walk a few steps by holding on to one's hand	22	62	90%	90%	--	--
Smith et al. (2017)	0.6	UK	Motor milestones	Sit	The age of first-time being able to sit up without support	1,247	2,705	48%	48%	42%	42%
Smith et al. (2017)	0.8	UK	Motor milestones	Crawl	The age of first-time being able to crawl on hands and knees	1,174	2,502	54%	54%	33%	33%
Smith et al. (2017)	1.1	UK	Motor milestones	Walk	The age of first-time being able to walk a few steps without any support	868	1976	84%	84%	0%	0%
Zi et al. (2023b)	0.5–1.3	Netherlands	Motor milestones (compound score of 5 milestones)	Roll over Sit without support Crawl Stand without support Walk without support	The age of first-time being able to roll over from back to belly sit without support crawl on hands and knees stand without support walk without support	8,043	15,163	52%	53%	38%	39%

(Continued)

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TABLE 3 (Continued)

Reference	Age Mean	Country	Trait	Instrument	Measurement details	N MZ pairs	N DZ pairs	Heritability males	Heritability females	Shared env. males	Shared env. females
Zi et al. (2024)	5	Netherlands	Gross motor skills (compound score of 7 skills)	Hop One-leg stand Throw a ball Kick a ball Catch a ball One foot stair climbing No hands stair climbing	Hop more than 1 time on the same leg Stand on one leg longer than 10s Throw a ball in a fixed direction Kick a ball in a fixed direction Catch a ball Walk down the staircase without putting both feet on a step at the same time Walk down the staircase without using the handrail	6,075	11,114	57%	65%	23%	16%
Total sample						17,473	34,042				
Sample size weighted means								55%	58%	31%	29%
Physical fitness											
Okuda et al. (2005)	6,5	Japan	muscular endurance	sit-ups	dynamic strength and endurance of the abdominal and hip flexor muscles	90	68	0%	0%	51%	51%
Silventoinen et al. (2021)	7	Portugal	muscular strength (compound score of 5 tests)	sit-and-reach standing long jump handgrip sit ups bent arm hang	Sitting reach distance of fingers maintained for 2 s Max distance jumped from standing Maximal isometric strength of arm Dynamic strength and endurance of the abdominal and hip flexor muscles Static upper body strength and endurance	87	129	67%	67%	0%	0%
Silventoinen et al. (2021)	7	Portugal	Coordination and cardiorespiratory (compound score of 4 tests)	Flamingo balance Plate tapping Shuttle run Run/walk 12 min	Dynamic balance Upper body reaction time Multi-stage endurance test Max distance covered in 12 min	87	129	76%	76%	0%	0%
Maes et al. (1996)	10	Belgium	cardiorespiratory	VO_2max	Maximal exercise test on treadmill	43	61	69%	87%	0%	0%
Maes et al. (1996)	10	Belgium	explosive power	vertical jump	Max jump height from standing position	43	61	65%	65%	0%	0%
Maes et al. (1996)	10	Belgium	flexibility	sit-and-reach	sitting reach distance of fingers maintained for 2 s	43	61	72%	51%	0%	43%
Maes et al. (1996)	10	Belgium	balance	Flamingo balance test	dynamic balance	43	61	41%	41%	0%	0%
Beunen et al. (2003)	11	Belgium	explosive power	vertical jump	Max jump height from standing position	91	105	47%	79%	0%	0%
Beunen et al. (2003)	12	Belgium	explosive power	vertical jump	Max jump height from standing position	91	105	59%	92%	0%	0%

(Continued)

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TABLE 3 (Continued)

Reference	Age Mean	Country	Trait	Instrument	Measurement details	N MZ pairs	N DZ pairs	Heritability males	Heritability females	Shared env. males	Shared env. females
Okuda et al. (2005)	12,5	Japan	explosive power	long jump	Max distance jumped from standing position	90	68	66%	66%	0%	0%
Okuda et al. (2005)	12,5	Japan	flexibility	sit-and-reach	sitting reach distance of fingers maintained for 2 s	90	68	55%	55%	0%	0%
Isen et al. (2014)	12	USA	muscular strength	Handgrip	Maximal isometric strength of static arm	788	466	88%	79%	0%	0%
Okuda et al. (2005)	12,5	Japan	muscular strength	Handgrip	Maximal isometric strength of static arm	90	68	77%	77%	0%	0%
Beunen et al. (2003)	13	Belgium	explosive power	vertical jump	Max jump height from standing position	91	105	85%	77%	0%	0%
Beunen et al. (2003)	14	Belgium	explosive power	vertical jump	Max jump height from standing position	91	105	74%	74%	0%	0%
Peeters et al. (2005)	14	Belgium	explosive power	vertical jump	Max jump height from standing position	42	63	61%	77%	0%	0%
Beunen et al. (2003)	15	Belgium	explosive power	vertical jump	Max jump height from standing position	91	105	63%	91%	0%	0%
Chatterjee and Das (1995)	15	India	explosive power	vertical jump	Max jump height from standing position	30	20	71%	71%	--	--
Silventoinen et al. (2021)	15	Portugal	muscular strength (compound score of 5 tests)	sit-and-reach standing long jump handgrip sit ups bent arm hang	Sitting reach distance of fingers maintained for 2 s Max distance jumped from standing position Maximal isometric strength of static arm Dynamic strength and endurance of the abdominal and hip flexor muscles Static upper body strength and endurance	87	129	73%	73%	0%	0%
Silventoinen et al. (2021)	15	Portugal	Motor ability and cardiorespiratory (compound score of 4 tests)	Flamingo balance Plate tapping Shuttle run Run/walk 12 min	Dynamic balance Upper body reaction time Aerobic capacity multi-stages running test The distance covered in 12 min	87	129	83%	83%	0%	0%
Williams and Gross (1980)	15	New Zealand	Balance	Stabilometer balance	dynamic balance	22	41	27%	27%	49%	49%
Chatterjee and Das (1995)	16	India	Flexibility	sit-and-reach	sitting reach distance of fingers maintained for 2 s	30	20	18%	18%	-	-
Beunen et al. (2003)	16	Belgium	Explosive power	vertical jump	Max jump height from standing position	91	105	0%	82%	65%	0%

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TABLE 3 (Continued)

Reference	Age Mean	Country	Trait	Instrument	Measurement details	N MZ pairs	N DZ pairs	Heritability males	Heritability females	Shared env. males	Shared env. females
Vandenberg (1962)	16	USA	Balance	Beam Balancing	dynamic balance	41	32	48%	48%	--	--
Schutte et al. (2016b)	17	Netherlands	Muscular strength	Handgrip	Maximal isometric strength of static arm	116	111	60%	60%	0%	0%
Schutte et al. (2016a)	17	Netherlands	Cardiorespiratory	VO_2max	Maximal exercise test on cycle ergometer	115	105	60%	60%	0%	0%
Schutte et al. (2016b)	17	Netherlands	Explosive power	vertical jump	Max jump height from standing position	116	111	49%	49%	0%	0%
Schutte et al. (2016b)	17	Netherlands	Flexibility	sit-and-reach	sitting reach distance of fingers maintained for 2 s	116	111	78%	78%	0%	0%
Schutte et al. (2016b)	17	Netherlands	balance	The Balance Error Scoring System	static balance	116	111	39%	39%	0%	0%
Beunen et al. (2003)	18	Belgium	explosive power	vertical jump	Max jump height from standing position	91	105	63%	78%	0%	0%
Sundet et al. (1994)	18	Norway	cardiorespiratory	VO_2max	Maximal exercise test on cycle ergometer	436	622	62%	62%	0%	0%
Silventoinen et al. (2008)	18,5	Sweden	muscular strength	Handgrip	Maximal isometric strength of static arm	1,582	1864	66%	66%	3%	3%
Total sample						5,067	5,444				
Sample size weighted means								65%	67%	3%	2%
Physical activity											
Saudino and Zapfe (2008)	2,1	USA	TPA	Actigraph (minimitter) accelerometer	Composite actigraph scores (rate per minute) across two days and four limbs	144	168	32%	32%	54%	54%
Saudino and Zapfe (2008)	2,1	USA	TPA	Toddler Behavior Assessment Questionnaire	Parental frequency rating for PA in 10 specific situations in the past month	144	168	82%	82%	1%	1%
Franks et al. (2005)	7,1	USA	TPA	Doubly labeled water method	Energy expenditure in PA (PAEE) in kcal/day	62	38	41%	41%	35%	35%
Franks et al. (2005)	7,1	USA	TPA	Doubly labeled water method	Physical activity level (PAL) as total EE/ RMR and measured in kcal/day.	62	38	0%	0%	65%	65%

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TABLE 3 (Continued)

Reference	Age Mean	Country	Trait	Instrument	Measurement details	N MZ pairs	N DZ pairs	Heritability males	Heritability females	Shared env. males	Shared env. females
Franks et al. (2005)	7,1	USA	TPA	Doubly labeled water method	Total Energy Expenditure (TEE) in kcal/day	62	38	28%	28%	46%	46%
Huppertz et al. (2012)	7,5	Netherlands	VEB	Multiple Survey items (parental report)	METh/wk. across all sports/exercise activities >3 MET	648	1,320	24%	22%	71%	67%
Zi et al. (2024)	7,5	Netherlands	VEB	Multiple Survey items (parental report)	METh/wk. across all sports/exercise activities >3 MET	1,293	2,339	23%	3%	68%	81%
Huppertz et al. (2016)	7,5	Netherlands	VEB	Multiple Survey items (parental report)	Categories (3) based on METh/wk. low <5; middle >5 and <20; high >20	1,262	2,384	14%	12%	80%	80%
Wood et al. (2008)	8,5	UK	TPA	Actigraph (minimitter) accelerometer	Sum of counts across a 2.5 h lab setting with unstructured breaks	150	113	35%	35%	40%	40%
Zi et al. (2024)	9,8	Netherlands	VEB	Multiple Survey items (parental report)	METh/wk. across all sports/exercise activities >3 MET	1,342	2,393	19%	10%	66%	73%
Huppertz et al. (2016)	9,8	Netherlands	VEB	Multiple Survey items (parental report)	Categories (3) based on METh/wk. low <5; middle >5 and <20; high >20	1,384	2,582	26%	26%	69%	65%
Huppertz et al. (2012)	10,1	Netherlands	VEB	Multiple Survey items (parental report)	METh/wk. across all sports/exercise activities >3 MET	620	1,141	66%	16%	25%	72%
Fisher et al. (2010)	11,0	UK	TPA	Actigraph 7,164 accelerometer	Average activity counts per minute, across 7 consecutive days in counts/min	57	60	14%	14%	63%	63%
Fisher et al. (2010)	11,0	UK	MVPA	Actigraph 7,164 accelerometer	Time spent in MVPA with count >2000 over 7 consecutive days in minutes/d	57	60	28%	28%	39%	39%
Aaltonen et al. (2020)	11,5	Finland	LTPA	Single Survey item (self-report)	Frequency (5) exercise/sports in leisure per week (no …-. every day)	815	1,564	30%	17%	35%	53%
White et al. (2014)	12,0	USA	TPA	3-day physical activity recall (3D-PAR)	METminutes/day across all activities on the three days	72	76	0%	0%	66%	33%

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TABLE 3 (Continued)

Reference	Age Mean	Country	Trait	Instrument	Measurement details	N MZ pairs	N DZ pairs	Heritability males	Heritability females	Shared env. males	Shared env. females
Huppertz et al. (2016)	12,3	Netherlands	VEB	Multiple Survey items (parental report)	Categories (3) based on METh/wk. low <5; middle >5 and <20; high >20	2,615	4,589	31%	27%	62%	65%
Zi et al. (2024)	12,3	Netherlands	VEB	Multiple Survey items (parental report)	METh/wk. across all sports/exercise activities >3 MET	2,583	4,460	31%	29%	54%	57%
Huppertz et al. (2012)	12,3	Netherlands	VEB	Multiple Survey items (parental report)	METh/wk. across all sports/exercise activities >3 MET	1,540	2,746	38%	36%	50%	50%
Maia et al. (2013)	13,0	Portugal	TPA	TRITRAC R3D accelerometer	Sum of counts of the accelerometer across wear time in 5 days	77	85	44%	44%	45%	45%
Stubbe et al. (2005)	13,5	Netherlands	VEB	Multiple Survey items (self-report)	YES/NO regular exercise participation at >4 METs and = > 60 min/wk.	276	370	0%	0%	84%	84%
Pérusse et al. (1989)	14,0	Canada	TPA	B3DPAR three-day PA record (self-report)	Sum of energy expenditure (EE) in all 15-min periods queried (96) across 3 days.	55	56	29%	29%	0%	71%
Pérusse et al. (1989)	14,0	Canada	MVPA	B3DPAR three-day PA record (self-report)	Sum of mean EE in 15-min periods with EE > 4,9 METS across 3 days.	55	56	0%	0%	12%	12%
Aaltonen et al. (2020)	14,0	Finland	LTPA	Single Survey item (self-report)	Frequency (5) exercise/sports in leisure per week (no …-. every day)	742	1,426	45%	32%	15%	28%
Maia et al. (2013)	14,5	Portugal	MVPA	TRITRAC R3D accelerometer	Sum of counts during PA of very vigorous intensity (VVPA)	48	59	72%	42%	0%	0%
Huppertz et al. (2016)	14,6	Netherlands	VEB	Multiple Survey items (self-report)	Categories (3) based on MET h/wk., low <5; middle >5 and <20; high >20	1,451	2,333	43%	40%	36%	43%
Zi et al. (2024)	14,6	Netherlands	VEB	Multiple Survey items (self-report)	METh/wk. across all sports/exercise activities >3 MET	1,527	2,463	51%	18%	19%	48%
Beunen and Thomis (1999)	15,0	Belgium	VEB	Single Survey item (self-report)	Time spent on sports each week within the past year, in number of hours/wk	43	61	83%	44%	0%	54%
Simonen et al. (2004)	15,0	Finland	LTPA	Multiple Interview items (self-report)	Recalled weekly hours spent in any LTPA during adolescence (age 12–18)	147	153	18%	--	37%	--

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TABLE 3 (Continued)

Reference	Age Mean	Country	Trait	Instrument	Measurement details	N MZ pairs	N DZ pairs	Heritability males	Heritability females	Shared env. males	Shared env. females
Maia et al. (2013)	15,0	Portugal	TPA	TRITRAC R3D accelerometer	Sum of counts of the accelerometer across wear time in 5 days	32	19	34%	34%	0%	0%
Haberstick et al. (2014)	15,1	USA	LTPA	Multiple Survey items	Time spent on leisure time physical activities in hours/d	1,374	1,471	7%	54%	43%	0%
Stubbe et al. (2005)	15,5	Netherlands	VEB	Multiple Survey items (self-report)	YES/NO regular exercise participation at >4 METs and = > 60 min/wk.	321	442	0%	0%	78%	78%
Aarnio et al. (1997)	16,0	Finland	LTPA	Multiple Survey items (self-report)	Five categories ranging from very active to inactive in leisure time	378	370	54%	46%	18%	18%
Aaltonen et al. (2013)	16,2	Finland	VEB	Single Survey item (self-report)	Categories (3): Inactive <1x wk.; moderate 1-3x wk.; very active, > 4x wk	769	1743	52%	52%	19%	24%
de Moor et al. (2011)	16,4	Netherlands	VEB	Multiple Survey items (self-report)	YES/NO regular exercise participation at >4 METs and = > 60 min/wk.	656	1,628	42%	36%	44%	52%
de Geus et al. (2003)	16,7	Netherlands	VEB	Multiple Survey items (self-report)	METh/wk. across all sports/exercise activities >4 MET	69	88	79%	79%	0%	0%
Huppertz et al. (2016)	16,9	Netherlands	VEB	Multiple Survey items (self-report)	Categories (3) based on METh/wk. low <5; middle >5 and <20; high >20	959	1,305	56%	49%	27%	31%
Schutte et al. (2019)	16,9	Netherlands	VEB	Multiple Survey items (self-report)	METh/wk. across all exercise activities >4 MET	85	76	67%	67%	0%	0%
Boomsma et al. (1989)	17,0	Netherlands	VEB	Single Survey item (self-report)	YES/NO Sports participation	44	46	77%	35%	0%	0%
Maia et al. (2002)	17,0	Portugal	LTPA	Baecke Questionnaire (self-report)	Composite score on non-exercise related LTPA	203	208	63%	32%	0%	38%
Maia et al. (2002)	17,0	Portugal	VEB	Baecke Questionnaire (self-report)	Composite score based on the two most frequently played sports	203	208	68%	40%	20%	28%
Aaltonen et al. (2013)	17,1	Finland	VEB	Single Survey item (self-report)	Categories (3): Inactive <1x wk.; moderate 1-3x wk.; very active, > 4x wk	724	1,614	44%	50%	24%	26%
Schutte et al. (2019)	17,1	Netherlands	VEB	Multiple Interview items (self-report)	METh/wk. across all exercise activities >4 MET	105	112	81%	81%	0%	0%
Kaartinen et al. (2021)	17,1	Finland	VEB	Multiple Survey items (self-report)	Total number of sports/exercise activities regularly engaged in.	831	1705	58%	40%	0%	26%

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TABLE 3 (Continued)

Reference	Age Mean	Country	Trait	Instrument	Measurement details	N MZ pairs	N DZ pairs	Heritability males	Heritability females	Shared env. males	Shared env. females
Kaartinen et al. (2021)	17,1	Finland	VEB	Multiple Survey items (self-report)	Number of solitary sports/exercise activities regularly engaged in.	831	1705	42%	51%	17%	18%
Kaartinen et al. (2021)	17,1	Finland	VEB	Multiple Survey items (self-report)	Number of team sports/exercise activities regularly engaged in.	831	1705	63%	0%	9%	60%
Stubbe et al. (2005)	17,5	Netherlands	VEB	Multiple Survey items (self-report)	YES/NO regular exercise participation at >4 METs and = > 60 min/wk.	248	395	36%	36%	47%	47%
Aaltonen et al. (2020)	17,6	Finland	LTPA	Single Survey item (self-report)	Frequency exercise/sports in leisure per week (no ….-. every day)	678	1,266	54%	43%	16%	16%
Koopmans et al. (1994)	18,0	Netherlands	VEB	Single Survey item (self-report)	YES/NO Sports participation:	578	1,000	48%	48%	38%	38%
Total sample						29,252	50,445				
Sample size weighted means								37%	29%	33%	49%

DZ = Dizygotic twin; EE = Energy expenditure; env. = Environmental; LTPA = Leisure-time physical activity; MET = Metabolic equivalent of task; METh/wk = Methours per week; MVPA = Moderate-to-vigorous physical activity; MZ = Monozygotic twin; PA = Physical activity; PAEE = Energy expenditure in PA; PAL = Physical activity level; RER = Respiratory exchange ratio; RMR = Resting metabolic rate; TEE = Total energy expenditure; TPA = Total physical activity; VEB = Voluntary exercise behavior; VVPA = Very vigorous physical activity.

with established knowledge in pediatric exercise and suggest that the cross-sectional association between motor competence and physical activity reflects reverse causality. We note, however, that causal effects of physical activity on motor competence do not rule out the potential for additional familial confounding. In addition, the systematic reviews, often observed a large heterogeneity in the intervention effects on motor competence, both across studies but also within primary study samples. We hypothesize that these individual differences in the response to intervention may largely be attributable to genetic or shared environmental confounding. We, therefore, also searched whether the systematic reviews and meta-analyses on intervention studies on the Stodden model had considered familial factors as potential moderators of variation in outcomes across primary studies applying an intervention. Again, we found no single mention of this possibility in the 106 systematic reviews and meta-analyses on interventions on physical activity.

4.1 Potential for familial confounding in the motor development–physical activity pathway

To examine whether the potential for familial confounding was real, we tested the core requirements for such confounding in the motor development - physical activity pathway: (1) the individual differences in motor competence are heritable and/or caused by shared environmental factors, (2) the individual differences in physical activity are heritable and/or caused by shared environmental factors, and (3) there is significant overlap in either the genetic or the shared environmental factors influencing both motor competence and physical activity. We used twin studies on the traits in the Stodden model as our main vehicle.

In our past work, we reviewed family and twin studies on physical activity and fitness traits in childhood and adolescence (de Geus, 2023) but Table 3 provides an update incorporating a number of recent large twin studies on motor competence (Zi et al., 2023a; Zi et al., 2024; Zi et al., 2023b). Across different types of physical activity, across different countries, and across assessment methods (device-based or self-report), we show heritability of physical activity to be around 29% for girls and 37% for boys. Shared environment contributes 49 and 33% to the variance in motor competence in girls and boys, respectively. These findings signal that the first two of the requirements for potential familial confounding are met. The remaining condition for confounding is a substantial overlap in either the genetic or the shared environmental factors influencing *both* motor competence and physical activity. This question has only been directly addressed in a single paper so far (Zi et al., 2024). Using longitudinal data across a 12-year time span in a large population-based sample of MZ and DZ twins, they investigated the prediction of future exercise behavior by early motor development. Early motor development explained 4.3% of the variance in future exercise behavior in boys but only 1.9% in girls. In boys, there was evidence for a significant overlap in the genetic factors influencing early motor development and future exercise behavior, while the regressions between the shared and unique environmental factors were not significant. In girls, neither genetic nor shared and unique environmental regressions were significant, possibly reflecting low power to detect such effects at this very low amount (1.9%) of explained variance.

4.2 Mediational pathways in the Stodden model

Three systematic reviews on the Stodden model explicitly examined the evidence for mediation of the association between motor competence and physical activity by perceived motor competence or physical fitness (Barnett et al., 2022; Jones et al., 2020; Robinson et al., 2015). Most comprehensive testing was done by Barnett et al. (2022). They conclude that there is indeterminate evidence for mediation by perceived motor competence across the age range 3 to 18 years. In contrast, mediation by physical fitness of the path between physical activity and (future) motor competence, and the reverse path were supported by strong evidence. However, just as is true for the direct associations, associations mediated by fitness could be due to genetic and shared environmental factors independently acting on the traits in the mediating paths, i.e., genetic or environmental confounding of the MC-fitness and fitness-PA pathways.

Past systematic reviews and meta-analyses had shown that, throughout childhood and adolescence, individual differences in cardiorespiratory and muscular fitness are dominated by genetic factors with only a minimal role for shared environmental factors (Miyamoto-Mikami et al., 2018; Schutte et al., 2016b; Zi et al., 2023a). The update on this literature shown in Table 3 confirms this with, on average, 65–67% of the variance in physical fitness traits in both girls and boys being explained by genetic factors, with negligible shared environmental effects. Given the heritability of motor competence and physical activity, this additional heritability of fitness compromises testing of the mediation of the association between motor competence and physical activity by physical fitness. By correcting the direct path for fitness, we correct for the genetic factors influencing fitness. If these genetic factors partly overlap with either those of motor competence or those of physical activity, this correction would attenuate the association between motor competence and physical activity, mimicking 'mediation by fitness.'

Direct support for a genetic overlap between fitness traits and physical activity comes from bivariate modeling in adolescent and young adult twin studies that assessed cardiorespiratory and muscular fitness phenotypes and daily regular exercise levels, both cross-sectionally and longitudinally (Schutte et al., 2019). This confirmed that physical fitness and physical activity behaviors are genetically overlapping, with genetic correlations between endurance capacity (VO_2max) and regular exercise and sports activities in leisure time as high as 0.43. In short, the substantial contributions of genetic factors to motor competence, physical fitness, and physical activity provide a clear potential for genetic confounding in the 'mediating' paths using physical fitness.

4.3 How to detect and correct for familial confounding in the Stodden model?

We conclude that to more completely test the pathways in the model by Stodden et al. (2008), studies are needed with designs that can detect and account for potential genetic and shared environmental confounding. In the past we were dependent on the use of behavioral genetics studies in (extended) twin families to achieve this. However, despite the elegance of the twin design, not all researchers will have readily access to twin family data. Fortunately, nowadays we can also rely on DNA sampling and genome-wide genotyping in the participants of any cohort, the added costs of which have gone down to ~50 Euro per participant. From these genome-wide genotype data we can create genetic instruments for Mendelian Randomization and extract polygenetic indexes (PGI's) using the publicly available current (and upcoming) summary statistics of genome-wide association studies (GWAS) on motor competence, physical fitness, and physical activity.

These two methods can be used to test causal hypotheses while controlling for confounding. Mendelian Randomization (MR) is the experiment of nature that comes most close to an RCT in which participants are allocated to different exposure levels independently of confounding. Like an RCT, MR also rules out reverse causality, but uses nature's randomization to lifetime exposure to DNA variants that influence the exposure (Davey-Smith and Hemani, 2014; Pingault et al., 2018; Speed et al., 2019). These are determined at birth and an advantage of MR over RCTs is that it captures effects of prolonged exposure to, e.g., a propensity to develop motor skills, rather than the mere weeks or months of motor skill training within an RCT. If a genetic instrument is also available for the outcome, e.g., a set of single nucleotide polymorphisms (SNPs) significantly associated with physical activity, bidirectional MR can explicitly test a possible reciprocal causal relationship between exposure (motor competence) and outcome (physical activity).

When our basic concern is to adjust for genetic confounding of an association, e.g., between motor competence and physical activity, the computation of a PGI is another useful strategy (Choi et al., 2020). If a DNA sample with genome-wide SNP genotyping is available for the study participants, the PGI for motor competence and physical activity can be computed using the summary statistics of GWAS on these traits. The PGI is the sum of all the (tiny) genetic effects on the trait across all hundreds or thousands of SNPs that the GWAS detected as meaningfully contributing to the trait (Kujala et al., 2020). If there is genetic confounding, such that the genetic risk for low motor competence is causing (future) low levels of physical activity, then stratifying observed cross-sectional or longitudinal associations for deciles of the PGI for motor competence should lead to attenuation/disappearance of the motor competence—physical activity relationship within each decile of the PGI. If the relationship does not attenuate in the genetically stratified analysis, the association is shown to not depend on genetic confounding. This means that even individuals with a high genetic vulnerability for low motor competence would see their physical activity levels increased by interventions on their motor competence. Indeed, computing the polygenetic propensity for the traits of the Stodden model can also be used to strongly enrich intervention trials. As explained above, the heterogeneity in responsivity to motor competence or physical activity interventions may be partly due to genetic factors. Intervention trials in youth targeting motor competence or physical activity could start to account for this genetic moderation of intervention effects, simply by adding sampling of DNA in the trial participants to the research protocol and using their PGIs as moderator variables.

To apply the MR and PGI approaches to evaluate the Stodden model, we need publicly available summary statistics of large international consortia performing meta-analyses of genome-wide association studies on hundreds of thousands of children. Such

summary statistics based on child samples are currently only available early motor coordination (Mountford et al., 2021) but the sample sizes of this GWAS was relatively modest. Larger GWAS efforts on motor milestones in much large samples are currently underway (Gui et al., 2024). However, for physical activity (Doherty et al., 2018; Klimentidis et al., 2018; Wang et al., 2022) and muscular (Willems et al., 2017) and cardiorespiratory fitness (Klevjer et al., 2022), we only have GWAS results based on adult samples, and the authors have not seen clear initiatives for GWAS on these traits in youth. This is where future work is direly needed because we cannot simply assume that the same genetic variants operate throughout the lifespan.

In summary, our synthesis of reviews leads us to fully support the viewpoint expressed earlier by Barnett et al. (2022) and Burton et al. (2023): To truly test the model authored by Stodden et al. (2008) the field is in need of robust longitudinal studies across early childhood and into adolescence. We agree with their recommendations that such longitudinal assessment should aim to include multiple traits from the model, use a combined motor competence assessment (i.e., process and product), and account for biological maturation. However, we offer an update to these recommendations by a strong plea for doing such studies in genetically informative samples that can quantify and account for potential confounding in all pathways of the Stodden model.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

YZ: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Visualization, Writing – original draft, Writing – review & editing. EG: Conceptualization, Data curation, Formal analysis, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fpsyg.2025.1480631/full#supplementary-material

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Inflammation and depression: an evolutionary framework for the role of physical activity and exercise

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Major Depressive Disorder (MDD) is a leading global health challenge, affecting nearly 5% of the population. Mounting evidence suggests that systemic low-grade chronic inflammation (SLGCI) plays a central role in the development and progression of MDD. This persistent inflammatory state results from unresolved immune activation and sustained exposure to modern lifestyle factors, such as sedentary behavior, poor diet, inadequate sleep, and psychological stress. Regular physical activity (PA), particularly exercise, has been shown to modulate inflammatory processes and improve depressive symptoms. This narrative review examines the complex interactions between inflammation and MDD, focusing on the role of PA and exercise in mitigating SLGCI and neuroinflammation. This is approached through an evolutionary lens, exploring how the mismatch between ancestral and modern activity levels may contribute to the rise of MDD. In addition, it highlights the potential risks of excessive exercise, including overtraining and its association with depressive symptoms. Finally, this work proposes a practical framework for optimizing PA and exercise as preventive and therapeutic tools for MDD by aligning modern PA patterns with ancestral behavioral norms.

KEYWORDS

Major Depressive Disorder, systemic low-grade chronic inflammation, neuroinflammation, mismatch, exercise, lifestyle

1 Introduction

Major Depressive Disorder (MDD) is a significant public health concern, affecting nearly 5% of the population worldwide (Malhi and Mann, 2018). Alarmingly, its prevalence appears to be rising, with several studies reporting increasing incidence rates over the past decades (GBD 2019 Mental Disorders Collaborators, 2022; Goodwin et al., 2022). While MDD is more prevalent in women (Li S. et al., 2023), it affects individuals across sexes (GBD 2019 Mental Disorders Collaborators, 2022) and age groups (Ghandour et al., 2019; Juul et al., 2021; GBD 2019 Mental Disorders Collaborators, 2022). Although various psychological and environmental factors are important in the etiology of MDD, growing research points to the central involvement of biological mechanisms in both its onset and progression (Miller and Raison, 2016; Malhi and Mann, 2018; Correia et al., 2023; Hassamal, 2023). These mechanisms include neurotransmitter dysregulation, altered hypothalamic–pituitary–adrenal axis function, impaired neuroplasticity, oxidative stress, and notably, chronic inflammation (Miller and Raison, 2016; Correia et al., 2023; Hassamal, 2023).

Regarding inflammation, it serves as an evolutionarily conserved mechanism essential for host protection and the restoration of homeostasis (Medzhitov, 2021; Meizlish et al., 2021). Under normal circumstances, it typically resolves once these functions are achieved (Furman et al., 2019). However, when inflammatory responses fail to resolve—due to intrinsic dysregulation or persistent exposure to stressors—they may evolve into a state of systemic low-grade chronic inflammation (SLGCI) (Furman et al., 2019). SLGCI is now recognized as a shared mechanism underlying several chronic diseases, such as cancer, autoimmune diseases, non-alcoholic fatty liver disease, type 2 diabetes, cardiovascular disease (CVD), chronic kidney disease, osteoporosis, sarcopenia, neurodegenerative diseases, and psychiatric disorders such as MDD (Haapakoski et al., 2015; Köhler et al., 2017; Arteaga-Henríquez et al., 2019; Furman et al., 2019; Osimo et al., 2019; Bai et al., 2020; Costanza et al., 2024; Vöckel et al., 2024; Yin et al., 2024).

A variety of intrinsic and extrinsic modifiable factors contribute to SLGCI, including smoking, environmental pollutants, psychological stress, sleep disturbances and circadian disruption, poor diets, excessive adiposity, and physical inactivity (Furman et al., 2019; Burini et al., 2020; Valenzuela et al., 2023). Interestingly, the advent of most of these stressors postdates the Neolithic and, particularly, the Industrial Revolution, representing a relatively short period on the evolutionary timeline for human physiology to fully adapt (Cordain et al., 2005; Carrera-Bastos et al., 2011; Ruiz-Núñez et al., 2013; Burini et al., 2020; Chaudhary and Salali, 2022). It can, therefore, be argued that the rapid emergence of various 'diseases of civilization'—including MDD—may reflect a mismatch between our ancestral physiology and modern lifestyles (Carrera-Bastos et al., 2011; Ruiz-Núñez et al., 2013; Burini et al., 2020; Chaudhary and Salali, 2022). Among these modifiable factors, sedentary behavior and physical inactivity stand out due to their widespread prevalence (Guthold et al., 2018, 2020) and its numerous pleiotropic effects (Burini et al., 2020; Kerr and Booth, 2022; Pinto et al., 2023).

From an evolutionary perspective, most of the human genome evolved under conditions characterized by high physical activity (PA) (Cordain et al., 1998; Boullosa et al., 2013; Booth et al., 2017). Virtually all hominins, including *Homo sapiens*—which arose approximately 200,000–300,000 years ago (Hublin et al., 2017; Richter et al., 2017; Schlebusch et al., 2017; Vidal et al., 2022)—depended on PA for survival, i.e., hunting and gathering, fleeing predators, digging, carrying loads, and other tasks involving both low- and high-intensity physical activities (Boullosa et al., 2013; Booth et al., 2017). However, after the Industrial Revolution and the advent of the Modern era, drastic changes in lifestyle occurred, reducing the need for PA at any intensity and increasing sedentary behavior (Eaton and Eaton, 2003). These lifestyle changes may have a pivotal role in contributing to diseases of civilization, such as MDD (Booth et al., 2017). Conversely, as will be discussed in subsequent sections, there is extensive evidence supporting the role of high levels of PA and regular exercise in reducing inflammation, as well as in preventing and ameliorating MDD. Notably, while pharmacological and psychotherapeutic approaches remain the mainstay of MDD treatment, current evidence suggests that exercise has antidepressant effects that are, in magnitude, comparable to traditional MDD therapies (Fabiano et al., 2025). Nevertheless, while these effect sizes are similar, exercise should not be seen as a replacement for conventional interventions but as an adjunctive therapeutic strategy (Fabiano et al., 2025). Interestingly, the mental health benefits of exercise appear to follow an inverted U-shaped curve, with very high levels of PA—exhibited typically by athletes, manual laborers, and individuals with exercise dependence—being associated with depressive-like symptoms (Armstrong and VanHeest, 2002; Gouttebarge et al., 2019; Golding et al., 2020; Golshani et al., 2021).

This narrative review explores how evolutionary insights can guide the use of PA and exercise in MDD prevention and treatment. We examine the interplay between inflammation and depression, the dual-edged nature of exercise, and how ancestral activity patterns may inform optimal PA prescriptions in modern settings.

2 Inflammation and depression

As previously mentioned, inflammation is a biologically-essential process that protects the host from pathogens, toxins, and other insults, while also facilitating tissue repair and restoring homeostasis (Medzhitov, 2021; Meizlish et al., 2021). However, this process involves metabolic and neuroendocrine changes that, if left unchecked, can impair survival and reproductive capacity (Straub and Schradin, 2016). Therefore, under normal conditions, inflammation is a time-limited acute response that resolves upon achieving its protective goals (Furman et al., 2019). Nevertheless, failures in the resolution of inflammation—due to impaired anti-inflammatory signaling, insufficient clearance of apoptotic cells, defects in efferocytosis, or chronic exposure to inflammatory stimuli—can lead to persistent immune activation (Kourtzelis et al., 2020; Doran, 2022; Panezai and Van Dyke, 2022; Collins et al., 2023). This sustained, dysregulated state is referred to as SLGCI, characterized by mildly elevated circulating inflammatory biomarkers and associated with a range of chronic degenerative conditions (Furman et al., 2019), including MDD (Arteaga-Henríquez et al., 2019; Costanza et al., 2024; Yin et al., 2024).

From an evolutionary standpoint, inflammation is tied to the concept of sickness behavior—an adaptive response featuring lethargy, anhedonia, social withdrawal, and reduced appetite, aimed at conserving energy to prioritize immune functions and recovery (Straub et al., 2010; Dooley et al., 2018). These behavioral and

metabolic adaptations likely conferred survival advantages in ancestral environments where acute threats were common (Straub and Schradin, 2016). However, in modern contexts marked by persistent stressors and lower pathogen exposure, these once protective pathways can drive SLGCI, contributing to the onset and progression of MDD (Miller and Raison, 2016). In this sense, SLGCI does not appear to be a normal or expected physiological state from an evolutionary perspective. Human physiology seems to have evolved to cope with acute, well-regulated inflammatory responses—not with persistent, low-grade inflammation (Furman et al., 2019; McDade, 2023). Supporting this notion, studies in traditional and non-industrialized populations—including the Melanesian horticulturalists of Kitava in Papua New Guinea (Carrera-Bastos et al., 2020), subsistence-agriculturalists in rural Ghana (Eriksson et al., 2013), the Shuar forager-horticulturalists of the Ecuadorian Amazon (McDade et al., 2012), and rural Filipinos (McDade, 2023)—have consistently documented extremely low baseline levels of C-reactive protein (CRP), despite frequent exposure to infectious agents and limited access to modern sanitation or medical care. These findings suggest that the low-grade chronic inflammatory state commonly observed in industrialized societies likely reflects a mismatch between modern environments and our evolutionary heritage.

2.1 Neuroinflammation

Neuroinflammation, a localized inflammatory response within the central nervous system (CNS), appears to be an important mechanism linking chronic inflammation to MDD. It is primarily mediated by glial cells, especially microglia—the brain's resident immune cells (Yang and Zhou, 2019; Li et al., 2024). Upon activation by stress, trauma, or peripheral inflammatory signals resulting from SLGCI, microglia adopt a pro-inflammatory phenotype, releasing inflammatory cytokines, such as tumor necrosis factor-α (TNF-α), interleukin-1β (IL-1β), and interleukin-6 (IL-6) (Li et al., 2024). These molecules can disrupt neuronal communication and impair neuroplasticity (Li et al., 2024; Pape et al., 2019). Moreover, they activate endothelial cells of the blood–brain barrier (BBB), increasing its permeability and facilitating the infiltration of peripheral immune cells—including monocytes, neutrophils, and T-cells—into the CNS (Felger, 2018; Lee and Giuliani, 2019; Beurel et al., 2020). This amplifies neuroinflammation by increasing the burden of pro-inflammatory molecules and further activating glial cells, which release reactive oxygen species (ROS) and nitric oxide (Beurel et al., 2020; Serafini et al., 2023; Kouba et al., 2024; Yin et al., 2024). The resulting oxidative and nitrosative stress impairs synaptic plasticity and disrupts the fronto-limbic network, which is critical for mood regulation (Kouba et al., 2024; Maas et al., 2017; Han and Ham, 2021).

Pro-inflammatory cytokines also affect neurotransmitter metabolism through activation of indoleamine 2,3-dioxygenase (IDO) (Seo and Kwon, 2023; Yin et al., 2024), which diverts tryptophan from serotonin synthesis toward kynurenine production (Seo and Kwon, 2023). Kynurenine is metabolized into neurotoxic compounds, such as quinolinic acid, which activate N-methyl-D-aspartate (NMDA) receptors and promote glutamate excitotoxicity (Kouba et al., 2024; Yin et al., 2024). This sequence of events impairs neuroplasticity, reduces hippocampal neurogenesis, and disrupts serotonin and dopamine signaling, contributing to anhedonia, motivational deficits, and other core symptoms of MDD (Cui et al., 2024). Additionally, chronic inflammation reduces levels of brain-derived neurotrophic factor (BDNF) (Yap et al., 2021), a key modulator of synaptic plasticity and neuronal resilience (Xiong et al., 2024), further impairing brain areas central to mood regulation, including the prefrontal cortex, amygdala, and hippocampus (Poletti et al., 2024).

2.2 Evidence linking chronic inflammation to depression

Multiple lines of evidence support the role of SLGCI in MDD. In animal models, systemic inflammatory triggers (e.g., endotoxins, cytokines) induce depressive-like behaviors and disrupt neurotransmitter regulation (Remus and Dantzer, 2016; Rhie et al., 2020; Yin et al., 2023). These models have elucidated specific inflammatory pathways involved in CNS dysfunction, such as the activation of IDO and its downstream effects. Epidemiological studies have consistently shown that elevated levels of inflammatory biomarkers are associated with increased depression risk (Smith et al., 2018; Li X. et al., 2023; Ji et al., 2024). Mendelian randomization analyses provide additional evidence by demonstrating a causal link between genetically predicted elevations in inflammatory biomarkers—such as CRP and IL-6—and increased susceptibility to depression (Khandaker et al., 2020).

Further support comes from meta-analyses and systematic reviews showing that patients with MDD exhibit higher concentrations of inflammatory biomarkers (Haapakoski et al., 2015; Köhler et al., 2017; Osimo et al., 2019; Li X. et al., 2023), which are also predictive of poor response to pharmacological antidepressant treatment (Arteaga-Henríquez et al., 2019). Moreover, these biomarkers are associated, in multiple epidemiological studies, with increased cardiovascular risk (Ridker, 2016; Li Y. et al., 2017; Li H. et al., 2017; Ni et al., 2020; Georgakis et al., 2021; Ridker et al., 2023, 2024a, 2024b; Khan et al., 2024), reinforcing the shared inflammatory underpinnings of MDD and CVD. In fact, recent meta-analytical evidence has associated MDD with a higher risk of cardiovascular mortality (Krittanawong et al., 2023).

Nevertheless, the most compelling evidence for the role of chronic inflammation in the etiology of MDD comes from randomized controlled trials (RCTs), which demonstrate the efficacy of anti-inflammatory agents—such as cytokine antagonists, nonsteroidal anti-inflammatory drugs, and omega-3 fatty acids—in reducing depressive symptoms in patients with MDD (Bai et al., 2020; Vöckel et al., 2024). Collectively, these findings support the role of inflammation as both a contributor to and a potential therapeutic target in MDD.

3 Physical activity, depression and inflammation

The inverse association between PA and MDD is supported by extensive epidemiological and clinical evidence. Individuals with depression consistently report lower PA levels and are approximately 50% less likely to meet public health guidelines recommending 150 min per week of moderate-to-vigorous PA compared to their age- and sex-matched peers (Schuch et al., 2017). In fact, they spend less time in all intensities of PA and more time in sedentary behavior

(Schuch et al., 2017). Conversely, greater engagement in leisure-time PA is consistently associated with a lower risk of incident depression (Schuch et al., 2018; Werneck et al., 2023). Longitudinal studies, including those spanning several years, confirm these relationships (Schuch et al., 2018). In individuals already diagnosed with MDD, even acute bouts of exercise have been shown to enhance mood and increase feelings of vigor and wellbeing (Bourke et al., 2022).

Exercise interventions—a structured subset of PA designed to improve or sustain one or more physical fitness valences, such as muscular strength or cardiorespiratory capacity—have consistently shown efficacy in reducing depressive symptoms in individuals with either clinical or subclinical depression (Heissel et al., 2023). A recent systematic review and meta-analysis of RCTs by Heissel et al. concluded that both endurance training (also known as aerobic exercise) and resistance training (also referred to as strength or weight training) produce moderate-to-large effect sizes (Heissel et al., 2023). Moreover, higher-intensity exercise interventions were associated with greater reductions in depressive symptoms than lower-intensity protocols (Heissel et al., 2023). These findings apply to both aerobic and resistance exercise modes. The main results from the Heissel et al. meta-analysis are summarized in Table 1. At the population level, prospective cohort studies have also shown an inverse curvilinear association between PA and depression risk: complete physical inactivity corresponds to the highest incidence of depression, while the risk steadily decreases as PA levels increase (Pearce et al., 2022). This graded pattern may partially reflect the cumulative physiological benefits of increased PA levels and regular exercise, including its capacity to modulate inflammation and enhance neurobiological resilience.

Despite the robust antidepressant effects of exercise, the underlying neurobiological mechanisms remain incompletely understood (Schuch et al., 2016; Stubbs and Schuch, 2019; Sun W. et al., 2023). A prominent hypothesis posits that exercise modulates several immune pathways, leading to long-term adaptations in the inflammatory response (Nieman and Wentz, 2019; Antunes et al., 2020; Scheffer and Latini, 2020; Sun S. et al., 2023; Langston and Mathis, 2024). Acute bouts of exercise initially elicit a transient pro-inflammatory response due to tissue stress and damage, especially in the cardiovascular and musculoskeletal systems (Cornish and Cordingley, 2024; Langston and Mathis, 2024). This response is required to clear cellular debris and facilitate tissue repair, thus leading to morphological adaptations (Langston and Mathis, 2024). Subsequently, an anti-inflammatory cascade is activated to restore homeostasis and promote the resolution of acute inflammation (Beiter et al., 2015; Docherty et al., 2022; Langston and Mathis, 2024). With consistent exercise training, this biphasic response becomes more efficient, and exercise contributes to long-term reductions in inflammation—not only at the skeletal muscle level but across various organs and systems, including the CNS (Scheffer and Latini, 2020; Di Ludovico et al., 2024).

However, findings from studies specifically examining the effects of exercise on inflammatory biomarkers in individuals with MDD remain limited and sometimes conflicting. A recent meta-analysis of 10 studies investigating the inflammatory response to exercise in people with MDD found no significant acute effects of diverse exercise interventions on IL-6, IL-10, or IL-8. In contrast, chronic exercise was associated with a small but statistically significant increase in TNF-α levels (Standardized Mean Difference = 0.296; 0.03–0.562, $p = 0.029$), while no significant chronic effects were observed for IL-6 or IL-1β (Guimarães et al., 2024). These results must be interpreted with caution due to methodological heterogeneity, the confounding anti-inflammatory effects of antidepressants (Patel et al., 2023), and a high risk of bias across studies. Additional high-quality trials are needed to clarify these findings and further evaluate the role of inflammatory modulation in the antidepressant effects of exercise.

TABLE 1 Effects of exercise on depressive symptoms: subgroup analyses by intensity and type.

Analysis	Number of RCTs	Meta analysis			
		SMD	95%CI		*p*-value
Main analysis	41	−0.946	−1.179	−0.714	**<0.001**
Exercise intensity					
Light	2	−1.041	−2.528	0.445	0.170
Moderate	26	−1.132	−1.453	−0.811	**<0.001**
Vigorous	10	−0.924	−1.472	−0.376	**0.001**
Exercise type					
Aerobic	30	−1.156	−1.461	−0.850	**<0.001**
Resistance	7	−1.042	−1.865	−0.218	**0.013**
Mixed[c]	10	−0.455	−0.797	−0.113	**0.009**

Summary of results from the systematic review and meta-analysis by Heissel et al. (2023), examining the effects of exercise interventions on depressive symptoms across different intensities and types. The analysis demonstrates that moderate and vigorous intensity exercise are associated with significant reductions in depressive symptoms, with aerobic and resistance training showing the largest effect sizes (Heissel et al., 2023).
Bold p-values indicate statistically significant results ($p < 0.05$). c refers to mixed exercise interventions combining aerobic and resistance modalities.
RCT, Randomized Controlled Trial; SMD, Standardized Mean Difference; CI, Confidence Interval.

4 Excessive exercise, overtraining and depression-like conditions

While regular physical activity and exercise confer significant benefits for mental health, excessive exercise may paradoxically lead to adverse psychological outcomes, including depression-like symptoms or even clinical depression. In such cases, individuals often experience persistent fatigue, mood disturbances, and performance decrements that require extended recovery periods. This maladaptive state, known as overreaching, is commonly conceptualized as a continuum, ranging from "functional overreaching" (FOR) to "non-functional overreaching" (NFOR) and, ultimately, "overtraining syndrome" (OTS) (Kellmann et al., 2018; Brenner et al., 2024). FOR, when strategically incorporated into training cycles, temporarily impairs performance but may ultimately enhance fitness. However, recent evidence challenges the necessity of FOR, suggesting that it may not be required for performance enhancement and could even be detrimental to health (Bellinger, 2020). In contrast, NFOR reflects a failure of adaptation characterized by negative psychological and physical changes and persistent performance deficits (Kellmann et al., 2018).

With prolonged exercise stress, insufficient recovery, and the compounding effects of additional factors, such as background stress, poor sleep, and inadequate nutritional status (Stellingwerff et al., 2021), athletes may progress from NFOR to a state of staleness or even

burnout. This more severe condition—often referred to as OTS—has been described as "athletes' depression" (Raglin et al., 2000; Armstrong and VanHeest, 2002). Unfortunately, no unified definition exists for these terms, and there is a lack of consensus across the literature. Moreover, the bidirectional relationship between depression and PA (Roshanaei-Moghaddam et al., 2009) complicates the differentiation between causation and correlation. As a result, recent literature has emphasized the need for greater conceptual clarity and standardization in this field (Kellmann et al., 2018; Eklund and DeFreese, 2021; Madigan, 2021). In line with these challenges, there is increasing recognition that "sport burnout" shares many psychological and physiological features with clinical depression (Armstrong and VanHeest, 2002). Burnout in exercise and sport contexts is often associated with reduced enjoyment and pleasure during exercise (Nixdorf et al., 2023). More than two decades ago, Armstrong and VanHeest identified multiple similarities between OTS and depression, including depressed mood, lack of motivation, changes in body composition, insomnia, appetite disturbances, and feelings of irritability and restlessness (Armstrong and VanHeest, 2002). In a study involving high-level adolescent Swiss athletes, burnout scores were significantly correlated with depressive symptoms ($r = 0.40$) (Gerber et al., 2018). Similarly, very high levels of exercise have been linked to worse mental health outcomes (Chekroud et al., 2018). In elite athletes, Grasdalsmoen et al. (2022) reported that such negative outcomes were primarily observed in female athletes training more than 14 h per week. Collectively, these findings underscore the shared mechanisms between OTS and depression and highlight the importance of prevention strategies and individualized training protocols.

Burnout, NFOR, OTS, and depression all share conceptual and mechanistic roots within the paradigm of chronic stress (Kenttä and Hassmén, 1998; Nixdorf et al., 2023). Smith, as early as 1986, was among the first to explicitly define burnout as a maladaptive response to chronic stress exposure (Smith, 1986). However, the specific mechanisms by which prolonged stress leads to burnout and OTS remain complex and incompletely understood. One proposed mechanism is that chronic psychological stress can interfere with physical recovery following strenuous or high-intensity exercise, potentially leading to delayed recovery of muscular function and reduced physical performance (Stults-Kolehmainen and Bartholomew, 2012; Stults-Kolehmainen et al., 2014a). In addition, high levels of psychological and life stress are well-established risk factors for the onset of depression (Turner and Lloyd, 2004; Hammen, 2005; Stults-Kolehmainen et al., 2014b). Individuals exposed to both physical and psychological stressors display varying degrees of resilience, depending on factors such as mental health status, physical fitness, and social support. Nonetheless, each individual has a finite threshold beyond which accumulated stress can exceed adaptive capacity and trigger maladaptive outcomes.

According to the "resources versus demands" model of stress, athletes who encounter excessive physical or emotional demands without adequate recovery resources—such as rest, sleep, nutritional support, or social–emotional buffering—are at higher risk of burnout and are less able to sustain the demands of training and competition (Brenner et al., 2024). The consequences often include loss of enjoyment, declining motivation, overuse injuries, and eventual withdrawal from sport (Raglin et al., 2000; Meeusen et al., 2006; DiFiori et al., 2014). Dysregulation of inflammatory pathways has been proposed as a possible link between prolonged stress exposure and the development of depressive-like conditions in this context, though conclusive evidence is still lacking (Kim et al., 2022; Hassamal, 2023).

From an evolutionary perspective, it is plausible that prolonged exposure to excessive stressors triggers a shift toward energy-conserving states, manifesting as depression-like behaviors aimed at reducing further physical, psychological, or metabolic strain. Alternatively, stress-induced depression may represent a more fundamental biological strategy to preserve homeostasis by withdrawing from unsustainable environmental demands (Beck and Bredemeier, 2016).

5 An evolutionary approach to exercise as a treatment for MDD through the reduction of inflammation

Based on the current evidence, two complementary evolutionary perspectives can guide the use of PA and exercise in the prevention and treatment of MDD: (1) modeling patients' PA patterns—including exercise—after those of ancestral human populations, and (2) selecting exercise modalities that specifically target SLGCI and neuroinflammation. Although exercise has demonstrated effects comparable to pharmacological and psychotherapeutic treatments for MDD (Fabiano et al., 2025), there is no consensus on the most effective types, intensities, or durations of exercise interventions (Heissel et al., 2023). By applying an evolutionary framework, exercise modalities can be selected not only for their anti-inflammatory properties but also for their compatibility with human physiology shaped by millennia of physically demanding lifestyles. This approach may provide broader physical and mental health benefits and extend to both prevention and treatment of MDD within a holistic, lifestyle-based perspective. In doing so, it may also enhance ecological validity and adherence to exercise-based interventions.

The available evidence supports a tentative recommendation for combining diverse forms of exercise within a context of reduced sedentary behavior—consistent with ancestral PA patterns. This would involve daily low-to-moderate PA interspersed with less frequent bouts of high-intensity activity (Boullosa et al., 2013). These activity levels exceed those typically observed in industrialized populations but are well within the physiological range of modern hunter-gatherer groups (Raichlen et al., 2017; Pontzer et al., 2018). This distinction is critical because excessive exercise—such as ultra-endurance training—has been associated with increased cardiovascular risk, potentially mediated by SLGCI (Celeski et al., 2024). Importantly, although individuals in both industrialized and ancestral societies may spend similar time resting, the latter use active resting postures (e.g., squatting), which promote greater muscle activation and favor musculoskeletal health (Raichlen et al., 2020).

Of note, the effectiveness of exercise interventions may be enhanced when performed in environments that optimize both mental and physical wellbeing—such as natural settings—and ideally involve social interactions with family or friends. These contexts have been shown to improve stress management (Antonelli et al., 2019; Bramwell et al., 2023), enhance enjoyment (Davis et al., 2021), and increase vitamin D levels via sun exposure (Wacker and Holick, 2013)—all factors associated with reduced depressive symptoms and systemic inflammation (Hansen et al., 2017; Gorman et al., 2019; Burns et al.,

2021; Yeon et al., 2021; Kuczynski et al., 2022; Moslemi et al., 2022; Lin et al., 2023; Mikola et al., 2023; Siah et al., 2023; Wang et al., 2023).

When selecting exercise modalities to decrease SLGCI and neuroinflammation, two primary therapeutic targets emerge: (1) improvement in key physical fitness components—such as aerobic capacity and muscular strength—and (2) favorable changes in body composition. With respect to the first target, it is now well established that regular exercise elicits a cascade of physiological and molecular adaptations that directly counteract inflammatory processes. These include increased fluid shear stress, the release of exerkines (e.g., IL-6 with anti-inflammatory properties, BDNF), improved mitochondrial function, and modulation of both innate and adaptive immunity (Gleeson et al., 2011; Fiuza-Luces et al., 2013; Casuso and Huertas, 2021; Gao et al., 2024; Zhou et al., 2024; Chatzigeorgiou et al., 2025). Together, these adaptations may reduce peripheral and central inflammation (Hu et al., 2024), enhance neuroplasticity via neurogenesis, synaptogenesis, dendritic arborization, and angiogenesis (Morland et al., 2017; Lin et al., 2018; Xie et al., 2021), and alleviate depressive symptoms (Xie et al., 2021). These mechanisms offer a biological rationale for how improvements in aerobic capacity and muscular strength may help downregulate inflammatory activity and alleviate depressive symptoms. Supporting this, multiple controlled trials and systematic reviews have shown that both aerobic and resistance training—individually or in combination—can significantly reduce pro-inflammatory biomarkers (Fedewa et al., 2017; Bautmans et al., 2021; Kanthajan et al., 2024). Moreover, preliminary evidence suggests these modalities may also attenuate neuroinflammation (Hu et al., 2024), although more high-quality trials are needed to confirm these effects.

The second therapeutic target concerns body composition, with particular emphasis on reducing visceral adipose tissue (VAT), a depot known to play a central role in SLGCI (Valenzuela et al., 2023). Located within the abdominal cavity and surrounding internal organs, VAT is more metabolically active than subcutaneous fat and exhibits greater lipolytic activity (Hill et al., 2018; Cypess, 2022; Valenzuela et al., 2023). As VAT expands in the context of obesity, it becomes prone to hypoxia due to inadequate vascularization and limited angiogenic capacity (Gealekman et al., 2011). This hypoxic microenvironment promotes oxidative stress, adipocyte fibrosis, and cell death, which in turn trigger inflammatory gene expression in tissue-resident immune cells (Valenzuela et al., 2023), especially macrophages (Guria et al., 2023). These cells release pro-inflammatory cytokines, such as TNF-α and IL-6, thereby sustaining local inflammation and contributing to SLGCI (Valenzuela et al., 2023). Consistent with this, several observational studies have reported a positive association between VAT and circulating CRP levels (Forouhi et al., 2001; Saijo et al., 2004; Park et al., 2010; Tsuriya et al., 2011). Encouragingly, exercise—even as a standalone intervention—has been shown to reduce both subcutaneous (Yarizadeh et al., 2021) and visceral fat stores (Vissers et al., 2013; Sabag et al., 2017), with aerobic training, particularly at high intensities, appearing especially effective in targeting VAT (Ismail et al., 2012; Chen et al., 2024; Poon et al., 2024).

In addition to reducing VAT, exercise may also influence brown adipose tissue (BAT), a thermogenic and metabolically active tissue involved in energy homeostasis (Dong et al., 2023). Compared to white adipose tissue, BAT appears less prone to inflammatory signaling and may exert local anti-inflammatory effects (Omran and Christian, 2020). Preclinical studies suggest that exercise can enhance BAT activity, potentially improving metabolic and inflammatory profiles (Dong et al., 2023; Stroh and Stanford, 2023). However, findings from human studies remain inconsistent—with some RCTs, such as the ACTIBATE trial, showing no change in BAT volume or activation following 24 weeks of exercise in young sedentary adults (Martinez-Tellez et al., 2022). While promising, current evidence is insufficient to conclude that BAT activation is a key mechanism by which exercise impacts SLGCI or MDD.

Taken together regularly incorporating a variety of aerobic and resistance exercises into a routine aligned with ancestral activity patterns—while minimizing sedentary behavior—may provide a practical and physiologically-relevant strategy to reduce SLGCI and depressive symptoms through simultaneous improvements in physical fitness components, including body composition.

Further reinforcing this strategy, alternative exercise protocols such as short sprint interval training (sSIT) have also demonstrated promise. Recent findings by Ribeiro et al. (2024) showed that sSIT led to significant reductions in depressive symptoms, along with improvements in aerobic power, lower limb muscle power, body composition, and incidental PA levels in women with MDD—all achieved with less than 1 hour of total exercise over 2 weeks (Ribeiro et al., 2024). These preliminary findings underscore the potential of innovative, time-efficient exercise modalities that merit further investigation alongside more established exercise interventions for the treatment of MDD.

Figure 1 provides an overview of the proposed mechanisms linking exercise to reductions in inflammation and depressive symptoms.

6 Limitations and future perspectives

The approach proposed in this narrative review is not without limitations. Our framework is informed by a diverse body of evidence, including observational, mechanistic, and interventional studies—such as RCTs—examining the effects of PA and exercise on SLGCI and depressive symptoms. However, many of the specific associations discussed remain correlational, particularly regarding the interaction between evolutionary mismatches, SLGCI, and depression. Moreover, the potential role of other associated pathophysiological processes—such as gut microbiota dysbiosis (Van Baalen et al., 2025)—should not be overlooked, although they fall outside the scope of the present review.

Furthermore, while our model draws on ancestral activity patterns to inform modern interventions, these patterns are inferred from archeological data and ethnographic studies of contemporary hunter-gatherer populations who are themselves influenced by modern environments. Accordingly, although it is conceptually sound to align PA and exercise strategies with evolutionary insights, empirical testing of these hypotheses in humans remains a challenge. Nevertheless, targeted and well-designed RCTs can assess the effects of specific exercise modalities and training loads—particularly when embedded within lifestyle interventions—on neuroinflammatory and depressive outcomes.

Lifestyle change is inherently complex and nonlinear, and its success depends on a constellation of behavioral, environmental, and individual factors. While *Homo sapiens* may have partially adapted to more sedentary living since the Neolithic era, the evolutionary argument for an active lifestyle remains compelling. Still, generalizations based on ancestral patterns may not apply universally. Therefore, exercise-based interventions should be tailored to the

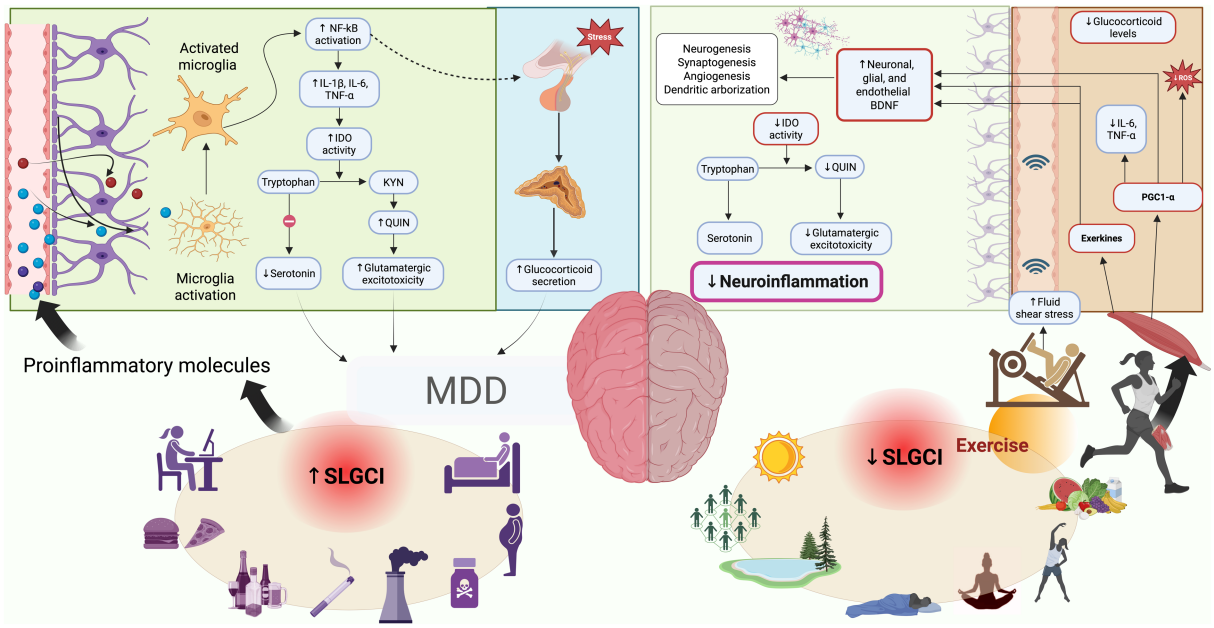


FIGURE 1
Conceptual framework illustrating how chronic inflammation contributes to Major Depressive Disorder (MDD), and how exercise and lifestyle factors may counteract it. On the left side, chronic low-grade inflammation (↑ SLGCI) is fueled by modern lifestyle factors such as poor diet, sedentary behavior, smoking, alcohol consumption, inadequate sleep, and psychosocial stress. This leads to increased systemic levels of proinflammatory molecules (e.g., IL-1β, IL-6, TNF-α), which can cross the blood–brain barrier and activate microglia. Activated microglia release additional cytokines and neurotoxic metabolites (e.g., quinolinic acid) via the kynurenine pathway, contributing to neuroinflammation, impaired serotonin signaling, glutamatergic excitotoxicity, reduced BDNF levels, and ultimately, the development of MDD or depressive symptoms. On the right side, regular exercise and healthy lifestyle habits—such as physical activity in natural environments, social interaction, adequate sunlight exposure, stress management, and a nutrient-rich diet—are associated with reduced systemic inflammation (↓ SLGCI). Exercise promotes anti-inflammatory effects through various pathways, including shear stress-induced production of exerkines (e.g., IL-6 with anti-inflammatory action, BDNF), improved mitochondrial function, and modulation of immune responses. These adaptations help decrease peripheral and central inflammation, enhance neuroplasticity, and alleviate depressive symptoms. BDNF, Brain-derived neurotrophic factor; IDO, indoleamine 2,3-dioxygenase; KYN, Kynurenine; MDD, Major Depressive Disorder. NF-κB, Nuclear Factor kappa-light-chain-enhancer of activated B cell; PGC1-α, Peroxisome proliferator-activated receptor gamma coactivator 1-alpha; QUIN, Quinolinic acid; SLGCI, Systemic low-grade chronic inflammation. Created with BioRender.com.

individual's physiological, psychological, and social context, ideally through a holistic strategy that targets priority lifestyle factors.

Importantly, humans did not evolve to "exercise" as a discrete activity (MacDonald et al., 2025), but to remain consistently active as part of daily life (Boullosa et al., 2013; Fiuza-Luces et al., 2018). Thus, lifestyle interventions should aim to identify the optimal combination of PA levels, reduced sedentary time, and intentional exercise that promotes long-term adherence through positive affective experiences. Future studies should explore how different exercise interventions—integrated within realistic, sustainable lifestyle strategies—can best modulate chronic inflammation and depressive symptoms across diverse populations and clinical contexts.

7 Conclusion

There is growing recognition that MDD is intricately connected to SLGCI, a condition driven and exacerbated by modern lifestyle factors that deviate from ancestral patterns of PA and environmental exposure. PA and, more specifically, exercise offer a robust, evidence-based intervention for modulating inflammation and improving depressive symptoms. Viewed through an evolutionary lens, aligning exercise patterns with those of our hunter-gatherer ancestors—characterized by regular low-to-moderate activities interspersed with occasional high-intensity efforts—emerges as a promising therapeutic strategy. This approach not only addresses some of the root causes of MDD but also provides broader benefits for general health and physiological resilience.

This narrative review highlights the dual role of PA and exercise as both preventive and therapeutic modalities for MDD, targeting key mechanisms such as SLGCI and neuroinflammation. While current evidence is encouraging, future research should focus on refining exercise protocols to maximize their efficacy, particularly for individuals with diverse backgrounds or comorbid conditions. Findings from the overtraining literature suggest that exercise may follow an optimal dose–response curve, in which excessively high levels could be counterproductive. In parallel, understanding the long-term effects of exercise on both mental and physical health in MDD populations remains a critical research priority.

Adopting a holistic perspective that integrates conventional treatment (e.g., anti-depressant medications) with exercise and other lifestyle modifications—including improved sleep hygiene, stress management, and dietary interventions—may offer the most comprehensive and sustainable approach for mitigating the global burden of MDD. By bridging ancestral behavioral patterns with contemporary science, exercise can reclaim its place as a cornerstone of mental health care, offering accessible, safe, and effective support for individuals worldwide.

Author contributions

PC-B: Conceptualization, Writing – original draft, Writing – review & editing. BB: Conceptualization, Writing – original draft, Writing – review & editing. MS-K: Conceptualization, Writing – original draft, Writing – review & editing. FS: Writing – original draft, Writing – review & editing. FM-O: Validation, Visualization, Writing – review & editing. PM: Writing – original draft, Writing – review & editing. J-RB: Writing – original draft, Writing – review & editing. DB: Conceptualization, Writing – original draft, Writing – review & editing.

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Correction note

This article has been corrected with minor changes. These changes do not impact the scientific content of the article.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

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Evolution of documents related to performance in boccia: a paralympic sport bibliometric analysis

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Background: The purpose of this study was to develop a bibliometric review of literature related to Boccia, aiming to analyse relevant information related to the adapted sport, and determine the existing relationships/networks between the different authors and countries, as well as methodological procedures of publications.
Methods: The Web of Science database was used, considering the keywords "Boccia" OR "Bocha" AND "Sport", applying the filter "topic" to identify documents containing this term in the title, abstract, or keywords. A total of 89 studies were found and 38 selected based on the criteria, published until November 2024.
Results: From 2012 forward, the number of studies increased by 81.87% from 2017 to 2024, with a notable rise between 2017 and 2020. Two documents had 20 or more citations, and a total of 119 authors were associated with 38 selected documents, an average of 3.6 authors per document. Portugal and Spain present the highest number of documents ($n = 9$), but Spain has more than twice thecitations compared to Portugal (58 vs.17). From a total of 29 resources, *Springer Nature* had the highest number of studies indexed in its platforms ($n = 7$). A total of 92 keywords were identified, and the terms with the highest occurrence were "boccia" ($n = 17$), "rehabilitation" ($n = 4$), and "disability" ($n = 4$). Brazil and Indonesia were the countries with the most recent scientific production, and 90.6% of the studies were written in English and 9.4% in Spanish.
Conclusions: The findings emphasize the limited research output in Boccia, particularly regarding performance analysis, coaching methodologies, and athlete development. Future studies should explore training strategies, physiological demands, and the impact of Boccia on athleteś development and social inclusion.

KEYWORDS

paralympic, publication analysis, adapted sport, research, trend

1 Introduction

In recent times, there has been a solid increase in the number of sports available for people with disabilities, at a recreational and competitive level, creating more opportunities for these athletes to participate in sports (1, 2). Adapted sports foster physical and emotional health, helping individuals with disabilities to focus on their potential (3, 4) and promoting numerous benefits to its practitioners, such as confidence and self-efficacy (1) and higher levels of quality and satisfaction with life compared with individuals not involved in sports (3, 5, 6).

Boccia is a sport that is inclusive of all genders, ages, and abilities (7). In sports such as Boccia, individuals compete intending to achieve success. This adapted sport aims to improve the quality of life of its participants and facilitate their integration into society (8). Beyond its physical benefits, Boccia emphasizes strategy, teamwork, and social interaction, which fosters emotional regulation, empathy, and interpersonal skills, contributing to the development of emotional intelligence (9).

This parasport was practiced for many years as a leisure activity, only introduced at the Stoke Mandeville and New York 1984 Paralympic Games as a competitive sport (10). Nowadays, people with cerebral palsy (CP) can compete in individual classes BC1, BC2 or BC3 (11), the BC4 individual class is associated to "athletes who are diagnosed with an impairment of non-neurological origin not affecting the central nervous system and who do not present tonal change or spasticity as their primary impairment" (12). This precision adapted sport is played on a court with two sides, each side has six balls (red or blue), and players must throw these balls, using a method determined by their classification, out into the playing zone and as close as possible to the jack (the white ball on a playing hard surface court measuring 12.5×6 m (13). Boccia can also be played in pairs or teams, and BC3 players receive assistance during the throw or resort to a ramp. By participating in activities such as Boccia, individuals with physical disabilities become active participants in community life (9). The outcome of the study conducted by Siavoshy and Bolurian (14), focusing on the effect of practicing Boccia on the social development of children with cerebral palsy and intellectual disability, showed that the intervention could significantly improve self-help in general, self-help eating, verbal communication, socialization, and locomotion. Unfortunately, the literature draws attention to the lack of sufficient research on the important components of training para-athletes or adapted sports (15), which in our perspective is related to the lower number of athletes compared to sports and less media impact (for example on television), situations that

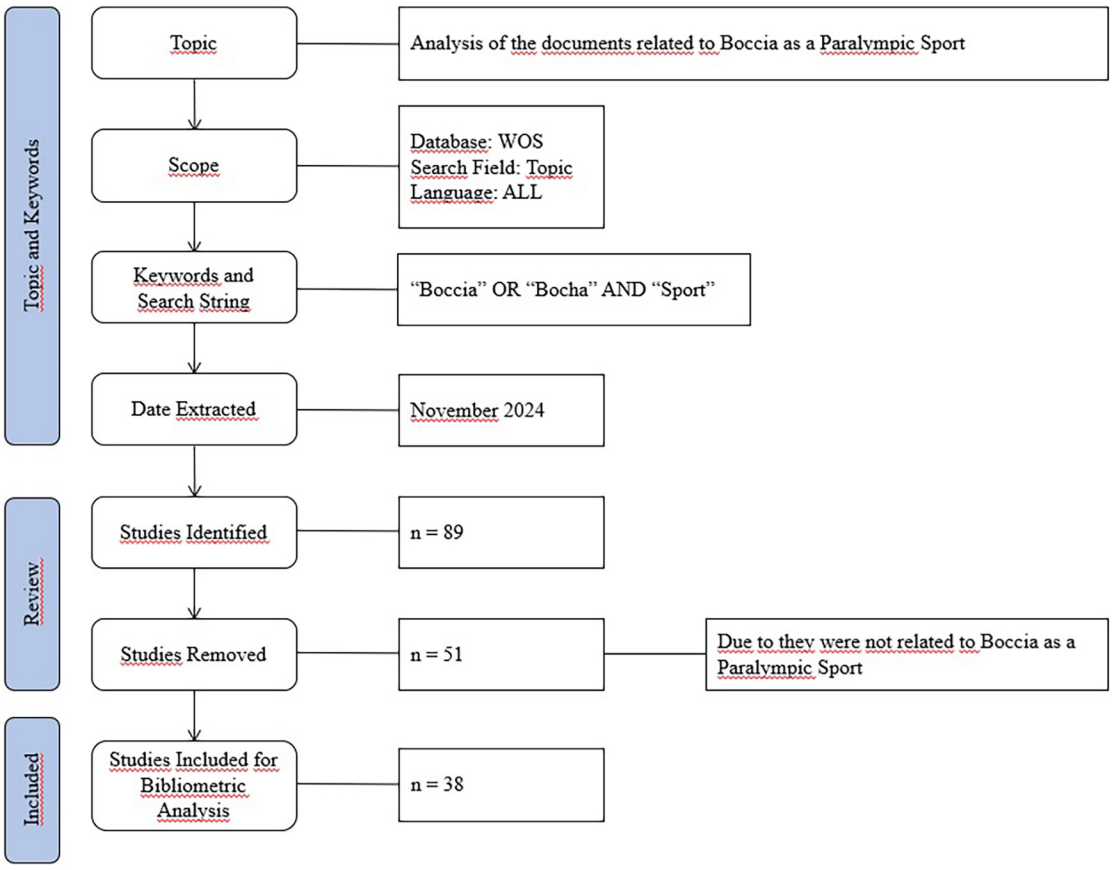


FIGURE 1
Flow chart of the document search.

seem to us to be improving in recent years in adapted sports, in general.

In addition, contact with the condition of disability and its clinical and social particularities has always created some barriers in society, which in our view have been broken down over the years, and we are currently seeing athletes with disability condition training and competing with athletes without a disability condition, which poses challenges in the training process and competitive moments. Boccia requires sustained concentration, and it is well established that regular mental stimulation improves the quality of life and independence (16). When individuals are playing Boccia, they have the opportunity to improve functionality and to interact with people with similar life problems. This adapted sport serves as a means of engagement for individuals with all types of disabilities, and based on studies, improves functional health and quality of life, helping in the inclusion/integration process in society (17).

Boccia has excellent effects on motor skills, and Williamson et al. (18) argued that the most important factor during the training of athletes with a disability is the coach's knowledge of aspects related to rehabilitation, skill level, awareness, and knowing how to provide the athlete with constant safety. Very little research has reported scientific evidence related to Boccia athletes. There is a great space and need for further research, particularly regarding "Coaching Science", to improve training conditions and optimize sports performance (19). Therefore, the main objective of this study was to develop a bibliometric review of the literature related to Boccia, aiming to analyse information related to the adapted sport (publications, citations, journals, keywords), and determine the existing relationships/network between the different authors and countries that have participated in publications related to Boccia.

2 Materials and methods

2.1 Study design

The main objective of the present work was to develop a bibliometric review of the existing literature, which is framed within the Theoretical Studies (20). In addition, due to the evaluation of existing information, it is classified within the studies with retrospective methodology (21). This method allows obtaining more information related to the research topic, as well as understanding the state of the art (22). In the same way, it allows collecting documents from the same database, as well as filtering and refining the search simply (23). Therefore, the following phases were followed for the elaboration of the present study: (1) selection of the topic, (2) selection of the research method, (3) collection of information, (4) analysis of the information, (5) visualization, and (6) interpretation.

2.2 Search strategy

To identify the documents, the following search phrase was used: "Boccia" OR "Bocha" AND "Sport" using the filter "topic" to identify those documents that contained this term in the title, abstract, or keywords. In addition, in order to select the largest number of documents related to the study topic, the documents had to be related to Boccia as the main topic of the study, that is, the research question had to be focused on the study of an area of this modality.

To this end, the search was carried out with the aim of reducing the bias of the results and increasing the reliability and validity of the selected papers. After the search, a total of 89 studies were

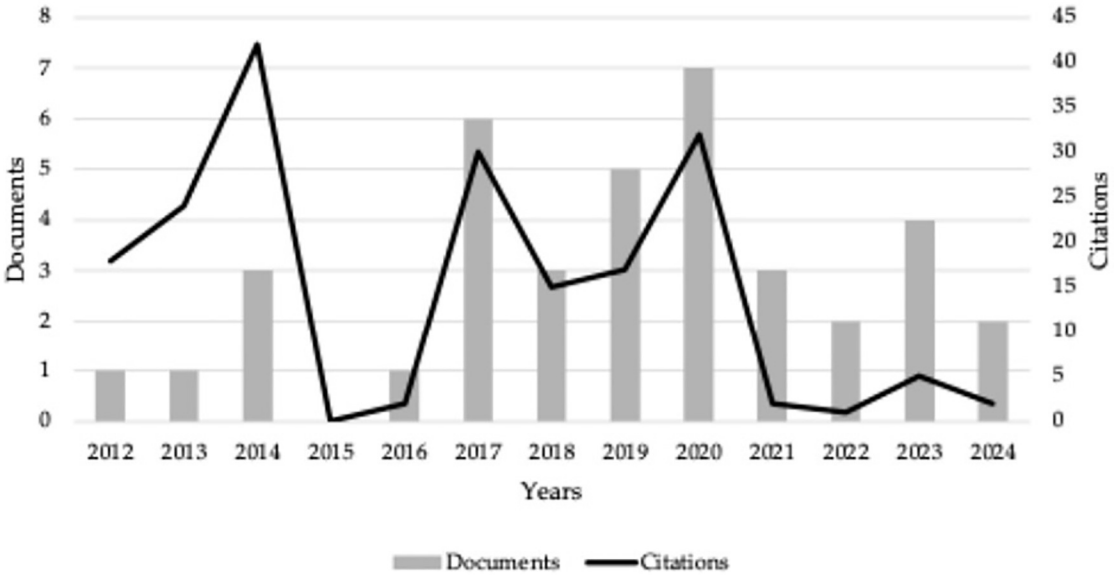


FIGURE 2
Evolution of documents related to Boccia.

identified in the first stage. Subsequently, after reading both the title and the abstract by the researchers, 51 studies were eliminated because they did not analyse Boccia as a Paralympic sport. Finally, a total of 38 studies were obtained, published with dates prior to November 2024, the date on which the search was carried out. Figure 1 describes the search process.

2.3 Data extraction

For the selection and extraction of information, the Web of Science (WoS) database was used, since it allows obtaining information related to the title, name of the publication (journal), year, abstract, and/or keywords. For this reason, it is one of the most widely used databases for the development of these works (24–26). Specifically, those documents indexed in the WoS Core Collection database were considered, a series of documents only indexed in this electronic platform. VOSviewer plays a pivotal role in visualizing collaboration patterns among countries and authors, facilitating the depiction of co-occurrence networks pertaining to keywords (27).

2.4 Data analysis

The laws of bibliometric studies (28) were considered in the development and extraction of data. In addition, different analyses were used for the extraction and interpretation of the results. To evaluate the exponential growth of the number of publications, Price's Law has been used, through the R^2

TABLE 1 Most cited documents information.

Authors	Article title	Study's aim	Times cited	Citations per year	Source title	IF	Quartil
de la Vega et al. (36)	Precompetitive Mood and Perceived Performance in Paralympic Boccia	This study examines the mood profile of the Spanish National Boccia team at the Paralympics in Beijing "08. Describes athletic performance perceived by the team, both in individual and collective competitions.	24	2.18	*Revista de Psicologia del Deporte*	0.7	Q4
Huang et al. (37)	Motion Analysis of Throwing Boccia Balls in Children with Cerebral Palsy	This study investigated the differences between children with cerebral palsy and normally developed children regarding throwing patterns of Boccia balls.	23	2.30	*Research In Developmental Disabilities*	2.9	Q1
Fong et al. (35)	Upper Limb Muscle Fatigue during Prolonged Boccia Games with Underarm Throwing Technique	This study investigated the acute fatigue pattern in neuromuscular activity after a simulated Boccia game and the effect of fatigue pattern on sport performance	18	1.50	*Sports Biomechanics*	2.0	Q3
Reina et al. (38)	Throwing Distance Constraints Regarding Kinematics and Accuracy in High-Level Boccia Players	The aim of this study was to investigate whether different throwing distances might have an impact on kinematics and accuracy across repeated throws.	14	2.33	*Science & Sports*	0.8	Q4
Ovenden et al. (16)	Here Everyone is the Same—A Qualitative Evaluation of Participating in a Boccia (Indoor Bowling) Group: Innovative Practice	This qualitative study explored the impact of a Boccia (modified indoor bowls) group on the lives of people with dementia and their careers.	12	2.40	*Dementia International Journal of Social Research and Practice*	2.4	Q2
Tsai et al. (39)	Seat Surface Inclination may affect Postural Stability during Boccia Ball Throwing in Children with Cerebral Palsy	The aim of the study was to examine how seat surface inclination affects Boccia ball throwing movement and postural stability among children with cerebral palsy (CP).	12	1.20	*Research In Developmental Disabilities*	2.9	Q1
Roldan et al. (40)	Inter-Rater Reliability, Concurrent Validity and Sensitivity of Current Methods to Assess Trunk Function in Boccia Players with Cerebral Palsy	Trunk function is a core factor to allocate Boccia players with cerebral palsy in BC1 and BC2 sport classes, according to the Boccia International Sports Federation (BISFed). However, the appropriateness of the current test to assess trunk function has never been studied to determine its reliability, validity and sensitivity to discriminate between different levels of impairment.	12	3.00	*Brain Sciences*	2.7	Q3
Houlihan and Chapman (41)	Talent Identification and Development in Elite Youth Disability Sport	The paper examines the talent identification and development process in three youth disability sports: wheelchair basketball, Boccia and disability tennis. The analysis is concerned to explore the extent of convergence in processes between disability sports and between disability and mainstream sports.	12	1.71	*Sport In Society*	1.5	Q3

coefficient (29), this analysis allows the identification of those obsolete and contemporary documents, closer to the present time. To identify those authors with the greatest number of documents, Lotka's Law (30) was used, through the use of the H index (31). Finally, for the analysis of the key terms used, Zipf's Law (32, 33), was used, including a total of 85 keywords.

Finally, Microsoft Excel (version 2006: Microsoft Corporation, Redmond, WA, USA) and VOSviewer (Center for Science and Technology Studies, The Netherlands) were used for data analysis and visualization. For the creation and visualization of the results, a fragmentation analysis (attraction: 3 and repulsion: −3) was used, according to the topic and temporality of the results (34).

TABLE 2 Classification of documents.

Type of document	Documents	%
Article	22	68.75
Congress	8	25.00
Book chapter	2	6.25
Early access	1	3.12
Meeting abstract	1	3.12
Review article	1	3.12

3 Results

3.1 Analysis of the documents and quotes

Considering the totality of the identified documents, we observed the existence of a study published in 2012, in which the main objective was to analyse the patterns of acute fatigue in neuromuscular activity after a simulated Boccia game, and its effect on sports performance (35). Until 2016, very few manuscripts were published. In detail, no manuscripts were published in 2015, only 1 in 2012, 2013, and 2016, with 2014 being the year with the highest number of publications between 2012 and 2016 (a total of 3). Establishing the study range from 2016 to 2024, an exponential growth of 81.87% of the sample is observed compared to 2012–2016. Notably, 2020 recorded the highest number of publications ($n = 7$). Taking as a reference the number of citations received by year, 2014 has been identified as the year with the highest number of citations ($n = 42$), and 2017 to 2020 the time frame associated with an exponential growth.

Regarding the reference to the number of citations received in each of the documents, and, after identifying the H index of the selected sample (9), it was observed the existence of two documents with 20 or more citations, more specifically, with a

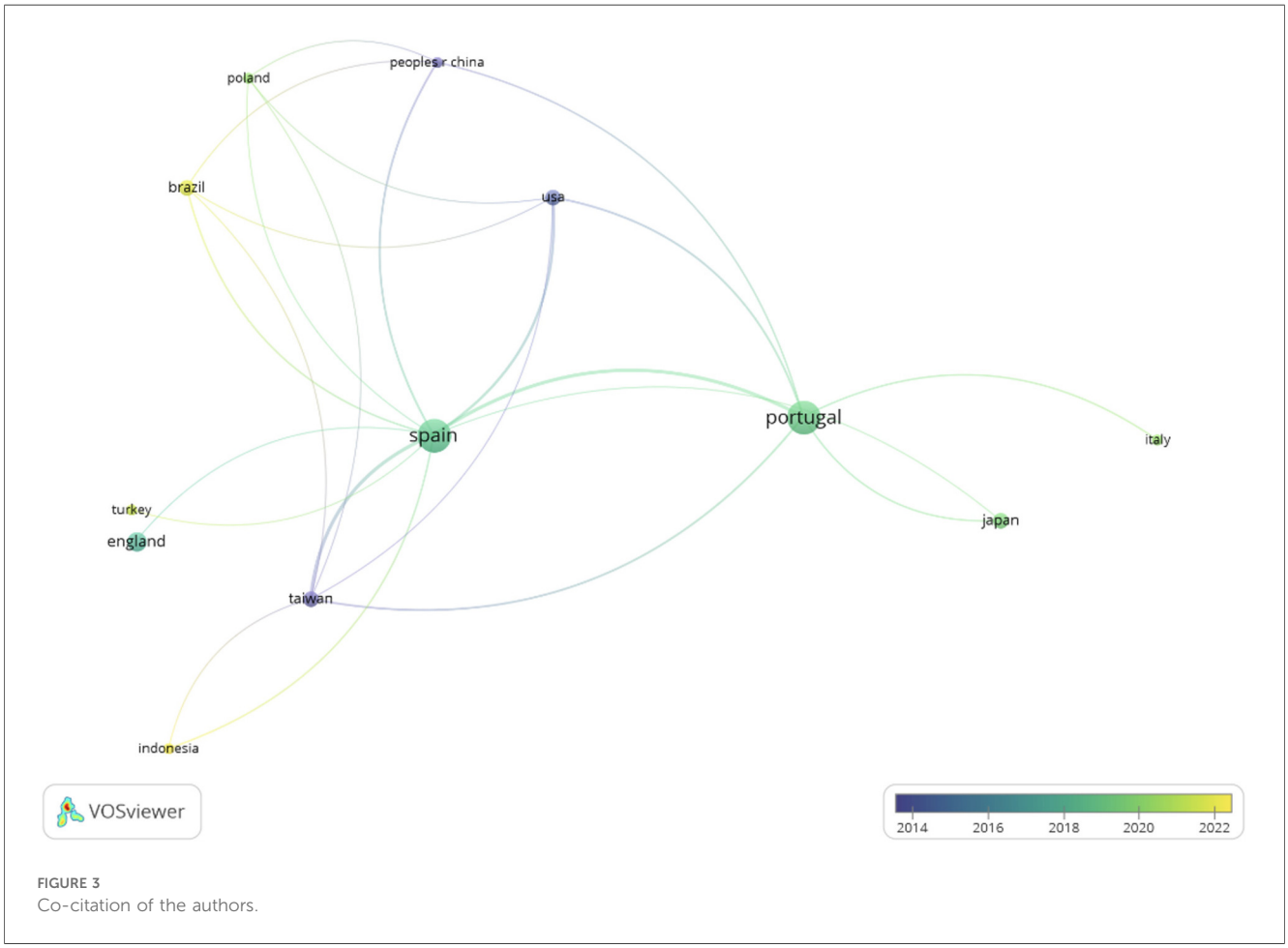


FIGURE 3
Co-citation of the authors.

total of 24 (36) and with 23 citations (37). Figure 2 shows the evolution of the documents in the range of dates mentioned above.

Table 1 shows the first 8 documents with the highest number of citations, as well as the average number of citations received per year since the publication. In addition, the resource (journal) in which it was published is shown, as well as the journal's Impact Factor and the Journal Citation Reports (JCR) quartile. This analysis provides the opportunity to identify those journals or platforms with the highest impact index in the scientific community, and to select them to carry out the publications, to obtain greater repercussion of research.

TABLE 3 Classification of the documents considering the country of the first author.

Countries	Documents	%	Citations
Portugal	9	28.12	17
Spain	9	28.12	58
England	3	9.37	11
Brazil	2	6.25	2
Japan	2	6.25	8

3.2 Type of documents

From the total number of studies ($n = 38$), a large spectrum of documents can be observed, which have been classified according to their structure and object of realization. For this purpose, the classification established by Gamonales et al. (42) has been established as a reference. This fact allows us to perform a classification of the studies according to their purpose and structure, with "Article" being the most used format ($n = 22$), followed by "Congress" ($n = 8$), whose purpose is to perform the presentation of papers in congresses for greater scientific dissemination. Table 2 shows the number of documents for each item. The total number is higher with the inclusion in the review because certain studies can be placed in different categories.

3.3 Network between authors of documents

Concerning the different authors who have contributed to the development of the different works, a total of 119 authors were associated with 38 selected documents, with an average of 3.6

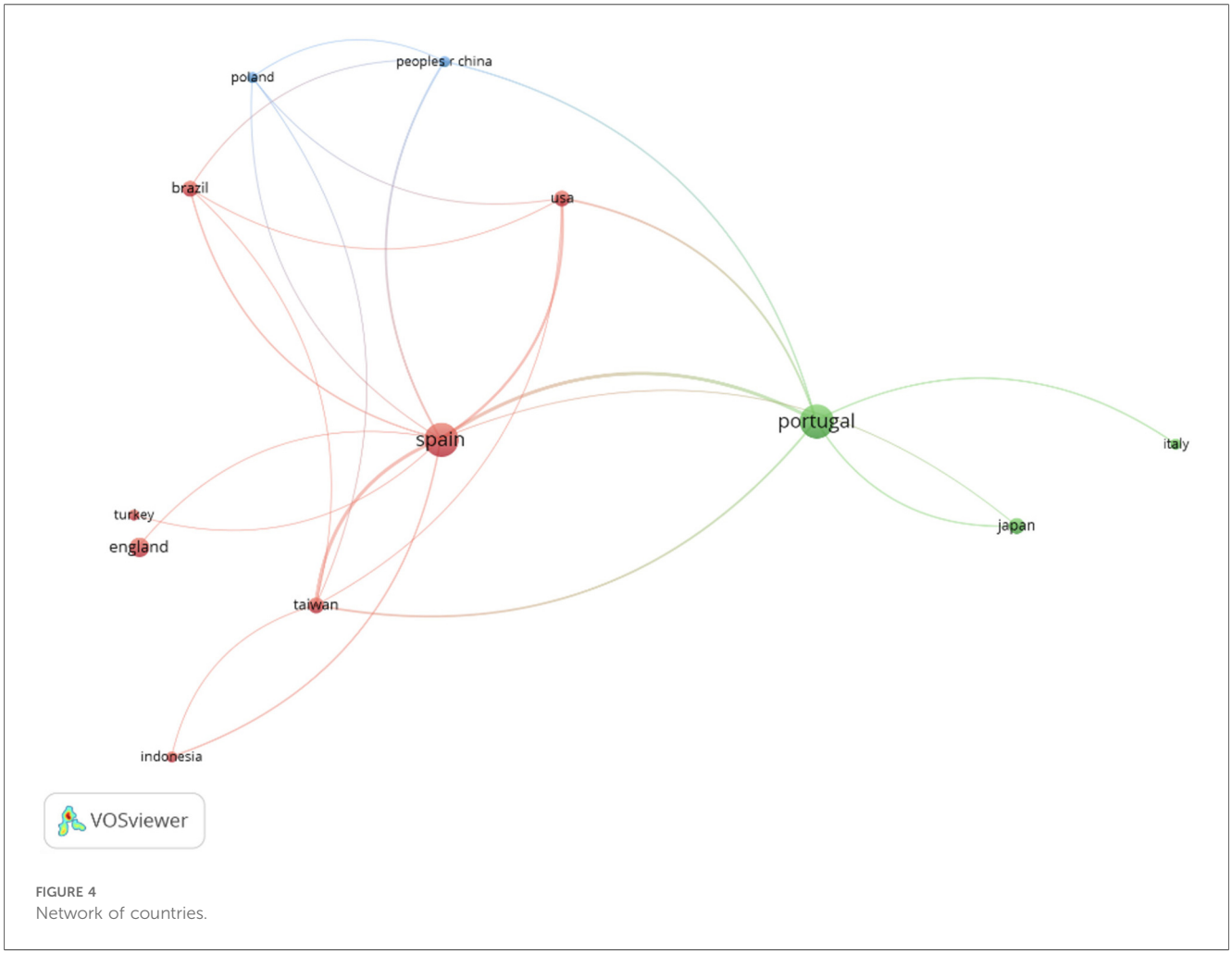


FIGURE 4
Network of countries.

authors per document, which suggested international collaboration. After a thorough analysis of the authors, it was observed that only 3 authors (Novais, P.; Silva, V.; Soares, F.) have carried out a minimum of 4 studies related to Boccia. On the contrary, considering the number of citations as the main variable of analysis, it is Raúl Reina and Alba Roldán who present the highest number ($n = 28$), with 3 published studies. Figure 3 shows the correlations between the authors, as well as the different groups identified.

3.4 Publications considering the country and language

Of all the countries included in the analysis ($n = 15$), Portugal and Spain are in the first position with the highest number of documents ($n = 9$). Table 3 shows the number of documents and citations received for each of the selected countries, and it can be observed that Spain, despite having the same number of published documents, has more than twice the number of citations compared to Portugal (58 vs. 17).

After performing a linguistic analysis of the different studies, it was found that 90.6% of the studies were written in English and 9.4% in Spanish.

Figure 4 shows the relationships between the different countries and Figure 5 highlights that Brazil and Indonesia are the countries with the most recent scientific production.

3.5 Analysis of the publishers and journals

About the journals that published the studies, there was a great disparity in the results, since a total of 29 resources were identified, highlighting a wide range of possibilities to publish research related to Boccia. *Springer Nature* was the publisher with the highest number of studies indexed in its platforms ($n = 7$), followed by *Elsevier* ($n = 4$) (Table 4). Similarly, considering the number of citations, *Research in Developmental Disabilities* was identified as the journal with the highest number of citations ($n = 27$), followed by *Revista de Psicología del Deporte* ($n = 17$). This information allows us to identify the platforms with more development of studies related to Boccia, as well as those works with the greatest impact. Figure 6 depicts the interactions between each journal according to the citations.

3.6 Keywords used by authors

A total of 92 keywords were identified. The terms with the highest occurrence were "boccia" ($n = 17$), "rehabilitation" ($n = 4$), and "disability" ($n = 4$) (Figure 7).

According to the temporality of the terms, there is a clear change in the keywords selected by the authors, focusing on the study of specific elements such as "physical exercise", "Paralympic sport", "game analysis" or "underhand throw", with

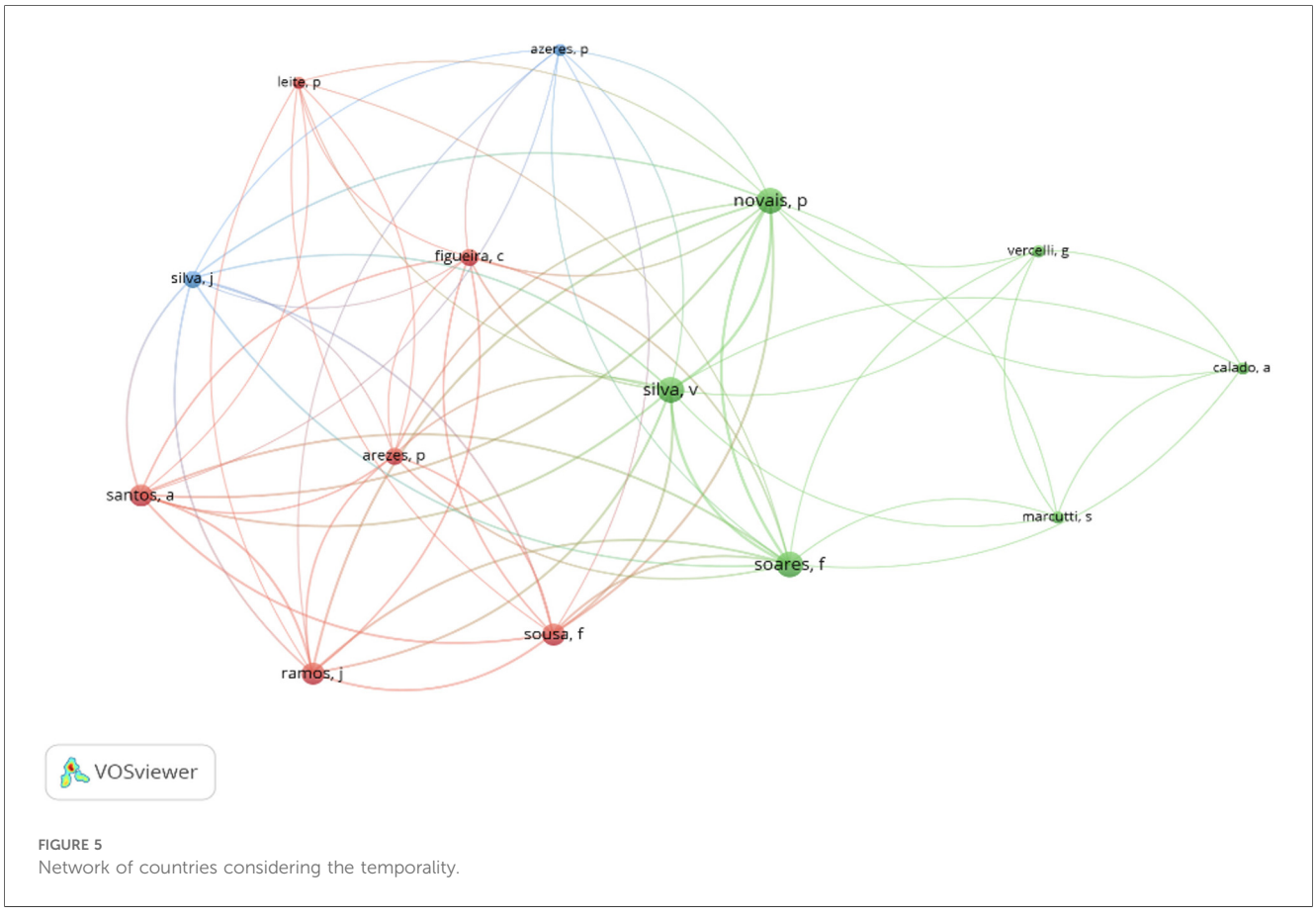


FIGURE 5
Network of countries considering the temporality.

TABLE 4 Publishers and journals associated with the published documents.

Publishers	Documents	%	Journal	Documents
Springer Nature	7	21.87	*Recent Advances in Information Systems and Technologies*	2
Elsevier	4	12.50	*Research in Developmental Disabilities*	2
Taylor & Francis	3	9.37	*Managing Sport and Leisure*	1
Federacion Espanola Asociación Docentes Educacion Fisica-Feadef	2	6.25	*Retos-Nuevas Tendencias en Educacion Fisica Deporte Y Recreacion*	2
Frontiers Media Sa	2	6.25	*Frontiers in Psychology*	1

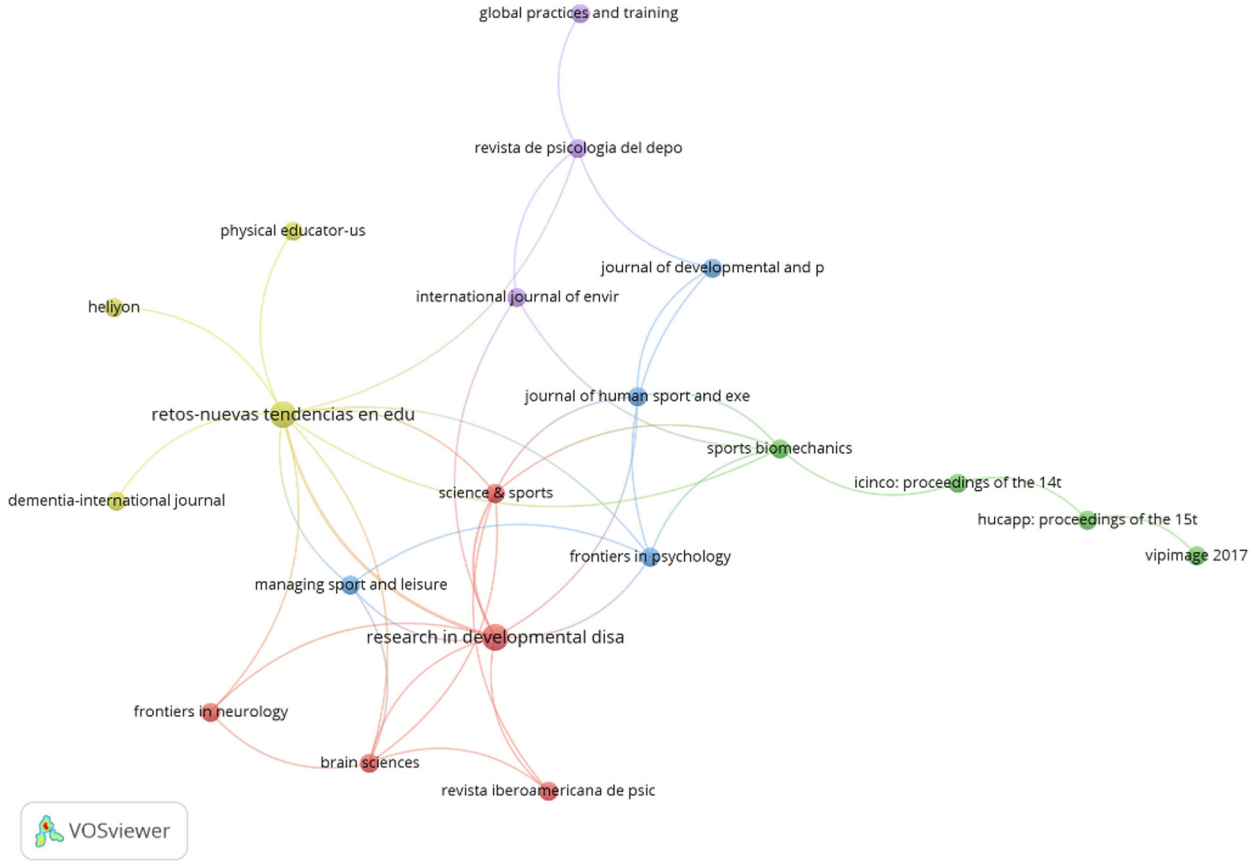


FIGURE 6
Interactions between journals according to the citations.

the aim of understanding and improving the performance of Boccia players (Figure 8).

4 Discussion

The purpose of this study was to develop a bibliometric review of literature related to Boccia, aiming to analyse relevant information related to the adapted sport, and determine the existing relationships/networks between the different authors and countries, as well as methodological procedures related to publications. Between 2012 and 2016, the highest number of publications per year was 3, in 2015. From 2017 to 2024, an exponential growth of 81.87% of the sample was observed comparing to 2012–2016, with particular emphasis from 2017 to 2020 (in this last year 7 publications), fact that we relate to the COVID-19 pandemic, which limited the involvement and participation in adapted sports, and consequently the access to data for research, observed in our results by the decreasing number of citations between 2020 and 2022. The COVID-19 pandemic period negatively impacted adapted sports even on a greater scale compared to sports because in adapted sports, such as Boccia, participants are more vulnerable, as previously stated by Durstine et al. (43).

Aiming for good sport training for people with disabilities, programmes should focus on flexibility, balance, accessibility, safety, enjoyment, cardiovascular endurance, agility, and muscular strength. Considering the number of citations received

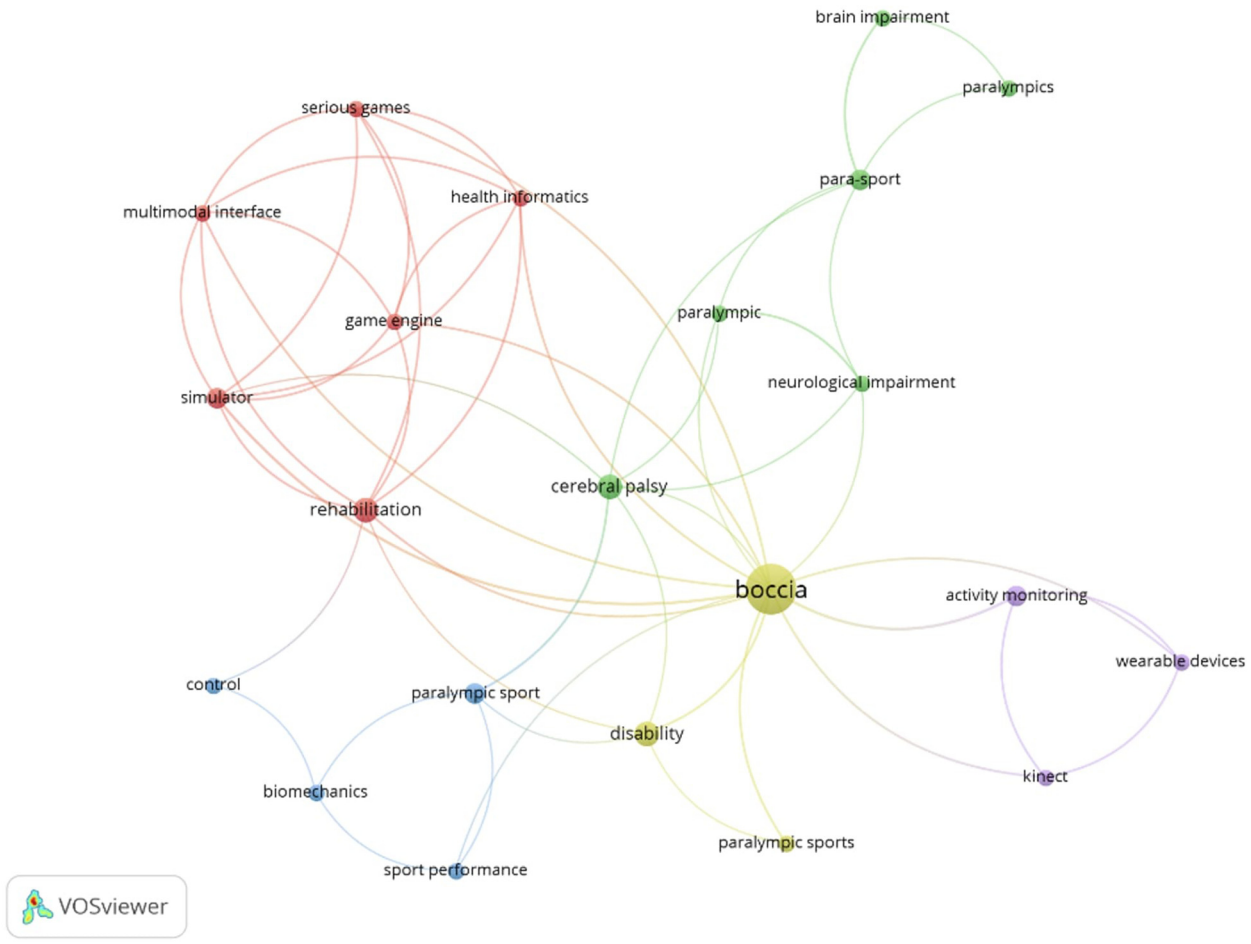


FIGURE 7
List of keywords used by the authors.

by year, 2014 has been identified as the moment with the highest number ($n = 42$). Still, between 2017 and 2020, a high and constant level of citations was observed, evidence that we attribute to the relationship between number of publications and citations (e.g., in 2014, 2017, 2020 and 2023 it was observed an increase in publications and commitment increase in citations), which we relate to self-citations, since they play an important role in the increase of the visibility (44). Articles and congresses were the two most found forms of dissemination, underlining the desire to find and share knowledge in Boccia, despite being in small numbers. This parasport is increasingly becoming recognized as a legitimate component of international sport, although we agree with DePauw and Gavron (45), who previously stated that in some instances the elite-level athletes with disabilities are still not taken as seriously as elite-level able-bodied athletes, and this has consequences in scientific knowledge and dissemination.

We observed a total of 119 authors associated with the 38 selected documents, an average of 3.6 authors per document, but only 3 authors (Novais, P.; Silva, V.; Soares, F.) associated with 4 studies related to Boccia. Regarding citations, Raúl Reina and Alba Roldán are the authors who present the highest number ($n = 28$) with 3 published studies. This evidence relates to another interesting finding, of all the countries included in the analysis ($n = 15$), Portugal and Spain are in the first position with the highest number of documents ($n = 9$), but Spain has more than the double of citation compared to Portugal (58 vs. 17). In our perspective, the level of Boccia in these two countries is very high considering the participation and results in international events and that led to the need of scientific support to practice, hence, the status of the countries in Boccia drove researchers to follow their scientific work in the adapted sport. Other countries with tradition and recent results in this parasport are Brazil and Indonesia, which we found to be the countries with the most recent scientific production. Nevertheless, 90.6% of the studies were written in English and 9.4% in Spanish, which is a challenge for the future because in some of the countries with more tradition in Boccia people speak and read preferably in Portuguese and Spanish.

It was previously stated that it is important to select and publish in journals with a high impact factor and use provocative titles (46). In this study, we found a total of 29 resources, particularly *Springer Nature* was the publisher with the highest number of studies indexed in its platforms ($n = 7$), followed by

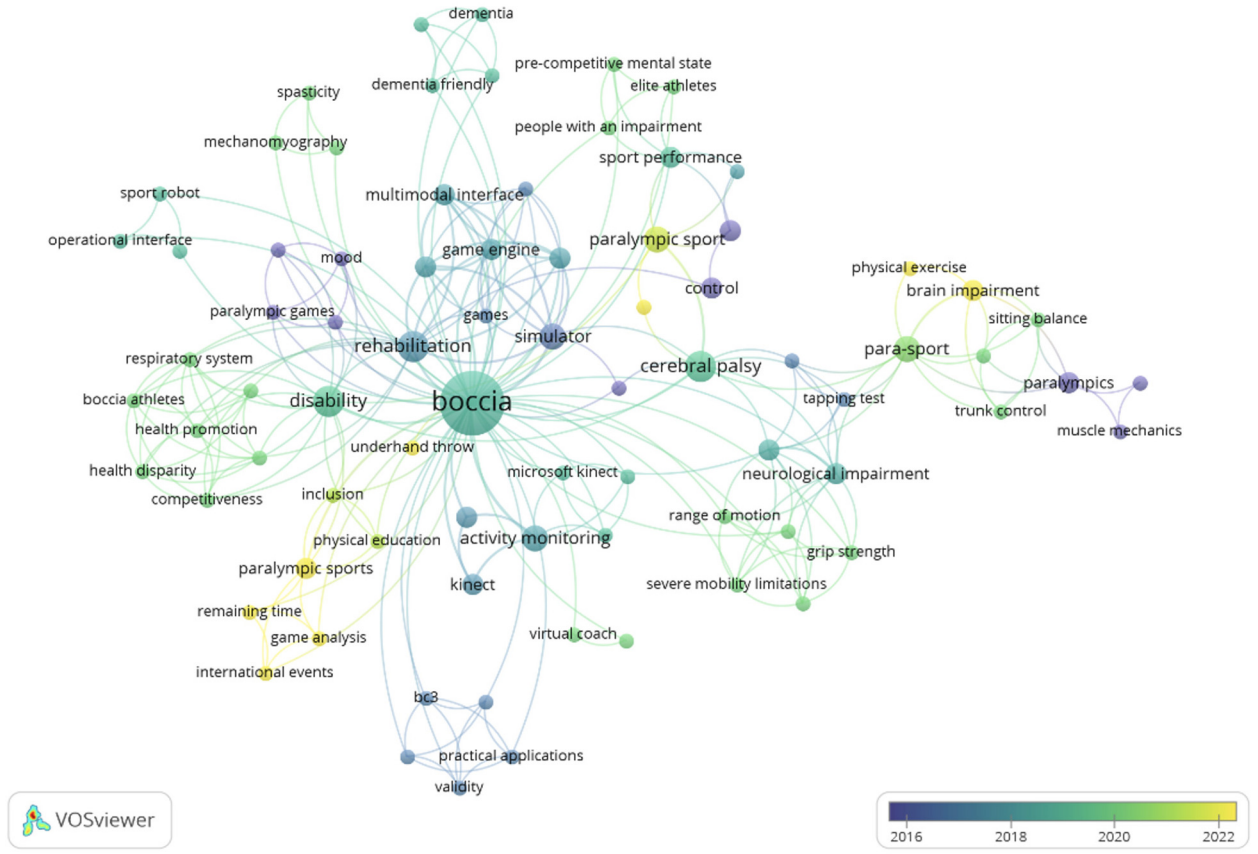


FIGURE 8
List of keywords based on the year of publication.

Elsevier ($n = 4$). Considering the number of citations, *Research in Developmental Disabilities* was identified as the journal with the highest number of citations ($n = 27$), followed by *Revista de Psicología del Deporte* ($n = 17$). Boccia is a growing movement parasport, practiced by more and more people, nevertheless, scientific support is still scarce, the number of journals and special issues related to adapted sport is much smaller compared for example to Sport and Exercise and Health, and this represents a challenge to dissemination.

Finally, we identified a total of 92 keywords, the terms with the highest occurrence were "boccia" ($n = 17$), "rehabilitation" ($n = 4$), and "disability" ($n = 4$). According to the temporality of the terms, there was a clear change in the keywords selected by the authors, focusing on the study of specific elements such as "physical exercise", "Paralympic sport", "game analysis" or "underhand throw". Benito-Peinado et al. (47), indicated that in order to increase the visibility and impact of the study in future searches, it is important to select the proper keywords, from the results in this study, Boccia is still linked to the area of rehabilitation rather than performance, one of the challenges for the future, since sports performance has developed in practitioners but not received adequate scientific support.

One of the limitations of the study is the selection of key terms. For the correct development of the study, as well as in the extraction of the results, it was necessary to select those words that are closest to the topic and, in this way, eliminate biases in the results, therefore, ensuring that the studies identified were specifically related to the study topic. On the other hand, one of the strengths of the study is that it allows us to understand the trends and co-authorships of the documents regarding the country or authors. For future research, it is proposed to analyse other areas closely related to Boccia, considering other keywords and databases along with the WoS. The analysis of the technical and tactical details associated with performance should shed light on the game dynamics and improve training and competitive strategies.

5 Conclusions

Despite scientific evidence that Boccia is important for the individual global well-being, and inclusive of all genders, ages, and abilities, the findings revealed that the initial document related to Boccia and focusing the Paralympic status was published in 2012, after being introduced as Paralympic sport in 1984. This study confirms the scarcity of research in Boccia, highlighting that Portugal and Spain have been the most prolific countries over the years, with their researchers also associated with more citations.

From our perspective, more journals and special issues in sports journals related to the study topic are necessary to provide the opportunity to support the practice with scientific knowledge, something that our results found between 2017 and 2020, but was afterward changed (in our perspective due to the pandemic phase). At this stage, more and better research is needed, from our point of view in other languages different than English to provide the opportunity not only to higher access by non-English native, but also in the perspective of establishing networks, which seems to be starting to materialize when we look at the countries most focused on research on this subject at the moment (Brazil and Indonesia).

Deepening knowledge in this study topic will allow an increasing number of countries and authors to be involved, and in this way improve the practice, training, and competitive performance in this adapted sport, along with the improvement in the quality of life of the population.

6 Practical applications

In essence, this research is crucial for the identification of trends and networks related to the study of Boccia in the context of Paralympic sport. Demonstrates the need for more applicable research in different perspectives of the game by the scientific community, returning to the growing interest before the pandemic. The findings of this study provide guidance for future investigations, sport rules, social and sport policies, and the creation of focused interventions aimed at encouraging a healthier and more inclusive society.

Data availability statement

The data that supports the findings of this study are available from the first and last authors, upon reasonable request.

Author contributions

CF: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. VH-B: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. JG: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. ME: Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing. JM-J: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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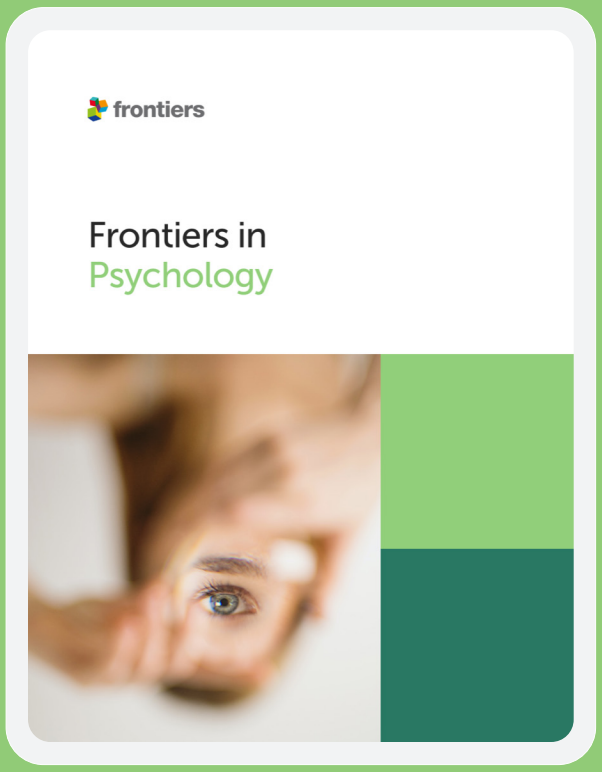
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