Research Topics

Responses and adaptations to novel exercise modalities

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Responses and adaptations to novel exercise modalities

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Editorial: Responses and adaptations to novel exercise modalities

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KEYWORDS

Bajiquan, high intensity (strenuous) exercise, hypoxic acclimation, interval training, neuromuscular activation, yoga

Editorial on the Research Topic
Responses and adaptations to novel exercise modalities

Introduction

Overwhelming scientific evidence supports the beneficial health and fitness effects of conventional exercise modalities, such as moderate-to-vigorous intensity aerobic (e.g., walking, cycling) and resistance training. Unconventional/novel exercise modalities are emerging as lifestyle approaches to enhance accessibility and long-term adherence, reduce common barriers to physical activity (e.g., lack of time, social influence, fear of injury), and improve health, fitness, and performance in a variety of individuals. Our Research Topic solicited studies performed to determine the physiological responses and adaptations elicited by unconventional exercise modalities that may enhance training, increase performance, and improve health outcomes. Several published studies included in our Research Topic are summarized below, which are divided into two categories: 1) Tech-Enhanced and Experimental Modalities, and 2) Traditional and Mind–Body Modalities.

Tech-enhanced and experimental modalities

Several studies published in our Research Topic examined the effects of different interval training regimens on physiological responses and adaptations. Compared to traditional aerobic and resistance exercise programs, high-intensity functional training (HIFT) is more time efficient and involves multi-joint, high-intensity exercises performed to improve health- and skill-related physical fitness. Smith and colleagues (Smith et al.) utilized a randomized, crossover study design in 12 young, trained adults to compare the physiological responses between two HIFT workouts matched for volume and exercises performed: continuous-based with varied time domain (rounds for time = RFT; ~12 min completion time) and interval-based with set time domain (every minute on the minute = EMOM; ~20 min completion time). The EMOM workout was designed to ensure that participants had at least 30 s rest after each exercise, whereas the RFT workout was performed "all-out". Compared to EMOM, RFT resulted in greater acute physiological stress as evidenced by higher heart rate, oxygen consumption (during and post-exercise), rating of perceived exertion, and blood lactate responses. Increases in serum creatine kinase at 24 h post-exercise did not differ between the workouts, indicating a similar degree of exercise-induced muscle damage. Both workouts are considered vigorous-intensity exercise that may be used to induce physiological adaptations, translating to improved health and performance. Future studies are needed to evaluate differences in training adaptations with high-intensity workouts varying in rest interval duration.

Bodyweight interval training (BW-IT) is a leading fitness trend promoted to increase exercise adherence and improve cardiometabolic health. Bellissimo and colleagues (Bellissimo et al.) used a single-group design to demonstrate in 14 inactive adults with obesity that a YouTube-instructed BW-IT program (3 days/week for 6 weeks) improved aerobic capacity, isometric muscular strength, and waist circumference. Body composition and biomarkers of cardiometabolic health (i.e., insulin resistance, blood lipids, C-reactive protein) were unchanged, suggesting that longer interventions may be needed to positively affect these health-related outcomes. The relatively small volume of independently performed BW-IT (20 min/session, 60 min/week) that led to improvements in health- and fitness-related outcomes is notable as lack of time and access to exercise facilities/equipment are common barriers to exercise among individuals with obesity.

Exercise intensity was also examined in adolescents. Su et al. compared sprint interval training (SIT) with moderate-intensity continuous training (MICT) in 24 male adolescents. Both 6 weeks interventions resulted in similar improvements in aerobic capacity. However, distinct metabolic adaptations were observed between training groups. SIT was associated with reduced circulating polyunsaturated free fatty acids, consistent with increased skeletal muscle lipid utilization. In contrast, MICT induced broader changes across multiple lipid classes, including sphingolipids and phospholipids. These findings suggest that while traditional cardiorespiratory fitness outcomes may be similar, exercise intensity differentially influences underlying metabolic remodeling in male adolescents.

Brandt et al. examined the physiological demands of Hyrox©, a rapidly growing hybrid fitness competition combining running with functional resistance tasks. Using a simulated competition format in 11 recreational Hydrox© athletes, the authors reported sustained elevations in heart rate, blood lactate, and progressive increases in perceived exertion across successive exercise stations and running segments. Performance was strongly associated with endurance capacity, as athletes with greater aerobic fitness completed the event more efficiently, whereas measures of maximal handgrip strength were not predictive of overall performance. The structure of Hyrox© shows how conventional aerobic and resistance exercises can be reorganized into novel formats that elicit substantial physiological stress and may appeal to a broad range of recreationally trained individuals.

Two studies published in our Research Topic examined the effects of electrical stimulation on neuromuscular function. Neuromuscular electrical stimulation (NMES) has been shown to improve muscle function and motor control in athletic and rehabilitation settings. Further, superimposing NMES onto voluntary muscular contractions (NMES+) results in greater improvements in muscle function and performance. Borzuola and colleagues (Borzuola et al.) investigated the acute neuromuscular effects of NMES+ (delivered to the tibialis anterior), passive NMES, and voluntary isometric contractions alone (ISO) in 17 young healthy adults. Experimental conditions involved 20 intermittent isometric ankle dorsi flexions performed at 20% of their maximum voluntary contraction. Surface electromyography was used to record myoelectric activity during steady force-matching contractions performed immediately after following each experimental condition. Compared to baseline levels and passive NMES, NMES + ISO increased motor unit discharge rate and the proportion of common synaptic input to spinal motor neurons and decreased the coefficient of variation of force (indicating improved force steadiness). Future research is needed to investigate the effectiveness of long-term NMES-based interventions to enhance rehabilitation and performance.

Research on whole-body electromyostimulation (WB-EMS) indicates enhanced body composition and muscle function. However, excessive/intense WB-EMS use may induce muscle damage. Knowledge is limited regarding the individual muscle damage response to intense WB-EMS. Teschler and colleagues (Teschler et al.) showed in 12 healthy adults that a single 20 min high-intensity WB-EMS training session (6 exercises, 4 sets x 5 reps) increased blood myoglobin and creatine kinase (CK) levels, peaking at 48 and 72 h, respectively. Individual peak myoglobin and CK responses to high-intensity WB-EMS were moderately predicted by post-WB-EMS blood lactate responses. Future research is warranted to determine factors that may explain differences in muscle damage temporal patterns following high-intensity WB-EMS, perhaps leading to individualized training and recovery sessions.

Finally, one study published in our Research Topic investigated adaptations to the innovative method of hypoxic training. Evidence is conflicting regarding enhancement of exercise training adaptations using innovative training methods, including the use of climate-controlled chambers to artificially induce hypoxia. Studies assessing the effectiveness of intermittent hypoxic training (IHT) (i.e., training in controlled hypoxic conditions while living in normoxic conditions) on exercise training adaptations in combat sports are lacking. Ambrozy and colleagues (Ambrozy et al.) utilized a randomized controlled trial in 20 elite-level boxers to demonstrate that 6 weeks of IHT (4 training sessions/wk at 230 m above sea level +4 training sessions/wk at a simulated altitude of 4,000 m) improved muscular endurance, anaerobic capacity, technical efficiency (i.e., number of punches delivered in 20 s), and post-exercise heart rate recovery compared to boxers who trained in normoxic conditions (8 training sessions/wk at 230 m above sea level). Training performed by both groups included aerobic, resistance, and technical and tactical boxing training (4 days/wk, 2 sessions/d (morning and afternoon), 480 min/wk). Future studies are needed to determine the potential performance benefits of innovative training methods for combat sports athletes.

Traditional and mind–body modalities

Several studies in this Research Topic examined traditional, culturally-rooted, and mind-body exercise modalities that have gained renewed interest as accessible alternatives to conventional aerobic and resistance training. Collectively, these studies highlight how movement forms grounded in tradition or integrated mind-body practice can elicit meaningful physiological adaptations while also addressing enjoyment, adherence, and clinical applicability.

Wang and colleagues (Wang et al.) evaluated an 8-week Bajiquan training program performed 5–6 days/wk in 30 young adults. Compared with a control group engaging in general fitness activities of similar frequency and duration, Bajiquan training resulted in greater improvements in cardiovascular endurance, body composition, explosive power, and core strength. Participants also reported higher perceived social and personal benefits, emphasizing the potential for martial arts-based training to enhance both physical fitness and psychosocial engagement.

Chen et al. examined the acute cardiopulmonary responses to Baduanjin, a traditional Chinese mind-body exercise, in 30 patients with chronic heart failure, compared to steady-state cycle ergometry exercise performed at a matched oxygen consumption. Despite similar metabolic intensity between the two modalities, Baduanjin elicited a distinct physiologic response characterized by lower respiratory rate and minute ventilation, alongside differences in hemodynamic responses, including lower cardiac output and stroke volume with greater reliance on peripheral oxygen extraction. Additionally, the intermittent movement associated with Baduanjin elicited a non-steady state oxygen consumption profile, reflecting the dynamic muscular demands inherent to the practice. These findings suggest that Baduanjin may be a feasible alternative to light-to-moderate-intensity exercise for clinical populations, distributing physiological load across the respiratory, cardiovascular, and peripheral systems.

Mind-body exercise was further explored by Campbell and colleagues (Campbell et al.), who compared acute metabolic responses to a single session of vinyasa yoga versus a single session of matched-intensity cycling exercise in 12 young adults. While cycling elicited larger changes in urinary metabolites associated with glycolysis and oxidative metabolism, vinyasa yoga produced more modest but distinct metabolic responses, likely reflecting its distributed muscular workload and combined strength, balance, and flexibility demands. These findings suggest that although mind-body modalities may impose lower localized metabolic stress, they engage alternative physiological pathways that may complement traditional aerobic exercise.

Collectively, these studies demonstrate that mind-body exercise modalities can elicit measurable physiological and functional adaptations across diverse populations. Martial arts-based training and meditative movement practices demonstrated improvements in physical fitness, metabolic responses, and functional capacity, while also offering potential psychosocial and adherence-related benefits. Although the magnitude and nature of these variations varied by modality, intensity, and outcome assessed, the findings support the inclusion of culturally-rooted and integrative movement practices within evidence-based exercise programming and prescription. Further research is warranted to clarify underlying mechanisms, long-term adaptations, and optimal integration with conventional training approaches.

Conclusion

Our Research Topic solicited studies assessing the responses and adaptations to unconventional exercise modalities, including those investigating tech-enhanced, experimental, and mind-body modalities. Further understanding of the responses and adaptations elicited by unconventional modalities, including those that merge emerging technology with conventional exercise modalities, may be applied to optimize training protocols, enhance performance, and improve human health. The diverse effects of unconventional modalities on physical and psychosocial health outcomes has broad public health implications and merit further exploration to develop individualized training protocols that maximize accessibility and improve overall health. Future mechanistic and longer-term studies are warranted to further elucidate differences between conventional and emerging, unconventional exercise modalities. We sincerely thank all authors and reviewers for their contribution to this Research Topic.

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Electrical stimulation: a potential alternative to positively impact cerebral health?

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An increasing body of evidence confirms the effectiveness of physical exercise (PE) in promoting brain health by preventing age-related cognitive decline and reducing the risk of neurodegenerative diseases. The benefits of PE are attributed to neuroplasticity processes which have been reported to enhance cerebral health. However, moderate to high-intensity PE is necessary to induce these responses and these intensities cannot always be achieved especially by people with physical limitations. As a countermeasure, electrical stimulation (ES) offers several benefits, particularly for improving physical functions, for various neurological diseases. This review aims to provide an overview of key mechanisms that could contribute to the enhancement in brain health in response to ES-induced exercise, including increases in cerebral blood flow, neuronal activity, and humoral pathways. This narrative review also focuses on the effects of ES protocols, applied to both humans and animals, on cognition. Despite a certain paucity of research when compared to the more classical aerobic exercise, it seems that ES could be of interest for improving cerebral health, particularly in people who have difficulty engaging in voluntary exercise.

KEYWORDS

neuromuscular electrical stimulation, functional electrical stimulation, cerebral blood flow, neuronal activity, cognition, neuroplasticity, humoral pathway

Highlights

- Electrical stimulation (ES) is known to improved physical functions in healthy participants or people in rehabilitation.
- Mechanistically, this modality of exercise is associated with an increase in cerebrovascular function, neuronal activity, the release of neurotrophins and exerkines, eventually contributing to cerebral health.
- ES exercises could be of interest for improving cognition.

Abbreviations: ATP: Adenosine triphosphate; BBB: Brain blood barrier; CBF: Cerebral blood flow; COPD: Chronic obstructive pulmonary disease; eNOS: Endothelial nitric oxide synthase; ES: Electrical stimualtion; BDNF: Brain-derived neurotrophic factor; FES: Functional electrical stimulation; FNDC5: Fibronectin type III domain-containing protein 5; HIIT: High intensity interval training; ICA: Internal carotid artery; MCA: Middle cerebral artery; NMES: Neuromuscular electrical stimulation; NO: Nitric oxide; PCA: Posterior cerebral artery; PE: Physical exercise; SCI: Spinal cord injury; TENS: Transcutaneous electrical nerve stimulation; VA: vertebral artery.

1 Introduction

Physical exercise (PE) is an essential part of a healthy lifestyle and is widely acknowledged as the most potent non-pharmacological approach to improve both physical and cognitive wellbeing (Hötting and Röder, 2013). Numerous studies have highlighted the positive effects of PE on cognition, coupled with cellular, molecular, functional, structural, and behavioral changes. For example, PE promotes hippocampal neurogenesis, synaptic plasticity, cerebral angiogenesis, as well as astrocyte and microglia plasticity (Hillman et al., 2008; Carlo Maria Di Liegro, 2019; El-Sayes et al., 2019). Mechanistically, these benefits are notably mediated by an elevation of the levels of cerebral brain-derived neurotrophic factor (BDNF), a molecule involved in neurogenesis and synaptic plasticity (Cefis et al., 2023) but also, insulin-like growth factor 1 (IGF-1), and vascular endothelial growth factor (VEGF). Although cerebral BDNF is known to be a determinant of plasticity (Cefis et al., 2023), the mechanisms underlying its upregulation in response to PE and the role of exercise modalities are not well-understood. Indeed, three mechanisms have been proposed (Cefis et al., 2023): (i) motor commands and afferent inputs from the periphery can increase neuronal activity in the brain and stimulate the expression of several growth factors (neuronal pathway), (ii) skeletal muscle can synthesize and secrete myokines, which enter the bloodstream and cross the blood-brain barrier to promote the expression of growth factors (endocrine pathway), and (iii) PE can increase cerebral blood flow (CBF), leading to an increase in shear stress and nitric oxide (NO) release, which can have multiple benefits for brain health (hemodynamic pathway). However, the relative contributions of these mechanisms remain unknown (Cefis et al., 2023). Nevertheless, it has been demonstrated that BDNF production by the cerebral vascular endothelium is both NO- and shear stress-dependent with the latter increasing during exercise (Monnier et al., 2017).

Recent data revealed that acute and chronic exercises performed at moderate intensities are associated with enhanced cognitive performances. However, people with physical limitations may not be able to perform such exercises. This predicament is particularly evident in spinal cord injuries (SCI) or stroke patients. Additionally, elderly individuals may grapple with obstacles to engage in active PE routines due to their physical frailty. Finally, various medical conditions, such as heart failure or chronic obstructive pulmonary disease (COPD) are associated with medical contraindications and exercise intolerance. Over the (recent) years, electrical stimulation (ES) has been proposed as a possible effective alternative to traditional voluntary physical exercise when the latter becomes compromised (Doucet et al., 2012; Maffiuletti et al., 2018). Indeed, it has been reported that ES can be used to preserve, restore or even improve physical and neuromsucular function. In addition, it is generally used in rehabilitation context, notably to improve muscle strength, increase range of motion, reduce inflammation, counter muscular atrophy and weakness, and reduce muscular pain.

Although it has received less attention than physical outcomes in the literature, a recent study evidenced that ES could be of great interest to improve cerebral health (Descollonges et al., 2024). In this narrative review, we have opted to present results in both humans and animals, since the latter allows us to approach mechanisms that would otherwise remain untouched while focusing solely on human studies, to explore the impact of ES on the cerebral and mental health.

2 Main text

2.1 Electrical stimulation

2.1.1 Definition

Electrical stimulation is a technique used to elicit muscle contractions by applying electrical impulses to the skin above the muscle or along the pathway of a superficial nerve (Deley et al., 2015; Blazevich et al., 2021). ES is now an integral part of clinical settings, especially in neurological rehabilitation, proving effective for patients with impaired voluntary contractions, such as those with spinal cord injuries or stroke (Deley et al., 2015; Stein et al., 2015). In addition, ES aims to preserve, restore, or even enhance physical and neuromuscular functions, with the primary goals of improving muscle strength, increasing one's range of motion, reducing inflammation, counteracting muscle atrophy and weakness, and alleviating muscle pain (Doucet et al., 2012). Regular use over weeks can induce neural adaptations, yield positive health outcomes, and enhance both quality of life and wellbeing, in turns, addressing both clinical and non-clinical objectives (Blazevich et al., 2021).

2.1.2 Models of electrical stimulation

Among ES techniques, two primary modalities can be distinguished: Neuromuscular Electrical Stimulation (NMES) and Functional Electrical Stimulation (FES) (Maffiuletti et al., 2018). Transcutaneous electrical nerve stimulation (TENS), a third technique employing a low-intensity and continuous electrical current on cutaneous nerve fibers, is mainly used for treating chronic and acute pain but falls outside the scope of this review. NMES is traditionally applied under isometric tetanic conditions, employing intermittent or high-intensity electrical stimuli to generate robust muscle contractions (Maffiuletti et al., 2018). This technique can be directed either to the muscle belly (myostimulation) or along the nerve pathway (neurostimulation). On another hand, FES involves applying moderate-intensity and cyclic electrical stimulations to selected muscles (Maffiuletti et al., 2018). The following sections focus on NMES, while we decided to dedicate the last part of this review to FES, even if it has recevied less attention to date.

2.2 Effects of NMES on the brain

As previously mentionned, three primary mechanisms associated with the cerebral benefits induced by PE have been evidenced: heightened neuronal activity, increased cerebral perfusion, and the release of exerkines from peripheral tissues (Cefis et al., 2023). After having delved into the influence of NMES protocols on these mechanisms in both human and non-human subjects, the following section will seek to describe its cognitive and behavioral effects.

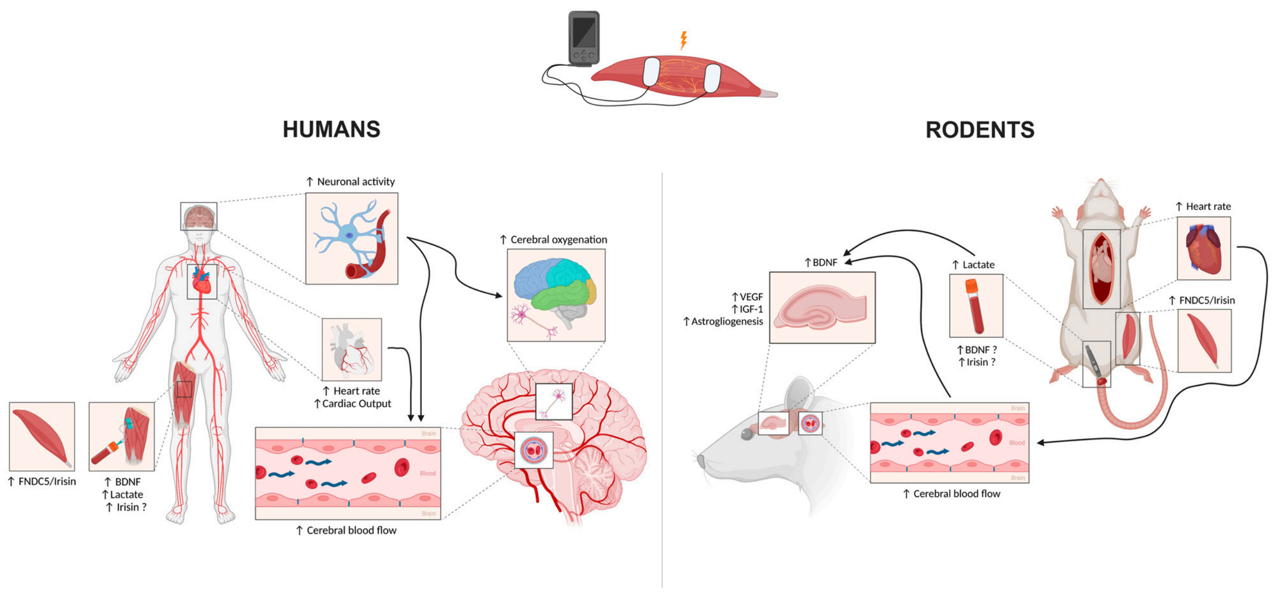

FIGURE 1
Potential mechanisms underlying the positive effects of electrical stimulation on cerebral health in both humans (left) and rodents (right). Black arrows pointing upwards represent an increase. Black arrows running between mechanisms represent potential links. BDNF: Brain-Derived Neurotrophic Factor; FNDC5: Fibronectin type III domain-containing protein 5. Created with www.BioRender.com.

2.2.1 Potential mechanisms involved in NMES induced cerebral benefits

Potential mechanisms involved in NMES-induced cerebral benefits are summarized in Figure 1.

2.2.1.1 Effects on neuronal activity

It is widely recognized that neuronal activity increases during either NMES or FES sessions on the upper or lower limbs in both healthy individuals and patients (Smith et al., 2003; Blickenstorfer et al., 2009; Chipchase et al., 2011; Joa et al., 2012; Wegrzyk et al., 2017). Both activate predominantly regions associated with sensorimotor control, the thalamus, and the cerebellum. The observed increase in neuronal activity within these regions, even in the absence of motor commands, could potentially stem from the activation of neuromuscular spindles in response to electrical stimulation (Francis et al., 2000) or the stimulation of skin afferences (Allison et al., 1991).

Several studies have indeed reported an elevation of H+ ions and a depletion of adenosine triphosphate (ATP) during NMES, which should lead to the activation of the metaboreflex to regulate heart rate (HR) and ventilation. However, the variations in HR and ventilation during NMES are minimal. Additionally, afferent signals from the metaboreflex primarily project to the brainstem, and to our knowledge, no imaging studies have reported an increase in neuronal activity in this region (Michelini et al., 2015). Furthermore, no change in c-fos hippocampal expression, a marker of calcium influx-induced neuronal activity, was observed in mice (1 session, 100 Hz, 0.1 ms, 40 contractions, sciatic nerve) (Gardner et al., 2020) and rats subjected to acute NMES (1 session, 100 Hz, 400 µs, 7s-ON/14s-OFF, 6–20 mA, lower limbs) (Chaney et al., 2024). In contrast to NMES, traditional treadmill PE has been shown to increase c-fos in both the sensorimotor cortex and cognitive regions (Cefis et al., 2019). This discrepancy between PE and NMES could be attributed to the absence of locomotion, coordination, intentions and spatial engagement during NMES, which are crucial for hippocampal activation (Eichenbaum, 2017; Joshi et al., 2023).

2.2.1.2 Effects on hemodynamic parameters

There is limited research on the effect of NMES protocols on CBF modulations. One study showed regional differences in the CBF response with an increase in the internal carotid artery (ICA) but not in the vertebral artery (VA), in response to NMES (1 session, 20 min, 4 Hz, 250 µs, maximal tolerable intensity, whole lower limbs) (Ando et al., 2021). These findings were recently corroborated by Descollonges et al. (2024) who observed that a single NMES session increases blood flow velocity through the middle (MCA) but not the posterior cerebral artery (PCA) (1 session, 25 min, 40 Hz, 400 µs, 6s-ON/6s-OFF, maximal tolerable intensity, quadriceps muscles) (Descollonges et al., 2024). These results align with a study in rats showing that a single session of NMES applied on lumbar nerve roots to contracted hindlimb muscles, increased CBF in the sensorimotor cortex (1 session, 30 min, 100 Hz, 200 µs, 6s-ON/3s-OFF, 2.5- to 5- fold the motor threshold, lumbar nerve roots) (Chaney et al., 2022). However, the authors also reported no increase of CBF in cerebral regions involved in cognition such as the prefrontal cortex and hippocampus evaluated by the phosphorylation level of the endothelial nitric oxide synthase (eNOS) (Chaney et al., 2022), which seems logical since neither of these areas is primarily supplied by the ICA or MCA.

To match the increase in metabolic activity, cerebral oxygenation increases in parallel with the increase in flow (Perrey, 2008; Smith and Ainslie, 2017). Accordingly, previous studies observed increases in cerebral oxygenation of the sensorimotor cortex (1 session, 30 Hz, 200 µs, wrist extensors muscles) (Muthalib et al., 2015) and left prefrontal cortex during NMES (Descollonges et al., 2024).

At the cardiovascular level, studies have reported a significant increase in cardiac output throughout NMES, which in turns would translate into an increase in CBF (Jordan and Sheel, 2017; Smith and Ainslie, 2017). In addition, to meet the resting metabolic demand of neuronal activity, approximately 15%–20% of the CBF is derived from cardiac output, the latter increase being directly dependent on the muscle mass involved in PE (Montalvo et al., 2022). Hence, the muscle mass emerges as a pivotal factor influencing the observed increase in CBF. This, however, needs to be confirmed by future research, especially using FES where, by design, a greater muscle masses is involved.

2.2.1.3 Effects on exerkines release

It is well-established that peripheral tissues such as skeletal muscle release exerkines, into the bloodstream, thereby inducing improvements in cerebral health (Chow et al., 2020; Cefis et al., 2023).

2.2.1.4 Lactate

Currently, lactate is the exerkine that has received the most attention in NMES studies. Notably, it has been documented that lactate can cross the brain-blood-barrier (BBB) (Pellerin et al., 1998; Proia et al., 2016) and is intricately involved in neuroplastic processes such as hippocampal neurogenesis and synaptic plasticity (Yang et al., 2014; Lev-Vachnish et al., 2019). For example, lactate can cross the BBB via its monocarboxylate transporters (MCTs) (Proia et al., 2016). Inhibition of this transporter prevents the improvement of spatial memory and synaptic plasticity in response to exercise (El Hayek et al., 2019). Futhermore, investigations have confirmed that an acute PE session leads to an immediate increase in cerebral lactate concentration in rats. In humans as well, acute PE raises lactate levels in the cerebrospinal fluid (Bisgard et al., 1978). Studies have reported elevated blood lactate levels following a NMES session targeting the quadriceps muscles in both humans and rats (Chaney et al., 2024). Interestingly, we recently observed positive correlations between lactate production and either Stroop Task improvement in healthy humans or hippocampal BDNF levels in rats following an NMES session (1 session, 100 Hz, 400 µs, 7s-ON/14s-OFF, 6–20 mA in rats, maximal tolerable intensity in humans, quadriceps muscles) (Chaney et al., 2024). The mechanisms through which lactate can influence brain health are multiple. They include the transport of lactate into neurons via MCT2, which increases the activity of the deacetylase sirtuin 1 (SIRT1). This increase can, in turn, enhance the transcriptional activity of PGC-1α, leading to the induction of BDNF (El Hayek et al., 2019) Interestingly, ES in rats increases hippocampal expression of SIRT1 (Chaney et al., 2024), suggesting a SIRT1-dependent mechanism in the beneficial effects of lactate in the context of ES.

When considered together, these findings strongly imply that lactate plays a pivotal role as an essential exerkine mediating the positive effects of NMES on cerebral health.

2.2.1.5 Cathepsin-B

As mentioned in a recent review (Cefis et al., 2023), cathepsin B (CTSB) is thought to play an important role in brain health, notably through its effect on BDNF and neurogenesis (Moon et al., 2016). Although studies that have examined the effects of NMES protocols on cathepsin-B are poor, a recent study showed that NMES applied at stimulation frequencies of 20 Hz induced significantly greater increases in serum cathepsin-B levels than evoked stimulation at 4 or 80 Hz or the control condition in healthy young subjects (1 session, 20 min, stimulation duration varied between 250 ms (4 Hz condition), 50 ms (20 Hz condition) and 12.5 ms (80 Hz condition), 100 µs, entire lower limbs) (Nishikawa et al., 2024). However, to date, only one study has investigated CTSB after NMES application, and it would be interesting in future to examine the effects of an NMES- or FES-based intervention on CTSB while measuring cognitive performance, in order to verify whether the link found between conventional PE and CTSB is also found with this intervention.

2.2.1.6 FNDC5/Irisin

Recent studies have provided compelling evidence indicating that the activation of the FNDC5/Irisin (Fibronectin type III domain-containing protein 5) pathway in skeletal muscle is involved in PE-induced cerebral plasticity (Bao et al., 2022). For instance, it has been reported increases circulating irisin after whole-body NMES combined with HIIT-type exercise in obese participants (1 session, 25 min, 85 Hz, 400 µs, 10s-ON/2s-OFF, whole body) (Ghalamsiah and Nourshahi, 2023). Interestingly, rodent data strongly suggest that fast-twitch fibers could be the key contributor to the surge in circulating Irisin levels after PE (Leger et al., 2024). This could be particularly relevant for disabled populations where the percentage of fast-type fibers is usually elevated (Schaufelberger et al., 1995; Toth et al., 2016).

On another hand, the effects of NMES on FNDC5/Irisin are less clear since an elevation in muscular concentration of FNDC5/Irisin has been reported in both humans and rodents after NMES (Maekawa et al., 2018; Petrie et al., 2020; Chaney et al., 2024), but without any changes in circulating irisin, at least 3, 4 and 24 h after an acute NMES protocol in rats (Maekawa et al., 2018; Chaney et al., 2024). Similarly, no changes were observed in hippocampal FNDC5/Irisin levels (Chaney et al., 2024). These conflicting data underline the necessity for further studies to clarify the impact of NMES on the production of circulating irisin.

2.2.1.7 Effects on brain-derived neurotrophic factor (BDNF)

Given the inherent challenges of *in vivo* quantitfication of BDNF in the brain, human studies are resorting to assessing circulating BDNF levels (Walsh and Tschakovsky, 2018). Despite being considered a potential biomarker of cerebral health in humans, it remains unclear whether circulating BDNF can cross the blood brain barrier (BBB) and could, therefore, really be considered a surrogate for brain levels of BDNF (Wu and Pardridge, 1999).

Over the last decade, it has been reported that NMES protocols have the potential to induce an increase in circulating levels of BDNF both in humans (Wahl et al., 2015; Miyamoto et al., 2018a; b; Kimura et al., 2019; Nishikawa et al., 2021; 2024; Ghalamsiah and Nourshahi, 2023) (Table 1) and in rodents (Ke et al., 2011; Lin et al., 2015b; Dalise et al., 2017; Maekawa et al., 2018; Chaney et al., 2024) (Table 2). However, some degree of discrepancy remains since few studies failed to observed increases in circulating BDNF levels in Parkinson's patients (Fiorilli et al., 2021) or in rats following NMES (Chaney et al., 2024). Interestingly, Nishikawa et al. (2022) showed that bilateral NMES of the entire lower limbs in healthy participants

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TABLE 1 Electrical stimulation programs used to investigate the effects on BDNF expressions in humans.

Authors	Population	Number	Stimulation	Frequency	Wide pulse	Current amplitude	ON/OFF	Sessions duration	Stimulated muscles	Main findings
Ghalamsiah and Nourshahi (2023)	Overweight	13	NMES	85 Hz	400 µs	-	10 s ON - 2 s OFF	1 session (25 min/session)	Whole body	↑ BDNF (Serum) ↑ Irisin (Serum)
Nishikawa et al. (2022)	Able-bodied	12	NMES	20 Hz	100 µs	Max. tolerable	Ranged from 50 to 200 ms	1 session (23 min/session)	Quadriceps Triceps surae	↑ BDNF (Serum)
Fiorilli et al. (2021)	Parkinson's patients	12	NMES	85 Hz	350 µs	Max. tolerable	4 s ON - 4 s OFF	1 session (20 min/session)	Quadriceps	No increase of BDNF (Serum)
Nishikawa et al. (2021)	Elderly	3	NMES	20 Hz	100 µs	4.85 mA	5 s ON - 10 s OFF	5 sessions/w during 8 weeks (23 min/session)	Quadriceps	↑ BDNF (Serum)
Kimura et al. (2019)	Able-bodied	11	NMES	20 Hz	50 µs	31.3 mA	4.5 s ON – 4.5 s OFF	1 session (20 min/session)	Quadriceps	↑ BDNF (Serum)
Miyamoto et al. (2018a)	Type II Diabete	14	NMES	4 Hz	200 µs	Max. tolerable	Unspecified	5 sessions/w during 8 weeks (40 min/session)	Gluteus Quadriceps HamstringsTriceps surae	↑ BDNF (Plasma)
Miyamoto et al. (2018b)	Able-bodied	13	NMES	4 Hz	250 µs	Max. tolerable	Unspecified	1 session (30 min/session)		
Wahl et al. (2015)	Able-bodied	13	FES-cycling vs NMES	60 Hz	400 µs	Max. tolerable	Continous for myostimulation	1 session/condition (60 min/session)	Lower limbs	↑ BDNF (Serum) only for FES condition

NMES: neuromuscular electrical stimulation; BDNF: Brain-Derived Neurotrophic Factor; ON: time of contraction; OFF: resting time.

TABLE 2 Electrical stimulation programs used to investigate the effects on BDNF expressions in animal's model.

Authors	Population	Stimulation	Frequency	Wide pulse	Current amplitude	ON/OFF	Sessions duration	Stimulated muscles	Main findings	Other results
Chaney et al. (2024)	Rats	NMES	100 Hz	400 µs	6 – 20 mA	7 s ON – 14 s OFF	1 session (80 contractions)	Quadriceps	↑ BDNF (hippocampus)	↑ FNDC5/irisin after 24 h (quadriceps) ↑ Lactate
Maekawa et al. (2018)	Rats	NMES	100 Hz	1000 µs	Motor Threshold	3 s ON - 7 s OFF	1 session (50 contractions)	Sciatic nerve	↑ BDNF protein/ mARN (hippocampus)	↑ FNDC5/irisin (hippocampus) NMES doesn't increase muscle BDNF and muscle FNDC5
Dalise et al. (2017)	Rats	NMES	50 Hz	150 µs	15 mA	5 s ON - 10 s OFF	5 sessions /w during 4 weeks	Brachial biceps Brachial triceps	↑ BDNF (Serum)	↑ ARNm BDNF (Hippocampus) for the low NMES dose ↑ Lactate
Lin et al. (2015)	Rats	FES	100 Hz	300 µs	Motor Threshold	0.15 ON – 0.6 s OFF	30 min/days during 2 weeks	Wrist extensors	↑ BDNF (hippocampus/ prefrontal cortex)	↑ TrkB (hippocampus/ prefrontal cortex)
Ke et al. (2011)	Rats	FES	100 Hz	300 µs	Motor Threshold	TA: 0.05 s ON MG: 0.15 s ON Both: 300 s OFF	7 days (30 min/days)	Tibialis Anterior Triceps surae	↑ BDNFm (Hippocampus/ striatum)	BDNF levels ++ in striatum for FES group but for hippocampus voluntary group is more efficient

NMES: neuromuscular electrical stimulation; FES: functional electrical stimulation; BDNF: Brain-Derived Neurotrophic Factor; FNDC5: Fibronectin type III, domain-containing protein 5; TrkB: Tropomyosin receptor kinase B; ON: time of contraction; OFF: resting time.

resulted in significantly higher serum BDNF concentration compared to stimulation of the quadriceps alone, indicating that circulating BDNF levels increase depending on engaged muscle mass (Nishikawa et al., 2022). Recently, same authors reported that NMES at 20 Hz induced significantly larger increases in BDNF serum levels than stimulation at 4 or 80 Hz or the control condition in healthy young adults indicating that BDNF levels increase depending also of the frequency of stimulation (Nishikawa et al., 2024). Collectively, most studies indicate that NMES stimulates the production of circulating BDNF, consistent with recent data obtained in mice showing that skeletal muscles can secrete BDNF into the bloodstream to regulate glucose homeostasis (Fulgenzi et al., 2020). Indeed, transgenic mice with a deletion of the bdnf gene in skeletal muscles exhibit reduced circulating levels of BDNF (Fulgenzi et al., 2020). Additionally, *ex vivo* electrical stimulation of the diaphragm induces the release of BDNF into the culture medium (Fulgenzi et al., 2020). However, whether muscle-secreted BDNF can have effects on the brain requires further research.

2.2.2 Cognitive and behavioral effects in response to NMES

There is no consensus regarding the effect a single bout of NMES on cognition. Indeed, some studies both in animal and human suggested no improvement in cognitive performance. For instance, in humans, neither the Stroop test nor the Wisconsin card task (assessment of cognitive flexibility and executive functions by requiring subjects to sort cards according to changing rules (color, shape, number)) (Miyamoto et al., 2018a), or a Go/No-Go task (reaction time task), were altered after a single NMES session with low frequencies (4–20 Hz, 250 µs) (Ando et al., 2024a; b; Sudo et al., 2024). However, a recent study reported reaction time improvements to the Go/No-Go task when NMES is combined with voluntary arm cranking (Ando et al., 2024a). In rodents, a study involving mice subjected to an acute sciatic nerve stimulation protocol (100 Hz, 0.1 ms, 40 contractions, 4-s ON/4-s OFF) revealed no improvement in performance in the Morris water maze, rotarod, and contextual fear conditioning test (Gardner et al., 2020). This lack of improvement was linked to an increase in astrogliogenesis without concurrent changes in hippocampal neurogenesis. On another hand, recent reports indicate that an acute isometric session of NMES applied to the quadriceps at both low (40 Hz) (Descollonges et al., 2024) or high frequencies (100 Hz) (Chaney et al., 2024) can enhance Stroop task scores and reduce anxiety in healthy participants. In these studies, a three-step Stroop task was performed and consisted of read the most color names (green, blue, yellow, and red) printed in black, name the most color patches, and state the most color words printed with inconsistent color ink for 45 s. However and while the literature on chronic use of NMES is even more scarce and limited to humans, it has been shown in advanced laryngeal cancer patients that 8 weeks of NMES did not demonstrate any advantages for anxiety, depression, or sleep quality (30 min/session, 2 sessions/week during 8 weeks, 2–100 Hz, maximal tolerable intensity) (Zhang et al., 2018). Nevertheless, if one wants to expand beyond the scope of this review, there is more literature suggesting that ES, including NMES, FES and Hybrid FES protocols, can be beneficial notably for the quality of life (Durmus et al., 2009; Descollonges et al., 2023; Ramezani et al., 2023). Lastly, a recent protocol study suggests evaluating the chronic effects of NMES on cognition and BDNF over 12 weeks in SCI patients, and this work should be followed closely in the future (Vints et al., 2024).

Taken together, these results are calling for more research on this topic, especially when considering the variety in stimulation parameters available from the literature thus far. Moreover, future clinical and preclinical studies are imperative to unravel the nuanced effects of NMES on cognitive function.

2.2.3 The specific case of functional electrical stimulation (FES)

As mentionned previously, NMES alone might be insufficient to improve cognition but this intervention can potentiate the effect of other strategies (i.e., FES) acting directly on cognition thanks to its effects on neuroplasticity processes. FES involves a voluntary contribution and therefore could potentially potentiate the effects of NMES. This modality holds promises, notably as it can induce functional movements and engage a substantial muscle mass (Deley et al., 2015). Currently, two modalities of FES are employed to induce muscle contractions in the lower limbs, namely, FES-Cycling and FES-Rowing. Both involve electrical stimulation to the lower limb, while voluntarily exercising either with lower- (cycling) or upper-body (rowing) muscles, eventually generating a complete rowing movement for the latter (Deley et al., 2015; Ye et al., 2021). In recent years, FES techniques have emerged as compelling alternatives and complementary solutions to assist patients in generating voluntary movement of moderate to high intensity.

A distinction can be made between exercises that are performed solely with FES (called FES-induced) and those where FES is used as an aid (FES-assisted). Only few studies focused on the mechanisms involved in neuroplasticity following demonstrating elevated blood lactate levels (Gojda et al., 2019) in healthy participants and cerebral oxygenation (Lo et al., 2018) in stroke patients following a FES-assisted as well as increases in brain activity during FES-induced wrist movement (Joa et al., 2012). In the future, studies would need to explore other FES-induced putative mechanisms involved in neuropalsticity such as alterations in cerebral blood flow.

There is a clear paucity of data on the acute effect of FES on cognition and/or behavior, either in humans or in animals. On another hand, it has been reported, using a stimulation protocol aiming to emulate a walking pattern resembling an FES protocol (100 Hz, 0.3 ms, 3 × 10 min/day for 2 weeks, running model at a speed of 12 m/min) in a rat model of cerebral hypoperfusion (bilateral carotid occlusion), that FES effectively restores performance on the object recognition test and the Barnes maze, assessing memory function (Lin et al., 2015b). The authors highlighted that these positive effects on behavior were associated with an increase in BDNF and downstream signaling pathways in the hippocampus (Lin et al., 2015a). Additionally, the authors observed an increase in synaptic protein levels, along with enhanced survival of hippocampal neurons (Lin et al., 2015a. These promising outcomes align with similar findings on the impact of FES on BDNF expression in both hippocampus and striatum in a rat model of stroke (middle cerebral artery occlusion) (Lin et al., 2015a). Intriguingly, the elevation in cerebral BDNF was similar to what is observed following both voluntary and forced treadmill exercise (Ke et al., 2011).

In humans, 30 weeks of FES in spinal cord injury (SCI) patients showed long-term psychological improvement and an antidepressant effect (Donna, 1992). Additionally, if one recent study reported that FES-assisted cycling do not impact cognitive performance (Go/No-Go task) in healthy participants (Ando et al., 2024b) it has been demonstrated that this modality could induce moderate-to-large progress in cognitive processing speed (Pilutti et al., 2019) and reduce delirium (Parry et al., 2014). Mechanistically, since cerebral BDNF cannot be measured *in situ* in humans, one has to rely on indirect markers. For instance, it has been suggested that the muscle mass involved and the stimulation parameters play a critical role in the measured outcomes on cognition and/or behavior. The involvement of a large muscle mass would translate into an elevation in CBF as a result of increased neuronal activity, hypercapnia and increased cardiac output (Jordan and Sheel, 2017; Smith and Ainslie, 2017), as well as increases of blood levels of irisin and lactate, which might be involved in cerebral BDNF upregulation (Cefis et al., 2023). Thus, when compared to NMES, it could be hypothesized that FES might have a greater impact on physical performance or indeed cognition than NMES, due to the larger muscle mass involved during the exercise. Taken together and despite the limited array of studies in the literature, it seems that FES interventions represent a promising methodology to improve cognition.

3 Methodological considerations

Electrical stimulation may have certain limitations, the main ones being listed thereafter.

3.1 Muscle damage

According to the stimulation parameters use, muscle damage could manifest histologically by the apoptosis of muscle fibers, the infiltration of inflammatory cells, and the disruption of sarcomeric organization (Mackey et al., 2008). While muscle damage can have a positive effect on strength, it is important to note that it can also negatively affect the effect of exercise on the brain. The mechanisms by which PE induces muscle damage exceed the scope of this review and have been described elsewhere (Fouré and Gondin, 2021). In animals, for example, it has been demonstrated that muscle injury could promote neuroinflammation and impair hippocampus-dependent memory (Guéniot et al., 2020). In addition, recent results showed that heightened activations of neuroinflammatory processes can lead to alterations in synaptic plasticity and BDNF expression (Golia et al., 2019). Thus, controlling the impact of NMES protocols on muscle damage appears crucial when targeting cerebral health enhancement but also to ensure patient's adherence to the training protocol.

3.2 Discomfort

On another hand, NMES is often associated with discomfort felt during the application of ES on the skin. This discomfort is even more pronounced in women and obese individuals (Maffiuletti, 2010), since adipose tissue acts as a capacitor, hindering the passage of current to the muscle tissue. Moreover, placing the electrodes on a motor point can reduce the sensation of discomfort and improve muscle activation (Gobbo et al., 2014). The size of the electrodes is also important: several experiments comparing different positionning configurations, reported higher tolerated intensities of stimulation (i.e., higher torque) and lower discomfort when using large electrodes (Maffiuletti et al., 2014; Barss et al., 2018). Indeed, with small electrodes, current density is higher and might produce a preferential excitation of small-diameter sensory fibers which are sensitive to current density in the dermo-epidermal junction (Mørch et al., 2011; Bergquist et al., 2017).

It is plausible that the perception of discomfort during ES affects its effects on the brain. For example, it has been reported that cortical activation during ES is correlated with the discomfort experienced by subjects. Thus, greater discomfort could induce a higher level of arousal and have short-term positive effects on cognition due to elevated arousal. Further studies would be interesting to evaluate the relationship between ES-induced discomfort, arousal levels, and cognition. On the other hand, ES can induce substantial muscle damage (as described in the manuscript) in the days following its application. The nociceptive nerve endings of skeletal muscles respond to the release of ATP due to sarcolemma permeabilization, muscle inflammation, pH variations, and muscle temperature changes. Various clinical and preclinical studies have highlighted the link between chronic pain, the emergence of anxiety-like behaviors, and impaired cognitive function. Therefore, it will be interesting in the future to evaluate cognition in the days following the application of ES. Moreover, it is also known that ES is perceived as less uncomfortable when combined with voluntary contraction. Hybrid FES may therefore be an interesting solution. Thus, it is therefore essential to carry out pre-conditioning and familiarization sessions, while modulating the intensity and/or force developed to reduce discomfort, muscle damage or fatigue.

4 Conclusion

Taken together, this review highlights the fact that ES has received little attention compared to aerobic exercise, but the available data suggest that ES could be of interest for improving cerebral health, particularly in people who cannot exercise voluntarily. Further studies are needed to confirm this postulate and elucidate the underlying mechanisms. In addition, stimulation protocols need to be optimized to reduce muscle damage and fatigue. It would, therefore, be appropriate to carry out comparative studies in humans and animals between conventional PE, NMES and FES.

Author contributions

MD: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. RC: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. PG: Supervision, Validation, Visualization, Writing–review and editing. AP-T: Supervision, Visualization, Writing–review and editing. JB: Conceptualization, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. GD: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Author MD was employed by Kurage.

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Inter-individual differences in muscle damage following a single bout of high-intense whole-body electromyostimulation

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Purpose: This brief report aimed to characterize inter-individual training responses following a single session of high-intense whole-body electromyostimulation (WB-EMS) using markers of muscle damage over a period of 72 h.
Methods: Twelve healthy individuals (5 men, 7 women; 32.0 ± 7 years) participated in a single 20-minute high-intensity WB-EMS training session. Markers of muscle damage, creatine kinase (CK) and myoglobin (Mb), were assessed before and immediately after training, as well as at 1.5, 3, 24, 48 and 72 h post-exercise. Lactate levels were determined pre- and post-exercise.
Results: Overall, WB-EMS induced significant CK elevations, peaking at 72 h (18.358 ± 21.380 U/L; $p < 0.01$), and correlating Mb levels peaking at 48 h (1.509 ± 1.394 ng/dl, $p < 0.01$). Despite significant inter-individual variability in CK levels, both slow (SR) and fast responders (FR) were identified. FR showed significant increases in CK at all time points post WB-EMS ($p < 0.05$), whereas CK in SR significantly elevated after 48 h. Post-WB-EMS lactate concentration was identified to predict peak CK and Mb levels (r ≥ 0.65, both $p < 0.05$).
Conclusion: High-intensity WB-EMS has the potential to induce severe muscle damage, as indicated by elevated levels of CK and Mb. We identified two distinct groups of individuals, SR and FR, indicating variability in response to WB-EMS. Furthermore, we suggest that individual responses to WB-EMS can be predicted based on post-WB-EMS lactate concentration.

KEYWORDS
creatine kinase, exercise, inter-individual difference, muscle damage, myoglobin, WB-EMS

Introduction

In the past decade, research on whole-body electromyostimulation (WB-EMS) has increased significantly, demonstrating its efficacy in altering body composition and enhancing performance across various health conditions and age groups (1, 2). This has led to a massive increase in WB-EMS centers and available home-training supplies, bringing WB-EMS to a large and often untrained population. Since WB-EMS application stimulates up to eight muscle groups simultaneously, the potential risks associated with too-intense and unsupervised use should not be underestimated. Excessive WB-EMS training, characterized by intense current impulses, may lead to severe muscle damage predominantly in untrained, unaccustomed users, characterized by significant increases in serum creatin kinase (CK) and myoglobin levels (3, 4).

Both CK and Mb are commonly used as markers of training intensity, influenced by various factors such as exercise type and individual physiological variations, including ethnicity and age (5). CK, a central enzyme in muscle cellular energy metabolism, facilitates the transfer of phosphate between creatine phosphate and adenosine triphosphate (ATP), providing energy, especially during short, intense exercise. Elevated blood levels of the CK-muscle type isoform, primarily found in skeletal muscle, indicate muscle damage or injury (5–7). Similarly, myoglobin (Mb), which stores and transports oxygen in muscle tissue, follows a parallel pattern. When muscle damage occurs, both CK and Mb are released into the bloodstream, marking muscle injury, typically defined as exertional rhabdomyolysis when CK levels exceeding 1,000 U/L (8). In case of Mb, it is important to consider its solubility during severe muscle damage, as Mb accumulation in the renal tubulus can lead to Mb-induced nephropathy, posing a risk to kidney health (9).

Given the current scientific focus on individual responses to (standardized) training (e.g., high vs. low responding) and sex-specific differences in physiological training adaptation (10–13), it is of particular interest to investigate the individual response to intense WB-EMS training since knowledge is still limited. Additionally, identifying markers that may indicate unfavorable outcomes is crucial. This report examines the inter-individual WB-EMS response by assessing serum CK and Mb levels over a time course of up to 72 h and analyzes potential predictors for the extent of muscle damage. Notably, we intentionally applied a non-recommended protocol for an initial WB-EMS application to provoke unusually high physiological responses, particularly in WB-EMS novices, deviating from the established guidelines for WB-EMS (14).

Materials and methods

Twelve (5 male; 7 female) healthy and recreationally active WB-EMS novices (for characteristics see Table 1) performed one single high-intensity session of WB-EMS training using an established protocol (3). Written informed consent was obtained from all participants. The study adhered to the ethical principles of the Declaration of Helsinki and was approved by the ethics committee of University Witten/Herdecke (#91/2018). Participants had no history of cardiovascular or musculoskeletal diseases, orthopedic problems, or contraindications for WB-EMS (15).

WB-EMS session

The clinically supervised WB-EMS session took place between 7 and 9 am at the medical rehabilitation center Klinik Königsfeld, Ennepetal, Germany. Prior to the WB-EMS session and during the time course, participants were instructed to maintain their usual activity level, nutrition, and hydration status.

The CE-certified WB-EMS device and equipment (miha bodytec type-II, Gersthofen, Germany) was utilized as described (1, 16), in combination with an established load protocol

TABLE 1 Peak values of muscle damage markers following WB-EMS by response.

Subject	Sex	Age	Height	Weight	SMM		Lactate	CK	Myoglobin	CRP
		[Years]	[cm]	[kg]	[kg]	[%]	[m/mol]	[U/L]	[mg/dl]	[mg/dl]
Fast responder (FR)										
1	Female	28	172.6	73.1	29.3	40.1	1.96	4,919[a]	515.7[a]	0.58[b]
2	Male	44	183.2	81.2	37.1	45.7	2.87	27,501[b]	3,064.9[a]	0.45[b]
5	Male	32	195.4	103	46.6	45.2	4.82	33,071[b]	2,579.3[a]	1.01[b]
9	Female	27	170.0	65.3	27.0	41.3	2.95	32,701[b]	2,608.3[a]	0.11[b]
10	Female	33	162.0	55.3	22.0	39.8	5.05	74,354[b]	7,097.4[b]	1.03[b]
	Mean	33	176.6	75.6	32.4	42.4	3.53	34,511*	3,173.1**	0.64***
	SD	7	12.9	18.1	9.6	2.8	1.34	25,088	2,405.5	0.39
Slow responder (SR)										
3	Female	29	170.8	72.3	26.2	36.2	1.79	1,398[b]	219.1[a]	0.26
4	Female	23	174.0	72.1	27.6	38.3	3.02	8,135[b]	921.2[a]	0.05
6	Female	34	176.4	82.4	30.0	36.4	1.70	585[a]	129.8[a]	0.11[b]
7	Male	33	185.0	85.5	39.2	45.8	3.58	5,331[b]	558.3[a]	0.17[b]
8	Female	42	176.0	61.9	27.0	43.6	4.31	9,898[b]	1,694.5[b]	0.07[b]
11	Male	18	169.0	74.1	34.8	47.0	2.40	20,029[b]	1,083.4[b]	0.08
12	Male	37	177.0	72.7	33.9	46.6	3.34	2,581[b]	365.4[b]	0.14[b]
	Mean	31	175.5	74.4	31.2	42.0	2.88	6,851	710.2	0.13
	SD	8	5.2	7.7	4.9	4.9	0.96	6,759	558.7	0.07
Overall MEAN		31.7	176.0	74.9	31.7	42.2	3.15	18,375	1,736.4	0.34
SD		7.4	8.7	12.3	6.8	4.0	1.13	21,369	1,970.5	0.36

Subject values are given as absolute and peak values; group values (FR, SR) are given as mean and standard deviation (SD). Statistical significance was tested using repeated measures ANOVA.
[a]after 48 h.
[b]after 72 h.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$; SMM, skeletal muscle mass; CK, creatine kinase; CRP, C-reactive protein; peak value.

(biphasic, 85 Hz frequency, 350 µs pulse width, 0.4-s pulse ramp, and a 3:2 current-rest ratio of 6 s vs. 4 s) (3). The WB-EMS session (20 min; 4 sets, 6 exercises with 5 repetitions each) was conducted dynamically, with stimulation applied primarily on top of eccentric muscle contractions, including movements such as squatting, lunge movements and combined arm movements (2). Individual current adjustments were applied to ensure muscular exhaustion, defined as rating of perceived exertion (RPE) of ≥18 via the 6–20 Borg Scale (17). Close monitoring, with a ratio of 1 trainee to 1 trainer, ensured standardized movement patterns throughout the session.

Assessments

Anthropometric data were obtained using the seca216 (seca, Hamburg, Germany) for height measurement and a direct-segmental multi-frequency bioelectrical impedance analysis device (Inbody720, BioSpace, Seoul, Korea) for weight, skeletal muscle mass (SMM), and extracellular water (ECW) assessment, serving as indicator for training-induced plasma volume shifts. Blood samples were collected from the antecubital vein pre and immediately post WB-EMS, and at five additional time points (after 1.5, 3, 24, 48, and 72 h), and analyzed at SYNLAB MVZ Laboratory GmbH (Leverkusen, Germany) for CK, Mb, and C-reactive protein (CRP). To monitor muscle damage-induced rhabdomyolysis, participants were instructed to promptly report changes in urine color during the timespan of 72 h. Lactate concentration was measured using capillary pre and post blood samples taken from participants' earlobes (20 µl heparinized capillary) using the Biosen S-line automated analyzer (EKF Diagnostics, Magdeburg, Germany). Muscle exertion was assessed through maximal isometric leg strength testing (extension and flexion) pre and post WB-EMS using DIERs myoline professional device (DIERs Biomedical Solutions, Schlangenbad, Germany).

Statistical analysis

Statistical analyses were conducted using SPSSv23 software (IBM, Armonk, NY, USA) and Prism 9.2 (GraphPad Software, La Jolla, CA, USA). Data are presented as mean ± standard deviation (SD). Statistical significance was set at $p < 0.05$. Non-normal distribution was assessed using Kolmogorow-Smirnov Test. Differences from baseline and differences between responding groups were analyzed using repeated measures ANOVA. Correlation analysis of peak values was performed using the bivariate Spearman correlation coefficient (r).

Results

Participants completed the protocol at a RPE of 18.3 ± 1.0, resulting in muscle fatigue, as evidenced by a reduced maximal isometric strength (leg extension: −145.8 ± 64.3 *N*, $p < 0.001$; leg flexion: −41.8 ± 52.8 *N*, $p < 0.05$). The protocol was performed under aerobic conditions, with a mean post-exercise lactate concentration of 3.15 ± 1.13 mmol/L ($p < 0.05$). ECW remained constant after WB-EMS (− 0.06 ± 0.27 L; $p = 0.072$), indicating no significant shift in plasma volume.

Immediately post-exercise, initial signs of muscle damage were identified through a significant increase in overall CK (pre-exercise, 178 ± 192 vs. post-exercise, 198 ± 201 U/L; $p < 0.001$) and Mb concentrations (pre-exercise, 38 ± 12 vs. post-exercise, 204 ± 183 ng/dl; $p < 0.05$). Subsequently, WB-EMS induced substantial and exponential elevations in both mean CK levels (at 1.5 h: 302 ± 219; 3 h: 486 ± 341; 24 h: 3,320 ± 3,421; 48 h: 10,584 ± 10,865; and 72 h: 18,375 ± 21,369 U/L) and Mb levels (at 1.5 h: 482 ± 479; 3 h: 457 ± 572; 24 h: 379 ± 347; 48 h: 1,510 ± 1,394; and 72 h: 1,320 ± 1,924 ng/dl). Peak levels were predominantly observed after 48 h for Mb and after 72 h for CK (all $p < 0.05$); with a strong correlation between CK and Mb concentrations ($r = 0.977$; $p < 0.001$).

Substantial inter-individual variability was evident regarding the maximal levels in both muscle damage markers, ranging from 585 to 74,354 U/L for CK and 130–7,097 ng/dl for Mb (see Table 1 and Figure 1).

Upon closer examination of individual time courses over time, two distinct profiles were identified, categorized as slow responders (SR) and fast responders (FR). A comparison between both groups revealed significant differences for CK at 3 h ($p = 0.019$), 24 h ($p = 0.013$), and 48 h ($p = 0.013$), and Mb after 1.5 h ($p = 0.035$), 24 h ($p = 0.011$), and 48 h ($p = 0.025$), with FR exhibiting higher peak levels for CK (34,511 ± 25,088 U/L) compared to SR (6,851 ± 6,759 U/L; $p = 0.018$) and for Mb (FR: 3,173 ± 2,406 vs. SR: 710 ± 559 ng/dl; $p = 0.009$). Additionally, CRP showed a highly significant time × group effect at 72 h, with elevations only in the FR group ($p < 0.001$).

Of importance, individual characteristics such as sex, age, SMM, or RPE did not affect maximal levels of CK and Mb. Notably, post-WB-EMS lactate levels exhibited a strong correlation with subsequent peak levels of both muscle damage markers, suggesting predictive potential for an individual WB-EMS response (CK: $r = 0.648$, $p = 0.02$; Mb: $r = 0.681$, $p = 0.01$; Figure 2).

Discussion

This report aimed to highlight the inter-individual variability in muscle damage induced by WB-EMS and to identify potential predictive factors for long-term CK and Mb elevations. A key finding is the identification of two distinct inter-individual response profiles to WB-EMS, with the extent of muscle damage potentially predictable by measuring post-WB-EMS lactate concentrations.

In general, markers of muscle damage exhibit heterogeneous increases depending on the type, extent, and intensity of exercise. For instance, CK levels can range from approximately 1,000 U/L after conventional resistance exercise to as high as 80,000 U/L following exhaustive eccentric exercise. While established laboratory reference values for CK typically fall between 60 and 400 U/L, various thresholds have been defined to categorize

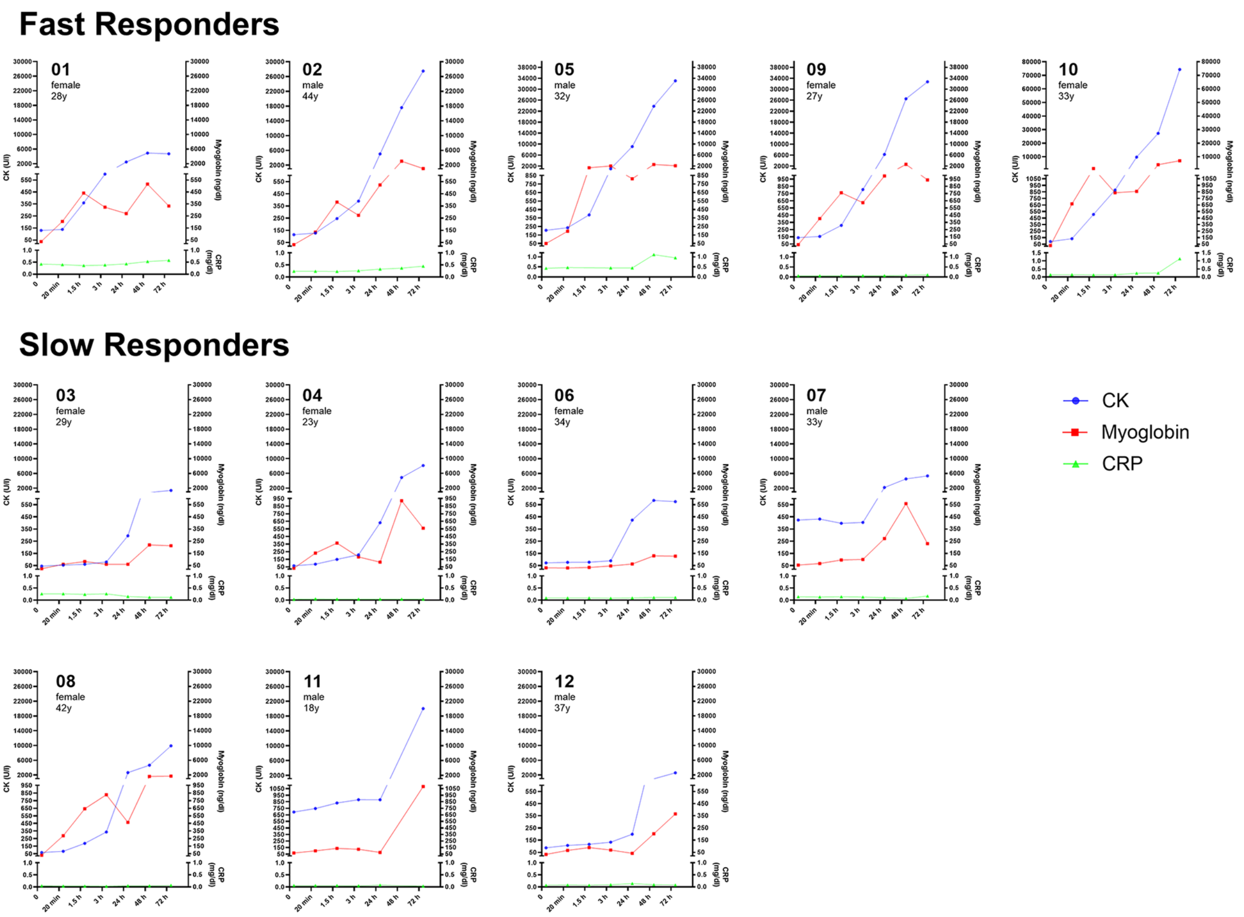

FIGURE 1
Individual time course of muscle damage markers (creatin kinase, myoglobin) and acute inflammation marker C-reactive protein by responder category.

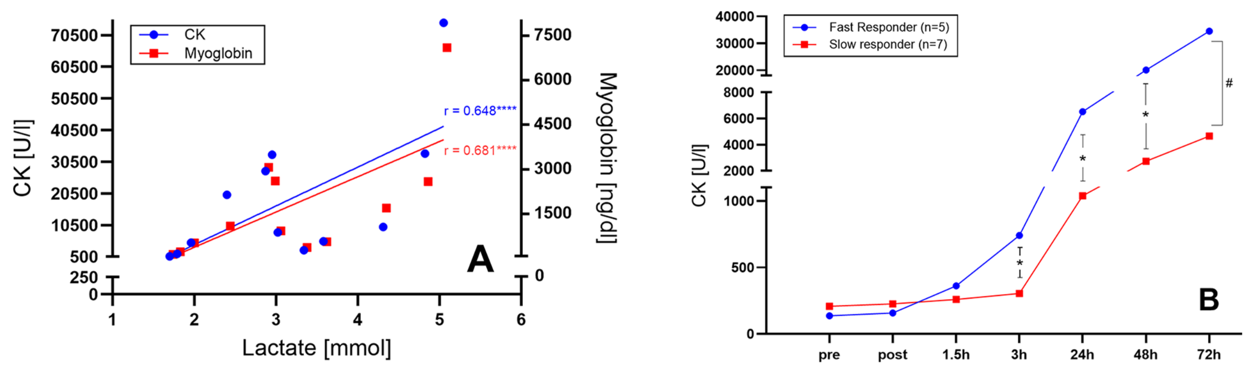

FIGURE 2
(A) Post-WB-EMS lactate levels predict muscle damage. Correlation and linear regression of peak creatine kinase (CK) and myoglobin levels with post-WB-EMS lactate concentration. Individual data points are shown. ****, significant correlation using bivariate Spearman correlation coefficient (*r*). (B) Time-course of CK levels identifies two distinct WB-EMS responder profiles. Mean CK values at the respective time points are shown. Curves were modelled using nonlinear fourth order polynomial regression. #, significant between-group interaction effect using two-way repeated-measures ANOVA, $p < 0.0001$. *, significantly different at time point, $p < 0.05$.

responses to exercise: low responders defined as <500 U/L, medium responders between 500 and 2,000 U/L, and high responders as >2,000 U/L (18). However, WB-EMS is known to substantially increase CK and Mb levels—by as much as 100-fold and 40-fold, respectively (3, 4)—when specific quality criteria are not met (15). This suggests that conventional response categories may not be entirely appropriate for WB-EMS application.

The current report not only provides further evidence that low and high responders to WB-EMS exist in terms of muscle damage, but our observation revealed two distinct groups based on time-dependent CK increases. The FR (fast responder) group exhibited a direct increase of CK and Mb immediately after WB-EMS (subjects 01, 02, 05, 09, 10; see Figure 1), suggesting a heightened sensitivity or reactivity to the WB-EMS stimulus. In contrast, the SR (slow responder) group demonstrated a delayed progression, with serum concentrations remaining constant for up to 24 h and showing ~80% lower peak levels (subjects 03, 04, 06, 07, 08, 11, 12; see Figure 1). These temporal patterns may depend on various factors, including genetic and epigenetic factors, fiber type composition, and environmental or behavioral aspects (6, 19, 20). Notably, CK and Mb levels in our study appeared to be independent of sex, age and SMM.

In addition, we found that post-exercise lactate concentrations could serve as a predictor of the subsequent development of muscle damage markers. Thus, measuring capillary lactate levels during and immediately after an initial WB-EMS session may serve as valuable tool to (1) prevent excessive WB-EMS intensity, (2) provide individualized post-WB-EMS information on potential development of muscle damage, and (3) tailor personalized recovery strategies before the next WB-EMS session.

Perspectives and significance

The inter-individual differences in muscle damage response highlight the importance of tailored training regimes. With two distinct response profiles—slow and fast responders—post WB-EMS lactate levels have shown promise as a predictive indicator of muscle damage. Routine monitoring of lactate concentration during and/or after WB-EMS may provide a simple, cost-effective method to adjust training intensity, particularly for newcomers. This monitoring approach ensures tailored recovery periods and regeneration strategies and minimizes the risk of injury from overuse. Further research should investigate whether acute lactate concentrations, comparable to CK levels, decrease over time with repeated WB-EMS sessions, potentially indicating improved muscle adaptation and tolerance to strain.

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.

Ethics statement

The studies involving humans were approved by Ethics committee University Witten/Herdecke. 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

MT: Writing – original draft, Investigation, Methodology, Project administration, Supervision, Visualization. MW: Writing – review & editing, Investigation, Supervision. BS: Writing – review & editing, Methodology. FM: Writing – review & editing, Methodology.

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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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Physiological and perceptual demands of singles and doubles beach tennis in women of different competition levels

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Purpose: To analyze and compare the physiological responses of women during singles and doubles beach tennis sessions.

Methods: In this crossover trial, twenty-two women with previous participation in amateur beach tennis tournaments randomly performed two experimental sessions: singles and doubles beach tennis. The routine for both sessions consisted of 10-min of seated rest, followed by 45-min of beach tennis and 30-min of post-exercise recovery. Participants were matched against opponents of the same competition level, defined according to their local beach tennis ranking (advanced or intermediate level). They warmed up with basic techniques for 5-min and played 3 matches lasting 12-min, interspersed with 2-min recovery intervals. Heart rate (HR), energy expenditure (EE), number of steps (STEPS), handgrip strength (HS), rating of perceived exertion (RPE), and enjoyment were assessed throughout the sessions. Generalized estimating equations were employed to examine the main effects between experimental sessions over the time and in relation to competition level.

Results: HRmean and HRmax (Δ: HRmean = 13 ± 3 bpm; HRmax = 11 ± 3 bpm) as well as EE and Steps (Δ: EE = 66 ± 22 kcal; RPE = 2 ± 0 A.U.; Steps = 250 ± 52 A.U.) were higher in singles than doubles ($p < 0.05$). The percentage of total time spent in the highest HR zone (91–100%HRmax) was significantly greater in singles than in doubles (39% ± 22% vs. 15% ± 18%; $p < 0.05$). Differences were found in the percentage of total time spent in each HR zone, recovery HR, and HS between competition levels ($p < 0.05$).

Conclusion: Singles beach tennis resulted in higher physiological demands than doubles in women, and players' competition level partly affects the training responses.

KEYWORDS

accelerometer, exercise physiology, recreational sports, heart rate, racket sports

1 Introduction

Beach tennis is a fast-growing sport with over 1 million practitioners in Brazil, regulated by the International Tennis Federation that promotes over 300 tournaments in 37 different countries (Tennis Rules and Regulations-ITF, 2024). The game is played on a sand court and is a mix of tennis and beach volleyball, as it uses racquets and lower pressurized tennis balls, however the ball is not allowed to touch the ground. A net split the court in half at 1.70 m in height. The sport can be played in doubles (2 vs. 2) or individually (1 vs. 1) in a court the same size of beach volleyball for doubles (16 m × 8 m) or smaller for singles (16 m × 4.5 m) (Tennis Rules and Regulations-ITF, 2024). Due to the characteristics of doubles beach tennis matches, in which the actions are divided with the partner, the game can result in different physiological demands when compared to singles, in which the same player hit the ball every time it crosses the net. Other factors such as training status of participants, sex, age, and previous experience in the modality may also influence the physiological demands of racket sports (Fernandez-Fernandez et al., 2009; Pluim et al., 2023). However, there is currently no published study on the physiological demands of singles and doubles beach tennis.

The practitioners of beach tennis engage in the activity for both competitive and recreational purposes (Rosa and Alvarez, 2021), with some focusing on health related benefits and others in improving game performance. Our research group recently evaluated the acute effects of a beach tennis session played in doubles on cardiovascular parameters of men and women with arterial hypertension. During the 45 min of activity, the mean reserve heart rate ($HR_{reserve}$) was ~60%, and a moderate rate of perceived exertion was reported during the game. Additionally, we assessed post-exercise hypotension after the beach tennis session and found a reduction in 24-h ambulatory blood pressure (systolic: ≈6 mmHg; diastolic: ≈3 mmHg). In this pioneer study, the focus was to assess benefits of the activity on blood pressure in a sample consisting of untrained participants (Carpes et al., 2021). Still, it seems relevant to investigate the demands of beach tennis in previously trained individuals regularly engaged in amateur tournaments of the sport, since the results can be used to optimize preparedness for competition or to improve health parameters.

Beach tennis appears to be an intense intermittent activity that may have some of the characteristics of hybrid sports (Batrakoulis et al., 2022) such as soccer, which has been shown at meta-analysis level to be a highly efficient training modality to improve physical fitness, as well as cardiovascular, metabolic and bone health (Milanović et al., 2015; Milanović et al., 2019; Milanović et al., 2022) in sedentary populations. Similar findings have been shown in team handball (Póvoas et al., 2018), floorball (Wikman et al., 2017) and futsal (Castagna et al., 2020). At the present, the acute effects of beach tennis were only assessed in untrained hypertensive participants, and there is no data available comparing the physiological demands of singles and doubles beach tennis. The ease of learning and low motor complexity of beach tennis have attracted a large number of middle-aged female practitioners, including those who had never previously practiced any other sport. Therefore, the evaluation of a sample composed of women is particularly important to fill the longstanding gap in sports research, which has historically concentrated on male participants, resulting in the underrepresentation of women in scientific studies. Therefore, the present study tests the primary hypothesis that beach tennis played in singles has a higher physiological loading compared to doubles in women. A secondary explorative hypothesis was that the physiological loading was dependent on the players' competition level.

2 Materials and methods

2.1 Study design and participants

This is a crossover trial in which the participants randomly performed two experimental sessions: Singles and Doubles Beach Tennis. The randomization list consisted of random blocks of four participants and was generated by independent researchers (that did not participate in the recruitment of participants or their assignment to intervention groups) using a computer software. Participants and the research team were blinded to the randomization list until the time of assignment.

Twenty-two middle-aged women were found eligible and volunteered to participate in the study. The sample size was estimated to detect a minimum difference of 10% (8 bpm) in maximum HR during singles and doubles beach tennis sessions (Alcock and Cable, 2009). The calculation was carried out using the PSS Health tool online version 19 (Borges et al., 2020), considering a power of 80% and a significance level of 5%. The inclusion criteria were middle-aged women (35–55 years old), affiliated to the Beach Tennis Federation of Rio Grande do Sul (Brazil) with previous participation in amateur tournaments of this federation. Exclusion criteria included ischemic heart disease, angina pectoris, stroke or heart failure diagnosed in the last 24 months, and musculoskeletal problems that hinder exercising. Recruitment was carried out through telephone calls or face-to-face invitations during beach tennis tournaments.

Ethical committee approval was obtained at the Institutional Review Board of Hospital de Clínicas de Porto Alegre, Brazil (approval number: 5.309.930). The study protocol was conducted in accordance with the Declaration of Helsinki and the Brazilian resolution number 466/12 of research involving human beings. All participants provided written informed consent before entering the trial. The experimental sessions were conducted between January and December of 2022 in the city of Porto Alegre (RS, Brazil).

2.2 Characteristics of the experimental sessions

Participants were instructed to avoid vigorous physical activity the day before the experimental sessions, to keep their regular diet, and to not ingest alcohol, caffeine, and other stimulants on the same day of the session. All sessions started between 8:00 and 10:00 a.m. (at the same time of the day to account for potential diurnal physiological variation) and lasted approximately 2 h. The participants were hydrated at the beginning of the session and were allowed to drink water *ad libitum* to ensure the maintenance of proper hydration throughout the sessions.

Temperature and relative humidity during the sessions were collected to ensure that both sessions were performed under the same environmental conditions, and the interval between the sessions was 5–7 days.

The players were blinded to their partners and opponents until the intervention day. They were assigned to the matches against other players of the same competition level, defined according to their local beach tennis ranking (defined by the Beach Tennis Federation of Rio Grande do Sul, Brazil), and confirmed by two researchers with previous experience in the modality. The Brazilian Beach Tennis Federation defines the beach tennis categories for amateur tournaments in levels A, B, C, D and beginners. "A" is the highest-level category of amateur tournaments, and "D" is the lowest level of amateurs' players with previous experience in beach tennis. For the purpose of this study, players were classified into 2 levels: Level 1 included advanced players with ranking in A and B (Advanced level), and level 2 included participants with ranking in C and D categories (Intermediate level).

Both sessions followed the same routine that consisted of 10 min of seated rest, followed by 45 min of beach tennis and 30 min of recovery after exercise. The participants warmed up with basic techniques for 5 min (volleys and serve) and played 3 matches of 12 min each, with 2-min intervals between matches. The games were played according to ITF beach tennis rules.

2.3 Assessments

Heart rate was monitored and recorded during and up to 5 min after the end of the session using a chest monitor (Polar H10, Finland). After the match, the heart rate data was downloaded to a computer, and the average and maximal heart rate was automatically calculated using the PolarFlow software. The data were categorized into heart rate zones to indicate total time spent at ≤60, 61–70, 71–80, 81–90, 91%–100% maximal heart rate (HR_{max}) using the same software. The individual HR_{max} was determined according to the following formula: 220 minus age or the highest HR value reached during the matches, if the value was higher than the estimated HR_{max}. The reserve HR ($HR_{reserve}$) was calculated using the following formula: ((exercise HR - resting HR)/reserve HR) *100 (Swain and Leutholtz, 1997).

Energy expenditure (EE) of the sessions was estimated based on the HR values through the PolarFlow software. The software was configured based on individual parameters including age, height, weight, maximal heart rate, and gender, enabling automatic EE calculations (Gilgen-Ammann et al., 2019).

Number of steps was measured during the matches using an accelerometer (GT3X - ActiGraph Inc, Pensacola, FL, United States). The equipment was placed in position by the research team at the beginning of the session (when they entered the court) and removed at the end of the match. The accelerometer was fixed at the waist, on the right iliac crest, using an elastic strap, programmed with 1-s epochs, which were then converted to 15 s, using ActiLife software (version 6.8.1; ActiGraph LLC, Pensacola, FL, United States).

Handgrip isometric strength was assessed before (pre) and after the sessions (post 5′ and 30′) using a hydraulic handgrip dynamometer (JAMAR® 5030J1, Sammons Preston Rolyan, Bolingbrook, IL, United States). The participants were seated in armless chairs, with their elbows flexed at a 90° angle, attached to their bodies, while their shoulders and wrists were maintained in a neutral position (Vargas-Pinilla and Rodríguez-Grande, 2021). Following instructions and a demonstration, a proficient researcher positioned in front of each participant grasped the device during the test and instructed them to exert maximum force while squeezing. This measurement procedure was repeated thrice on each arm, with a 1-min interval between readings. All participants used the same second handle position, and standardized verbal encouragement was provided during the measurements.

Rating of perceived exertion (RPE) was assessed after the warm-up, and immediately after each 12-min match (intra 1, intra 2, and intra 3) using the CR-10 Borg scale (Borg, 1990). Participants were previously familiarized with the use of scale in a preliminary session.

Internal load of participants was estimated using an additional RPE assessed 15 min after the completion of exercise (Haddad et al., 2017). Basically, the participant answered a simple question: "How was your training?" using the CR-10 Borg scale (Foster et al., 2001). A single arbitrary unit representing the magnitude of the internal training load for each session was calculated by multiplying the RPE and the session time (minutes).

The enjoyment level during the sessions was assessed using the Physical Activity Enjoyment Scale (PACES) (Teques et al., 2017). During the post-exercise period (15–30 min after the end of each session) the participant received an electronic questionnaire and was asked to rate the level of enjoyment based on the following question: "How do you feel at the moment about the physical activity you performed?" The questionnaire consisted of 18 items rated on a 7-point bipolar rating scale. A total of 11 items were reversed and scored. Summing the individual item scores generated an overall PACES score. This yielded a possible range of 18–126, and higher PACES scores reflect greater levels of enjoyment.

2.4 Statistical analyses

Data were entered in duplicate by two separate researchers. The statistician was not involved in the recruitment or assignment to the experimental sessions and was blinded to the interventions. The assumption of normality was assessed using the Shapiro-Wilk test. Results were presented as means and standard deviation (Table 1) or standard error (Table 2–4) for variables with a normal distribution. Generalized estimating equations (GEE) analyses were employed to examine the main effects between experimental sessions (2 sessions: Singles and Doubles beach tennis) over time and participant level (session*time). To compare the differences between participant competition levels, an additional GEE analysis was conducted, incorporating a new factor (level 1 vs. 2). Post-hoc comparisons were conducted using Bonferroni tests. Paired Student's t-tests were used to assess direct comparisons between Singles and Doubles sessions, and the association between HR and RPE was performed using Pearson's correlation test. Statistical significance was set *a priori* at $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics for Windows, version 19 (IBM, Armonk, NY, United States).

TABLE 1 Characteristics of the participants.

Variables	Total (n = 22)	Level 1: Advanced (n = 11)	Level 2: Intermediate (n = 11)	*p*-Value
Age, years	40.7 ± 6.6	42.1 ± 6.9	39.3 ± 6.3	0.330
Weight, kg	65.1 ± 9.2	66.6 ± 9.2	63.6 ± 9.3	0.463
Height, m	1.7 ± 0.1	1.7 ± 0.1	1.7 ± 0.1	0.663
BMI, kg/m^2	23.2 ± 2.9	23.5 ± 2.8	22.9 ± 3.3	0.632
Practice time, months	43.9 ± 24.5	51.9 ± 28.1	36 ± 18.4	0.131
Frequency, days.week^{-1}	2 (2)	3 (3)	2 (2)	0.357
Time per week, hour.week^{-1}	3.7 ± 2.6	4.6 ± 2.9	2.8 ± 2	0.104
Duration, min.day^{-1}	91 ± 30	106 ± 28	76 ± 25	**0.015**

Values are mean ± standard deviation (SD) for parametric distribution data, and median (interquartile range) for non-parametric distribution data; BMI: body mass index; *p*-value is comparing the competition levels separately. Bold p-values indicate significant results ($p < 0.05$).

3 Results

The characteristics of the participants are shown on Table 1. Overall, they had healthy weight, were physically active (Thivel et al., 2018) and had over 3 years of experience playing the sport. The participants had similar characteristics, except for the training duration that was higher for advanced than intermediate players ($p = 0.015$). Temperature and relative humidity were similar for both sessions (singles: 13.7°C ± 3.5; 89.5% ± 7.3; doubles: 13.0°C ± 3.2; 92% ± 8.2). No adverse events occurred throughout the study.

No correlations were identified between the intrasession HR and RPE (after warm-up, and immediately after each set) during Singles and Doubles beach tennis sessions ($p > 0.05$ for all comparisons). Similarly, no correlation was found between the internal load and mean $HR_{reserve}$ after Singles ($p = 0.251$) and Doubles ($p = 0.395$) beach tennis sessions.

3.1 Comparison between singles and doubles sessions

The mean and maximal HR loading, EE (total and by min), RPE, number of steps, the internal load, and the enjoyment level are presented in Figure 1 and Table 2. Overall, the values of these variables were higher in singles than doubles ($p < 0.05$), except for the enjoyment level that was similar for singles and doubles ($p = 0.72$).

Figure 2 shows the percentage of total time spent in each intensity zone expressed as percentage of players' maximal heart rate (%HR_{max}), with significant differences between singles and doubles at 61%–70%, 71%–80%, and 91%–100% HR_{max} ($p < 0.05$).

Figure 3 shows the recovery HR of the first 5 min after the sessions, and the maximal handgrip isometric strength assessed before, after 5′and 30′of the match. Recovery HR was higher after singles than doubles (Δ Time 0': 18 ± 7 bpm, $p = 0.013$; 1': 14 ± 4 bpm, $p = 0.001$ and 5': 7 ± 3 bpm, $p = 0.028$). In relation to maximal handgrip isometric strength, the participants presented similar values before the sessions (Singles: 39/36 KgF; Doubles: 38/35 KgF). After the sessions, doubles presented higher handgrip strength in the dominant arm than singles at post 5'(Δ 2 KgF, $p = 0.001$).

3.2 Comparison between intermediate and advanced players

We ran additional analysis to explore potential differences between participants of different competition levels (Advanced and Intermediate players) during doubles (advanced vs. intermediate) and singles (advanced vs. intermediate) sessions (Tables 3, 4).

Significant differences were observed between the levels for the percentage of total time spent in each intensity zone. No significant differences were found for the number of steps, EE, RPE, mean HR, or maximal HR.

During the recovery period after exercise, advanced players exhibited a higher HR compared to intermediate players ($p = 0.037$) immediately after singles (post 0′). No other difference was found between competition levels for this variable.

Regarding isometric handgrip strength, advanced players consistently showed higher strength in the dominant arm compared to intermediate players at multiple time points (pre-exercise, post 5′and 30′ after the exercise session) after singles and doubles sessions.

The results of the percentage of total time spent in each intensity zone by level are shown in Table 4. In doubles, intermediate players spent more time at 91–100%HR_{max} than advanced players ($p = 0.041$).

4 Discussion

Beach tennis can be played individually (singles) or in pairs (doubles). In singles, the same player must cover the entire court and respond to every ball that crosses the net, potentially leading to

TABLE 2 Heart rate and rating of perceived exertion responses during singles and doubles beach tennis sessions.

Variables	Singles	Doubles	Δ	*p*-Value
Warm-up (5 min)				
HR	132 (125–138)	134 (124–144)	−2 (−9 to 6)	0.726
RHR	56 (50–61) (Moderate)	58 (50–66) (Moderate)	−2 (−8 to 5)	0.642
RPE	2 (1–3) (Light)	2 (2–3) (Light)	0 (−1 to 1)	0.213
Intra session 1				
HR	161 (156–165)	146 (140–153)	15 (9–19)	**<0.001**
RHR	80 (77–84) (Vigorous)	68 (63–72) (Vigorous)	12 (8–16)	**<0.001**
RPE	4 (3–5) (Moderate)	3 (2–3) (Light)	1 (1–2)	**<0.001**
Intra session 2				
HR	164 (159–169)	146 (139–154)	18 (10–23)	**<0.001**
RHR	83 (79–87) (Vigorous)	68 (63–74) (Vigorous)	15 (9–20)	**<0.001**
RPE	4 (3–5) (Moderate)	3 (2–3) (Light)	1 (1–2)	**<0.001**
Intra session 3				
HR	166 (161–171)	147 (140–154)	19 (11–24)	**<0.001**
RHR	85 (81–88) (Vigorous)	69 (64–74) (Vigorous)	16 (10–20)	**<0.001**
RPE	4 (3–5) (Moderate)	3 (2–3) (Light)	1 (1–2)	**<0.001**
Total session (45 min)				
HR_{max}	181 (151–160)	171 (151–160)	10 (5–16)	**<0.001**
HR_{mean}	156 (151–160)	143 (137–150)	13 (7–18)	**0.001**
RHR	76 (72–80) (Vigorous)	66 (61–71) (Vigorous)	10 (6–14)	**<0.001**

Values are mean (95% confidence interval). HR: heart rate (bpm); RHR: reserve heart rate (%); RPE, rating of perceived exertion according to Borg CR-10 scale (A.U.). *Verbal descriptor of intensity according to the American College of Sports Medicine and Gunnar Borg. Bold p-values indicate significant results ($p < 0.05$).

different physiological demands compared with doubles, in which the workload is shared between two players. To the best of our knowledge, this is the first study to evaluate the physiological demands of beach tennis in women. Using a crossover trial, we also compared the physiological responses between singles and doubles matches, considering the potential influence of the training

TABLE 3 Heart rate recovery and handgrip strength after singles and doubles beach tennis session stratified by the competition level of the participants.

Variables	Level 1: Advanced (n = 11)	Level 2: Intermediate (n = 11)	Δ	*p*-Value
Heart rate$_{rec}$ (bpm)				
Post_0′				
Singles	156 ± 5 (150–166)*	142 ± 4 (133–150)	14 ± 7 (1–28)	**0.037**
Doubles	126 ± 8 (110–143)	138 ± 6 (126–151)	−12 ± 10 (−32 to 9)	0.254
Post_1′				
Singles	129 ± 4 (122–136)*	127 ± 3 (120–134)*	2 ± 5 (−8–12)	0.727
Doubles	114 ± 5 (105–123)	115 ± 4 (108–122)	−1 ± 5 (−13 to 10)	0.778
Post_2′				
Singles	119 ± 2 (115–123)	119 ± 3 (114–124)	0 ± 3 (−7 to 6)	0.897
Doubles	111 ± 4 (102–119)	119 ± 4 (111–127)	−8 ± 6 (−20 to 3)	0.169
Post_3′				
Singles	115 ± 4 (108–123)	112 ± 3 (107–117)	3 ± 5 (−6–12)	0.461
Doubles	108 ± 6 (92–119)	111 ± 3 (106–116)	−3 ± 6 (−16 to 9)	0.627
Post_4′				
Singles	112 ± 4 (104–119)	106 ± 2 (102–111)	6 ± 4 (−3–14)	0.234
Doubles	102 ± 6 (91–113)	108 ± 3 (102–113)	−6 ± 6 (−18 to 6)	0.326
Post_5′				
Singles	106 ± 4 98–114)*	102 ± 3 (97–108)	4 ± 5 (−6–14)	0.440
Doubles	94 ± 5 (84–104)	102 ± 3 (97–107)	−8 ± 6 (−19 to 3)	0.161
Handgrip strength (KgF)				
Pre				
Singles	43 ± 2 (39–48)	35 ± 1 (32–38)	8 ± 3 (3–14)	**0.002**
Doubles	41 ± 2 (37–44)	36 ± 1 (34–38)	5 ± 2 (0–9)	**0.034**
Post 5′				
Singles	42 ± 2 (38–46)	37 ± 1 (35–39)	5 ± 2 (1–10)	**0.018**
Doubles	43 ± 2 (39–47)	38 ± 1 (36–40)	5 ± 2 (1–10)	**0.024**
Post 30′				
Singles	42 ± 2 (38–46)	36 ± 1 (34–37)	6 ± 2 (1–10)	**0.010**
Doubles	43 ± 2 (39–48)	37 ± 1 (35–39)	6 ± 3 (1–11)	**0.020**

Values are mean ± standard error (95% Confidence Interval); *Singles is different from Doubles ($p < 0.05$); p-value is comparing the levels separately in the session (level 1 vs. level 2). Bold p-values indicate significant results ($p < 0.05$).

TABLE 4 Percentage of total match time spent in each intensity zone expressed as percentage of players' maximal heart rate during singles or doubles beach tennis session stratified by the competition level of the participants.

Variables	Level 1: Advanced (n = 11)	Level 2: Intermediate (n = 11)	Δ	*p*-Value
Heart rate				
Time <60%HRmax (%)				
Singles	2.7 ± 0.7 (1.2–4.1)*	3.4 ± 1.4 (0.6–6.1)	0.7 ± 1.6 (−3.8 to 2.4)	0.658
Doubles	8.9 ± 1.9 (5.1–12.8)	6.4 ± 3.3 (−0.1–12.9)	2.5 ± 3.8 (−5.0–10.0)	0.514
Time 61–70%HRmax (%)				
Singles	8.1 ± 1.2 (5.6–10.5)*	8.2 ± 1.7 (4.8–11.6)	0.1 ± 2.1 (−4.3 to 4.1)	0.963
Doubles	26.8 ± 5.7 (15.7–38.0)	13.6 ± 4.1 (5.7–21.4)	13.2 ± 6.9 (−26.9 to 0.4)	0.057
Time 71–80%HRmax (%)				
Singles	13.6 ± 1.5 (10.7–16.5)*	18.7 ± 3.1 (12.6–24.9)*	5.1 ± 3.5 (−11.9 to 1.7)	0.138
Doubles	35.7 ± 3.1 (29.5–41.9)	25.0 ± 4.5 (16.2–33.8)	10.7 ± 5.5 (−21.5 to 0.8)	0.052
Time 81–90%HRmax (%)				
Singles	31.8 ± 3.3 (25.3–38.3)	32.0 ± 3.1 (25.9–38.1)	0.2 ± 4.6 (−9.1 to 8.8)	0.971
Doubles	21.9 ± 5.4 (11.4–32.6)	33.1 ± 4.9 (23.4–42.9)	11.2 ± 7.3 (−25.6 to 3.4)	0.129
Time 91–100%HRmax (%)				
Singles	44.0 ± 5.7 (32.8–55.2)*	38.0 ± 5.8 (26.6–49.4)*	6.0 ± 8.1 (−9.9–21.9)	0.462
Doubles	6.6 ± 3.6 (−0.4–13.6)	21.8 ± 6.5 (8.9–34.6)	15.2 ± 7.5 (−29.8 to −0.6)	**0.041**

Values are Means ± standard error (95% Confidence Interval); HRmax = maximal heart rate; *Singles is different from Doubles ($p < 0.05$); p-value is comparing the competition levels separately in the session (level 1 vs. level 2). Bold p-values indicate significant results ($p < 0.05$).

status of participants. The main results suggest that singles beach tennis induced a higher physiological loading than doubles, and participants of advanced categories may respond differently to those playing in the intermediate level. Moreover, independently of the competition level or characteristic of the match, a reduced RPE and a high level of enjoyment were achieved during the session. Taken together, our findings confirm the differences of physiological and perceptual demands of singles and doubles beach tennis matches and a possible influence of training status of participants in some but not all responses, which should be taken into account during the training organization and competitions of the modality for different populations such as patient groups or amateur athletes.

As a sport characterized by short intermittent bouts of small distance accelerations/decelerations, change of direction, and jumps on the unstable sandy surface, beach tennis players must react fast to always hit the ball before it touches the ground, resulting in a high stimulation of the cardiovascular system. Estimates of exercise intensity during a game may offer valuable information to optimize training methods, as well as to indicate how it may aid cardiovascular health of recreational practitioners. For example, in the well-research sport concept, Football Fitness, it has been shown that small-sided games can be modified to alter the exercise intensities, where altering the pitch size and/or number of players has great impact on the physiological loading (Randers et al., 2014b; Randers et al., 2014a). In the present study, relative and maximum HR were assessed to describe the cardiovascular strain of singles and doubles beach tennis games. When expressed as percentages of $HR_{reserve}$ (i.e., $\%VO_{2max}$), an average of 76% for singles and 66% for doubles were found, being classified as vigorous and moderate physical activities, respectively (Garber et al., 2011). Players reached a peak HR loading of 181 ± 3 and 171 ± 3 bpm in singles and doubles, respectively, with values approaching maximum in singles. In addition, during singles matches players spent 39%, corresponding to 18 min of the total time in the 90–100%HR_{max} zone. In doubles, the HR value is considerably and significantly lower, with players spending only 15% or 7 min of the total time at this intensity. The HR loading values during beach tennis are comparable to women´s collegiate soccer (mean ~75% HR_{max}) (Jagim et al., 2020), tennis players (mean HR 128–164 bpm) (Cádiz Gallardo et al., 2023), and women´s recreational team handball players (mean 77%–79% HR_{max}) (Pereira et al., 2023). Thus, it can be classified as an efficient method to provide a

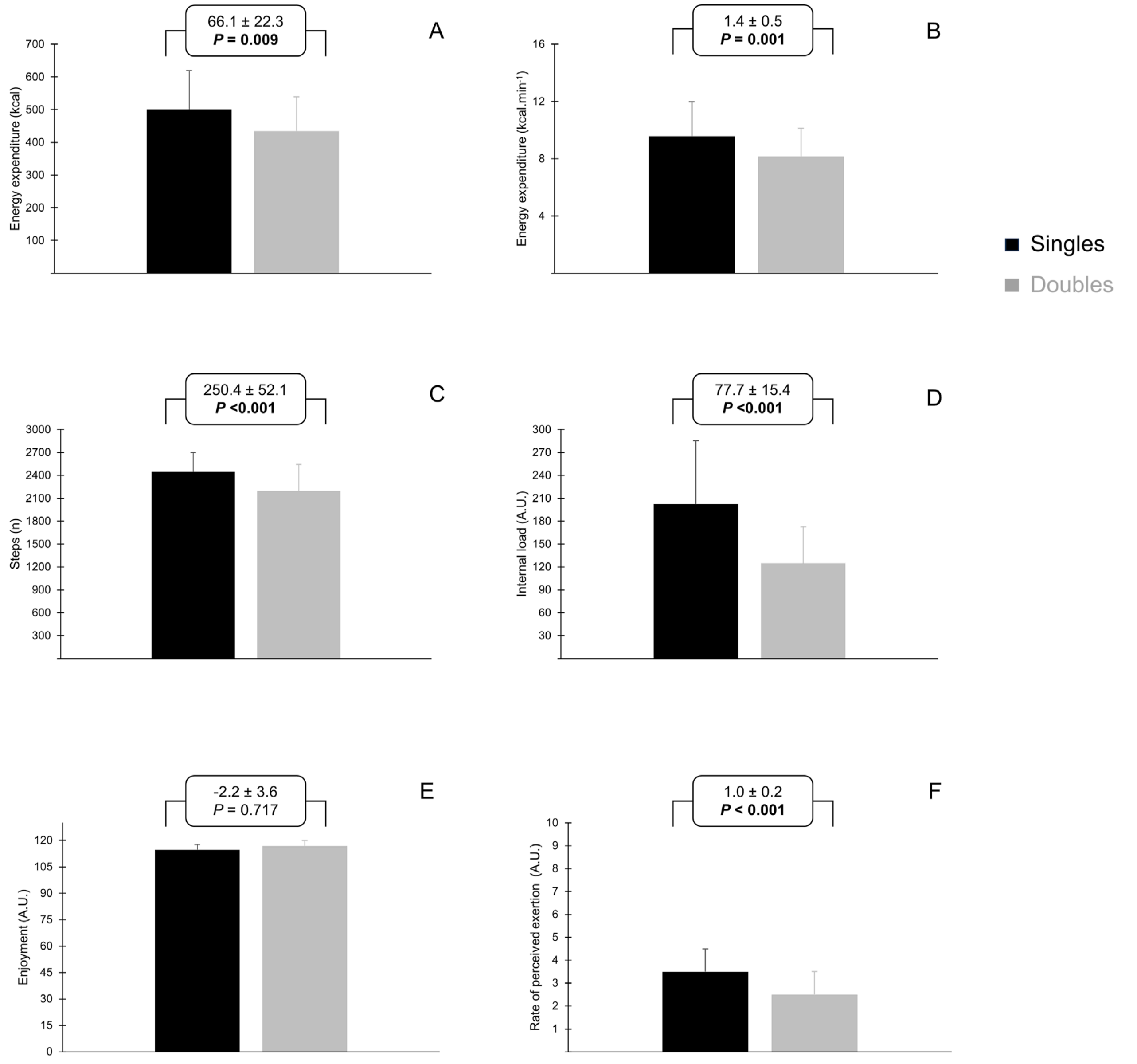

FIGURE 1
Absolute values of mean energy expenditure [panel **(A)**], energy expenditure per minute [panel **(B)**], number of steps [panel **(C)**], internal load [panel **(D)**], enjoyment [panel **(E)**], and rating of perceived exertion [panel **(F)**] during singles and doubles beach tennis sessions.

high HR loading, which is paramount for optimal improvement of cardiovascular health status (Batrakoulis et al., 2022).

The estimation of the metabolic responses through EE provides important information to the exercise prescription for both health and performance. We observed an EE of ~8 kcal min^{-1} for doubles and ~10 kcal min^{-1} for singles, with the EE of singles being ~15% higher than doubles. These values are comparable to those achieved during traditional exercise modalities such as aerobic and combined exercises (Ferrari et al., 2018). Moreover, the number of steps was ~10% higher for singles than doubles sessions. In fact, and in line with our primary hypothesis, we expected higher values when playing beach tennis individually, but it was uncertain how large this difference would be and how these values would be comparable to other types of physical activities. Grip strength influences game performance and also contributes to the prevention of musculoskeletal injuries (Elliott, 2006). In our study, the participants demonstrated mean grip strength values of ~40 KgF in the dominant arm. Although the absence of studies assessing handgrip strength in beach tennis limits directs comparisons, it is noteworthy that our observed values surpassed those documented in a study involving female tennis athletes (18 years old) that presented mean grip strength of 33 KgF in the dominant arm (Pereira et al., 2011). We also assessed the handgrip strength 5 and 30 min after sessions to determine whether singles or doubles matches would result in forearm fatigue. We found no significant reduction of strength compared to baseline after singles. After doubles, we found an

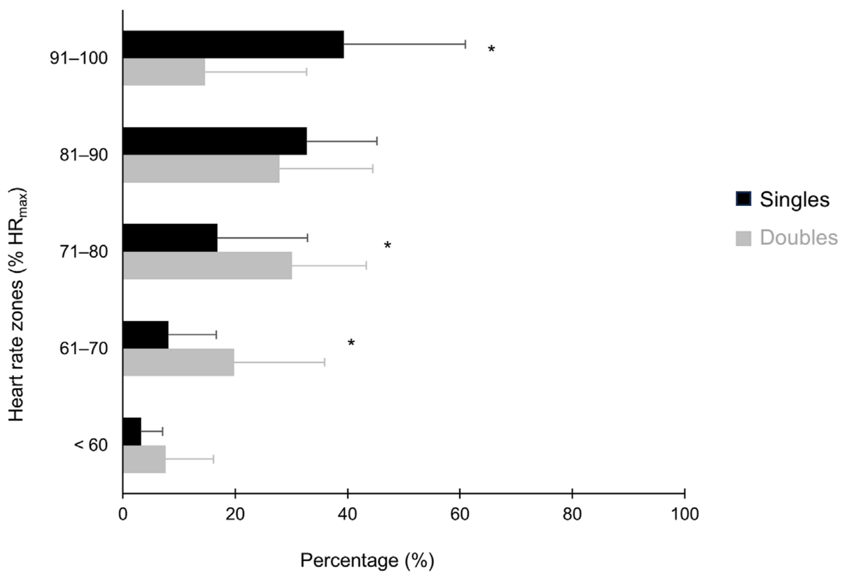

FIGURE 2
Percentage of total match time spent in each intensity zone expressed as percentage of players' maximal heart rate during singles and doubles beach tennis sessions.*Singles different from doubles beach tennis session ($p < 0.05$).

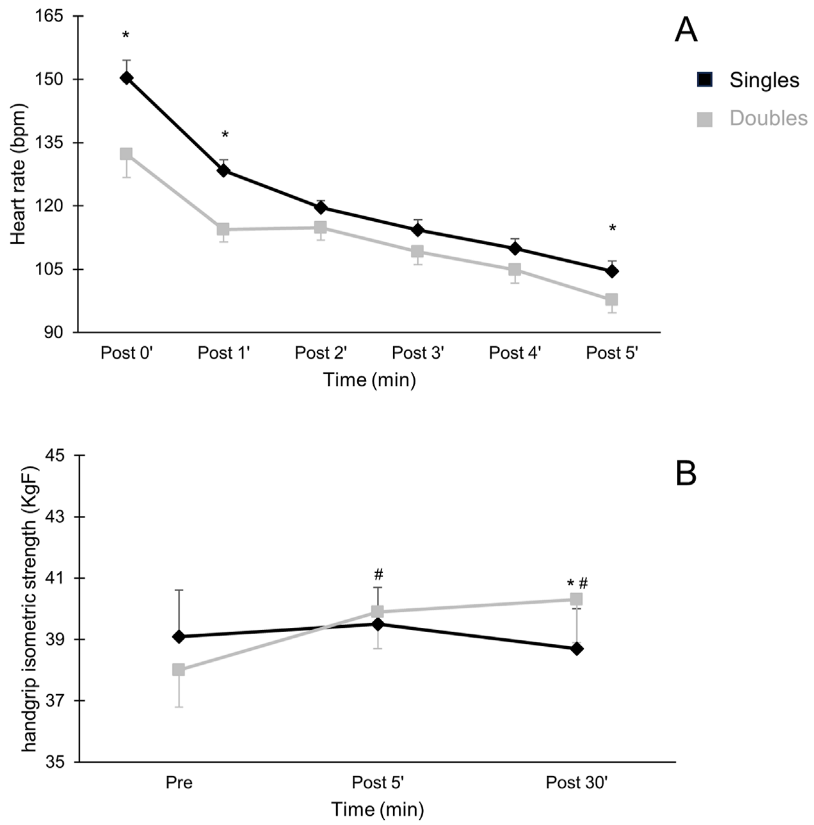

FIGURE 3
Recovery heart rate [panel **(A)**] and handgrip strength [panel **(B)**] after singles and doubles beach tennis sessions.*Singles different from doubles beach tennis session ($p < 0.05$). #Different from pre values of the same session ($p < 0.05$).

increase in handgrip strength when compared to baseline values and when compared to the singles session in the same period of time. We speculate that the local neuromuscular demand of singles may cause fatigue in the handgrip muscles because there is a necessity to activate it every action, while in doubles the demand is shared with the partner, allowing a better recovery between actions and reducing the local muscular fatigue.

The influence of training status on the physiological demands of beach tennis was also investigated in the present study. An important finding was that intermediate players spent more time at 91–100%HR_{max} zone than advanced players in doubles matches (22% *versus* 7% of total session's time). Additionally, advanced players presented higher handgrip strength compared to intermediate in all time points (pre, post 5′and 30′). Taken together, these results suggest that advanced players are physically more conditioned than intermediates, highlighting the importance of physical fitness development to reach higher levels of competition. And confirms that beach tennis is a great training method for both levels and that players at intermediate level can also obtain high cardiovascular stimulation during the match. Future studies should explore the long-term training responses of recreational players of different competition levels.

The RPE values assessed during the exercise are directly associated with the physiological demand (i.e., HR) of traditional aerobic exercises (Cádiz Gallardo et al., 2023). The absence of correlation between these two variables during singles and doubles beach tennis suggests that RPE scale should be used with caution to control the exercise intensity of recreational sports. In fact, participants of recreational sports have to focus on elements of the game and seem to perceive less their effort (Carpes et al., 2021), and the high level of enjoyment during the practice (i.e., 91% and 93% for singles and doubles, respectively) may also contribute to the reduced perceived effort during exercise.

Some limitations should also be considered to properly interpret our findings. The convenience sample recruited in the study may present a possible selection bias and may not represent all the population who practice beach tennis, preventing us from the generalization of our findings to other levels such as beginners or professionals' players. Besides, our sample consisted of women only, therefore limiting the generalization of our findings to the male population. The main strength of this study is its design, which included randomization and allocation concealment to reduce bias and ensure objective outcome assessment. We also employed standardized protocols and gold-standard measurements, such as HR monitors and accelerometers, to enhance the consistency and accuracy of the data collected.

5 Conclusion

Singles beach tennis resulted in higher physiological demands than doubles in women. Additionally, participants of different categories (intermediate *versus* advanced players) may respond differently in some but not all variables. Moreover, a reduced RPE during the matches and a high level of enjoyment after singles and doubles beach tennis were described by physically active women of different competition levels. These results may help coaches and beach tennis amateur players to better prepare for competitions, presenting beach tennis as an alternative to traditional exercises to improve physical fitness and cardiovascular health.

Beach tennis allows participants with chronic diseases or low physical and technical levels to practice the activity under the same rules, without the need to adapt the activity to make it attractive and effective for different populations. Other important advantages such as easy access to sand courts, the necessity of only 2–4 participants per match, allowing people of different age groups and levels of fitness/skills to play a sport that promotes pleasure and satisfaction during the activity, and lower risk of injury compared to traditional invasion sports (Kujala et al., 1995; Berardi et al., 2020), highlight the potential of beach tennis for both competitive and recreational purposes.

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 Institutional Review Board of Hospital de Clínicas de Porto Alegre - Brazil (grant number n°2021-0449). 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.

Author contributions

NJ: Investigation, Methodology, Writing–original draft, Writing–review and editing. LC: Formal Analysis, Methodology, Supervision, Writing–original draft, Writing–review and editing. LD: Investigation, Methodology, Writing–review and editing. RA: Methodology, Writing–review and editing. MM: Writing–review and editing, Writing–original draft. RF: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Project administration, 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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Distinct lipidomic profiles but similar improvements in aerobic capacity following sprint interval training versus moderate-intensity continuous training in male adolescents

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Background: Exercise-induced metabolic changes, especially lipidomic changes are generally associated with improvements in cardiovascular health. Despite numerous previous studies, the differences in lipidomic profile response to different types of exercise training remain unclear. This study aimed to investigate how two different exercise intensities affect aerobic capacity and serum lipidomic profiles in healthy adolescents.

Methods: Twenty-four healthy untrained male adolescents (13.08 ± 0.88 years old) were recruited and randomly assigned to moderate-intensity continuous training (MICT) group or sprint interval training (SIT) group to complete a specific training on a cycle ergometer for 6 weeks. Peak oxygen uptake (VO_2peak) and body composition were measured, and blood samples were collected for serum lipoproteins and lipidomic analysis. Anthropometric, VO_2peak, and serum biochemical data were analyzed using two-way repeated analysis of variance, while targeted lipidomic analysis was performed by principal component analysis and paired-sample *t*-test.

Results: VO_2peak significantly improved from 39.05 ± 8.17 to 47.52 ± 8.51 [$F(1, 44) = 14.75$, $p < 0.05$] for MICT and from 40.13 ± 6.37 to 48.42 ± 7.01 [$F(1, 44) = 14.75$, $p < 0.05$] for SIT. A total of 28 lipids in MICT and 5 lipids in SIT showed significant changes out of 276 identified lipids (FC > 1.5 or <1/1.5, FDR <0.05). In MICT, 21 lipids, including sphingolipid (SP) and phospholipid (PL), decreased, while 7 lipids increased. In SIT, all 5 lipids, which were free fatty acid (FFA), decreased.

Conclusion: Although both MICT and SIT induced similar and significant improvements in VO_2peak, serum lipid adaptations to the training differed.

The primary changes in serum lipidomic intermediates for both types of training were reductions; however, SIT affected FFA, while MICT predominantly influenced SPs and PLs.

KEYWORDS

lipidomic, aerobic capacity, moderate-intensity continuous training, sprint interval training, adolescents

1 Introduction

Cardiorespiratory fitness (CRF) among children and adolescents is a concern, as highlighted by a previous study involving 25.4 million individuals aged 6–19 years from 27 countries (Tomkinson and Olds, 2007). CRF is an important marker of cardiovascular health (Raghuveer et al., 2020) and higher level of CRF is related to reduced risks of cardiovascular diseases (Lavie et al., 2015; Keteyian et al., 2008; Al-Mallah et al., 2018; Chu et al., 2020). Cardiovascular disease typically manifests during late adulthood, but evidence suggests that it originates early in life (Mintjens et al., 2018). It is well known that lipoprotein particles and some lipidic intermediates are major contributors to the pathological process of cardiovascular diseases (Soppert et al., 2020). Exercise is one of the effective and cost-efficient strategies to favorably modify cardiovascular risk (Pressler et al., 2020). Both moderate-intensity continuous training (MICT) and sprint interval training (SIT) have been proven effective in improving CRF (Shepherd et al., 2013; Cocks et al., 2016; Scribbans et al., 2014). MICT corresponds to approximately 65%–70% of peak oxygen uptake (VO_2peak), while SIT is performed at or near 100% VO_2peak (Gist et al., 2014a; Gist et al., 2014b). The intensity and duration of specific exercises are crucial factors in mediating substrate utilization and intermediate metabolism. Low to moderate-intensity exercises, such as MICT, primarily stress fat oxidation, while high-intensity exercises like SIT place a greater load on carbohydrate metabolism. Although lipids are involved in different exercise-related changes, it is still unclear that the extent and specific types of lipids are involved regarding the exercise intensity, duration and frequency.

Many studies have been conducted on obese adults to investigate the metabolic adaptations induced by different exercise intensities (Keating et al., 2017). Previous studies revealed that acute MICT exerts a more pronounced effect on lipid metabolism than high-intensity interval training (HIIT) in both sedentary (Siopi et al., 2019) and trained male adults (Peake et al., 2014), particularly on serum monounsaturated free fatty acids (FFAs). Studies on the long-term effects of physical exercise on serum lipid metabolism have predominantly focused on serum lipoproteins, such as high-density lipoprotein cholesterol (HDL-C) and low-density lipoprotein cholesterol (LDL-C). Motiani (Motiani et al., 1985) reported that 2 weeks of MICT and SIT could enhance HDL and LDL subclasses, along with increased VO_2peak, with the improvement after SIT surpassing MICT. Shepherd et al. (2013) observed that 6-week MICT and SIT both effectively enhanced the net breakdown rate of intramuscular triglycerides and comparably improved insulin sensitivity in sedentary adult males. While the long-term MICT and SIT generally yield favorable outcomes for lipid metabolism in adults, their effects on adolescents remain controversial. A total of 14 studies have examined the effects of long-term physical exercise on lipid metabolism in adolescents, with seven of these studies observing significant positive changes, including reductions in LDL-C and enhancements in HDL-C, while the other six reported no significant changes, and one study even observed a negative effect on HDL-C (Stoedefalke, 2007). Therefore, it is speculated that although clinical lipid measures can reflect the benefits of exercise training to a certain degree, it is difficult to detail the variations in the types and quantities of various lipid species.

The lipidome comprises all biomolecules classified as lipids, including those with vast structural diversity and complexity (Merrill et al., 2013). Lipid intermediates regulate various essential functions in normal physiology (Kuo and Hla, 2024). Sphingolipid (SP), a lipid intermediate, is considered an essential constituent of the plasma membrane, where it interacts with cholesterol to form lipid rafts for signal transduction and protein sorting (Chaurasia et al., 2016). Ceramide (Cer), an important SP species involved in the formation of membrane domains (Carreira et al., 2015), can influence the formation and secretion of exosomes (Trajkovic et al., 2008). On the other hand, dysregulation of Cer can affect metabolic functions, and the accumulation of serum Cer levels is associated with the pathogenesis of obesity, insulin resistance, and cardiovascular diseases (Castro et al., 2014). Animal studies have shown that increased Cer levels lead to reduction in insulin action, probably by inhibiting protein kinase B (Hannun and Obeid, 2018). Attenuation of Cer synthesis enhances insulin signaling in diabetes (Kurek et al., 2014) and alleviates obesity-related cardiac dysfunction (Hodson et al., 2015). Some specific serum Cer species are considered as potential indicators of cardiometabolic diseases (Stith et al., 2019; Summers et al., 2019), such as Cer 18:0 and 18:1. Increases in these Cers have been identified as critical predictors of adverse cardiac outcomes in healthy individuals (Havulinna et al., 2016). Fatty acids are not only vital energy substrates for lipid oxidation, but also regulate gene expression, cellular signaling cascades, and arterial function under normal physiological conditions (Yu et al., 2024). However, elevated FFAs in plasma can contribute to obesity, non-alcoholic fatty liver disease, arterial hypertension, and atherosclerosis (Günenc et al., 2022; Savary et al., 2012). Specifically, an excess of saturated FFAs contributes to lipotoxicity (Engin, 2017), which in turn causes the dysfunction and apoptosis of vascular endothelial cells (Raja et al., 2022).

With development in lipidomic techniques combined with bioinformatic analysis, it is now possible to comprehensively study the serum lipidomic profiles in response to different intensities of exercise training. Using targeted lipidomic approach, we previously observed that 6 weeks of SIT on male adolescents induced significant changes in some lipidic intermediates that were strongly associated with alterations in inflammatory markers (Wang et al., 2023). As a continuation of this project, the present study applied MICT and SIT to two groups of male adolescents for 6 weeks to investigate metabolic adaptations

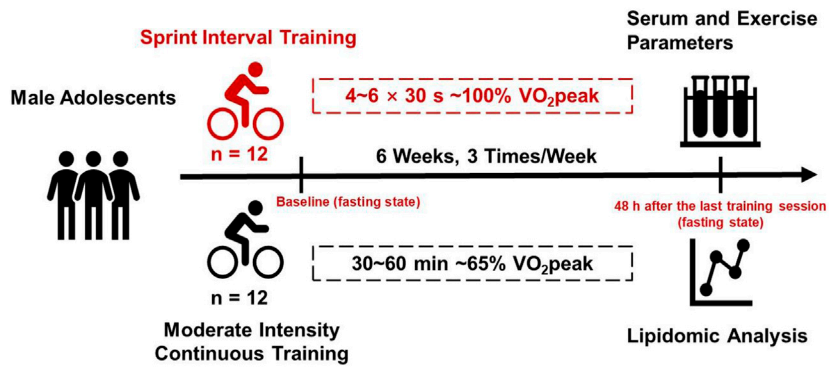

FIGURE 1
Experimental design of this study. Two groups of male adolescents took part in two different exercise training programs (SIT and MICT) for 6 weeks. Both before and 48 h after the last training session, VO_2peak was measured and blood samples were collected at fasting state from all the participants and analyzed for lipid metabolism using targeted lipidomic analysis.

in terms of serum lipidomic profiles and lipoproteins. By comparing the effects of these two distinct types of physical exercise training on lipidomic profiles in adolescents, we aimed to provide new insights into the physical exercise features in improving metabolic and cardiovascular fitness in adolescents.

2 Materials and methods

2.1 Study design

Two groups of male middle school students took part in two different exercise training programs for 6 weeks. Both before and 48 h after the last training session, VO_2peak was measured and blood samples were collected at fasting state from all the participants and analyzed for lipid metabolism using lipidomic analysis. The experimental design was illustrated in Figure 1.

2.2 Participants and grouping

Twenty-four healthy male middle school students were recruited through recruitment posters in the campus of a local boarding school. The inclusion criteria were 1) 12–14 years old male adolescents; 2) volunteer to take part in the research; 3) no regular physical training in the past year. Exclusion criteria were 1) history of skeletal muscle/joint injury or pain in the last 3 months; 2) history of exercise-related injuries; 3) chronic disease such as cardiovascular diseases, metabolic diseases, or psychiatric diseases; 4) medicine intake such as anti-inflammation or immunosuppression in the past 3 months. The 24 students were randomly and evenly assigned to either SIT group (n = 12) or MICT group (n = 12) to take part in a specific physical training program for 6 weeks.

Biometric data, including body mass, height, body mass index (BMI), blood samples, and muscle mass were collected from the students both before and 48 h after the last training session at around the same time of the days (8:00–10:00 a.m.). To minimize the impact of an acute training session on circulating metabolites, blood sample was collected 48 h after the completion of the training. The data was collected after overnight fast and refrained from caffeine or any extra nutritional supplementation. VO_2peak of the students was also measured. All the participants went to the same school and were provided with similar diets; thus, there was no additional dietary control. During the study, the students were instructed to keep their normal dietary habits but refrain from any alcohol or extra physical training. All the twenty-four participants completed all the tests and the whole training process.

The study was approved by the local ethic committee of the Sports Science Experimental Ethics Committee at Beijing Sport University (2020139H) and conducted according to the Declaration of Helsinki. All the participants provided their informed written consent by their p*arents* or guardians, and the privacy of the participants was guaranteed.

2.3 VO_2peak test

VO_2peak was measured on the Monark 839E (Sweden) using a metabolic gas analysis system (Cortex MetaMax 3B, Cortex, Isernhagen, Germany) for respiration analysis, as described previously (Wang et al., 2023). The participants took a standard warmed-up of 15 min at 25 W, 60 rpm, followed by a 3 min rest. The test started with an initial cycling loading of 25 W, increasing the load by 25 W every 2 min till exhaustion. Test was terminated when: 1) RER>1.1; 2) HR_{max} ≥ 175 b/min; 3) Peak oxygen uptake is maintained for 30s; 4) Rate of perceived exertion (RPE) ≥ 17.

2.4 Body composition measurement

A body composition analyzer Inbody 230 (InBody Co., LTD., Seoul South Korea) with bioelectrical impedance analysis technology was used for body composition measurement, including body mass, lean mass, fat mass, and BMI. The measurement was conducted at around 9:00 a.m. in the morning after overnight fasting and reframed from even water.

2.5 Blood sample collection

Blood samples were collected via venipuncture through the superficial forearm vein at approximately the same time of the days (8:00 a.m.) and into a tube containing a procoagulant (serum tubes). The samples were coagulated at room temperature for 30 min and then centrifuged at 3,000 rpm and 4°C for 10 min. Serum samples were extracted and frozen at −80°C for further tests. The serum was divided into two parts, one for standard clinical analysis and the other for targeted lipidomic analysis.

2.6 Serum lipoprotein profiles

Serum levels of lipoproteins, including total cholesterol, triglyceride, LDL-C, and HDL-C were measured according to routine clinical procedures. Serum concentrations of total cholesterol, triglyceride, LDL-C and HDL-C were determined using biochemical analyzer, Beckman Coulter AU2700 (Brea, CA, United States). Concentration of fasting blood glucose (FBG) was determined using glucose dehydrogenase assay, ACCU-CHEK Active Blood Glucose Meter (Roche Diabetes, Mannheim, Germany). All procedures followed the protocols of manufacturers.

2.7 Targeted lipidomic analysis

The procedures of targeted lipidomic analysis referred to our previous study (Wang et al., 2023; Zhang et al., 2023). Initially, lipids were extracted from the serum samples through simple protein precipitation using precooled isopropanol (IPA) at 4°C (Sarafian et al., 2014). Briefly, 95 μL of serum or a pooled quality control sample was spiked with 5 μL of lipid internal standard mixture, followed by the addition of 500 μL of pre-cooled IPA. The mixtures were vortexed for 1 min, placed at −20°C for 10 min, and then vortexed again for another 10 min. After incubating at 4°C for 2 h, the samples were centrifuged at 10,300 × g for 10 min at 4°C, and the supernatants were transferred to a 96-well plate for ultra-high performance liquid chromatography–tandem mass spectrometry analysis.

A semi-quantitative approach was employed using a Waters Iclass-Xevo TQ-S ultra-high-performance liquid chromatography–tandem mass spectrometry system (Waters, Milford, MA, United States) in electrospray ionization mode. Lipid classes were analyzed using a Waters Acquity UPLC BEH Amide column (1.7 μm, 2.1 × 100 mm). Mass spectrometry multi-reaction monitoring method was developed for the confirmation and quantitative evaluation of diverse lipids. Each lipid species had a dwell time of 3 ms. The source nitrogen gas temperature was set to 120°C with a flow rate of 150 L/h. The desolvation gas temperature was maintained at 500°C with a flow rate of 1000 L/h. Capillary voltage was adjusted to 2.8 kV for the positive mode and to 1.9 kV for the negative mode respectively. The autosampler operated at 4°C while the column compartment remained at a constant temperature of 45°C throughout the analysis duration. Solvent A and solvent B consisted of 95% and 50% acetonitrile, respectively, with 10 mM ammonium acetate. The mobile-phase gradient ranged from 0.1% to 20% B for 2 min, followed by an increase from 20% to 80% B for the next 3 min before re-equilibration for an additional 3 min, all at a flow rate of 0.6 mL/min. A volume of 1 μL was injected. System blanks consisting of 95 μL distilled water, 5 μL lipid internal standard mixture, and 500 μL IPA as well as process blanks (IPA) were initially injected thrice each to verify instrument conditions. Quality control samples were injected thrice prior to analyzing biological samples. This process was repeated every 12 samples. Lipidomic raw data processing was performed in TargeLynx in MassLynx v4.1 (Waters, Milford, MA, United States). Each peak was automatically integrated and validated and rectified manually as necessary. The retention time corresponding to internal standards of each lipid class confirmed accurate peak integration for lipids within the same class.

High-performance liquid chromatography (HPLC)-grade acetonitrile, methanol and IPA were purchased from Merck (99.9%; Merck KgaA, Darmstadt, Germany). HPLC-grade ammonium acetate (≤97%) and a lipid internal standard mixture (Avanti Splash Lipidomix™ lipid standards; Avanti Polar Lipids, Inc., Alabaster, AL, United States) containing d7-phosphatidylcholine (15:0/18:1), d7-phosphatidylethanolamine (15:0/18:1), d7-phosphatidylglycerol (15:0/18:1), d7-phosphatidylinositol (15:0/18:1), d7-lysophosphatidylcholines (15:0/18:1), d7-lysophosphatidylethanolamine (15:0/18:1), d7-diacylglycerols (15:0/18:1), d7-TAGs (15:0/18:1), d9-sphingomyelins (18:1), d7-cholesteryl esters (18:1), d7-monoacylglycerols (18:1), and d7-phosphatidic acids (15:0/18:1) were purchased from Sigma-Aldrich (United States).

2.8 Training protocol

The training protocols of MICT and SIT referred to a previous study (Macpherson et al., 2011). In brief, the MICT program included continuous cycling workouts on an ergometer (Monark 839E, Sweden) at a workload equal to 65% of VO_2peak, 3 days a week for 6 successive weeks. For the first 2 weeks, each training session was 30 min, and the third and fourth week, each training session was 45 min, and the last 2 weeks, each training session was 60 min.

The SIT program was consisted of 4-6 bouts of 30-second "all-out" cycling on an ergometer (Monark 884, Sweden) with a resistance of 7.5% of body weight (kg), 4-min resting intervals between two bouts. For the first 2 weeks, each training session included four bouts, the third and fourth week of five bouts, and the last 2 weeks of six bouts. The training frequency per week was the same as MICT.

For both training programs, each training session started with 10 min of warm-up and ended with 10 min cool-down on the ergometer at 60 rpm and 25 W. All training sessions were supervised by professional trainers.

2.9 Statistical analysis

Statistical analysis was performed using the SPSS 23.0 (SPSS Inc., Chicago, IL) and GraphPad Prism 8.3.0 (GraphPad Software, LLC) software packages. Anthropometric, biometric

TABLE 1 Biometric data before- and after 6-week physical training.

	MICT		SIT	
	Pre	Post	Pre	Post
Age (year)	13.33 ± 0.89	-	12.83 ± 0.83	-
Height (cm)	164.65 ± 5.25	165.68 ± 5.45	165.28 ± 9.49	166.35 ± 9.42
Weight (kg)	60.85 ± 17.87	61.89 ± 17.72	58.57 ± 13.54	59.80 ± 13.33
BMI (kg/m^2)	22.20 ± 5.35	22.30 ± 5.15	21.25 ± 3.69	21.43 ± 3.60
Muscle Mass (kg)	25.97 ± 4.55	25.98 ± 5.21	26.28 ± 5.66	27.23 ± 5.41
Fat Mass (kg)	13.50 ± 6.53	13.66 ± 7.68	12.26 ± 4.4	12.34 ± 5.33
VO_2peak (mL/min/kg)	39.05 ± 8.17	47.52 ± 8.51*	40.13 ± 6.37	48.42 ± 7.01*

Note: Data are presented as means ± SD (n = 12 per group).
*$p \leq 0.05$.

TABLE 2 Serum clinical measurements before- and after 6-week MICT and SIT.

	MICT		SIT	
	Pre	Post	Pre	Post
TCHO (mmol/L)	3.79 ± 0.50	3.97 ± 0.50	3.76 ± 0.69	3.87 ± 0.73
HDL-C (mmol/L)	1.49 ± 0.26	1.55 ± 0.28	1.49 ± 0.21	1.57 ± 0.26
LDL-C (mmol/L)	1.97 ± 0.32	2.02 ± 0.25	1.91 ± 0.57	2.05 ± 0.51
TAG (mmol/L)	1.06 ± 0.47	1.07 ± 0.49	0.87 ± 0.26	0.89 ± 0.29
FBG (mmol/L)	5.21 ± 0.36	4.99 ± 0.35	4.83 ± 0.29	5.02 ± 0.44

Note: Data are presented as means ± SD (n = 12 per group). TCHO, total cholesterol; HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; TAG, triacylglycerol; FBG, fasting blood glucose.

data, and serum biochemical measurements were analyzed with two-factor repeated analysis of variance (ANOVA), with group factor (SIT versus MICT) and time factor (pre-training versus post-training) and a significance level set at $p < 0.05$. Tukey's *post hoc* tests were used to analyze group differences. Generic format data were processed with one-factor statistical analysis using MetaboAnalyst 6.0 (https://www.metaboanalyst.ca/home.xhtml) to conduct principal component analysis (PCA) and generate volcano plots. Lipids with more than 50% missing values were deleted and the KNN (feature-wise) method was used to estimate missing values for the remaining lipids. All lipids were logarithmically transformed (base 10) and automatically scaled (centered on the mean and divided by the standard deviation of each variable) to approximate a normal distribution. Paired-sample *t*-test was used for lipidomic data analysis, with a significance level set at false discovery rate (FDR) adjustment (Benjamini–Hochberg) < 0.05, fold change (FC) of less than 1/1. 5 or greater than 1.5, and a 95% confidence interval (CI). Based on the results of significant improvements in VO_2peak ($p < 0.001$ and partial eta-square of 0.944 in time factor) in both groups, posteriori statistical power was calculated, with a power of 1 by G*Power (version 3.1.9.7) repeated measures ANOVA module. Thus, the sample size of 12 participants in each group was statistically proper.

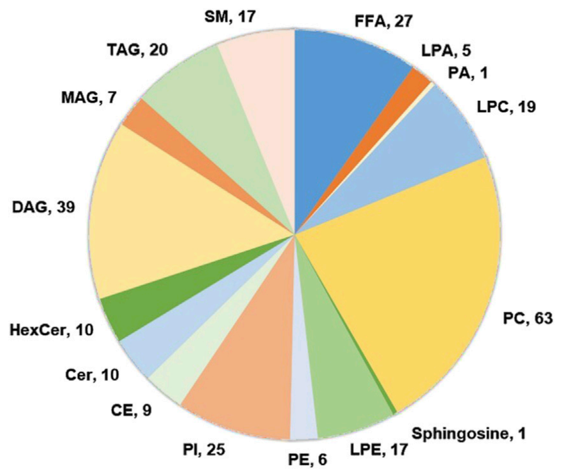

FIGURE 2
The overall class distribution of lipids measured in serum. FFA, free fatty acyl; LPA, lysophosphatidic acid; PA, phosphatidic acid; LPC, lysophosphatidylcholine; PC, phosphatidylcholine; LPE, lysophosphatidylethanolamine; PE, phosphatidylethanolamine; PI, phosphoinositide, CE, cholesteryl ester; Cer, Ceramide; HexCer, hexosylceramide; MAG, monoacylglycerol; DAG, diacylglycerol; TAG, triacylglycerol, SM, sphingomyelin.

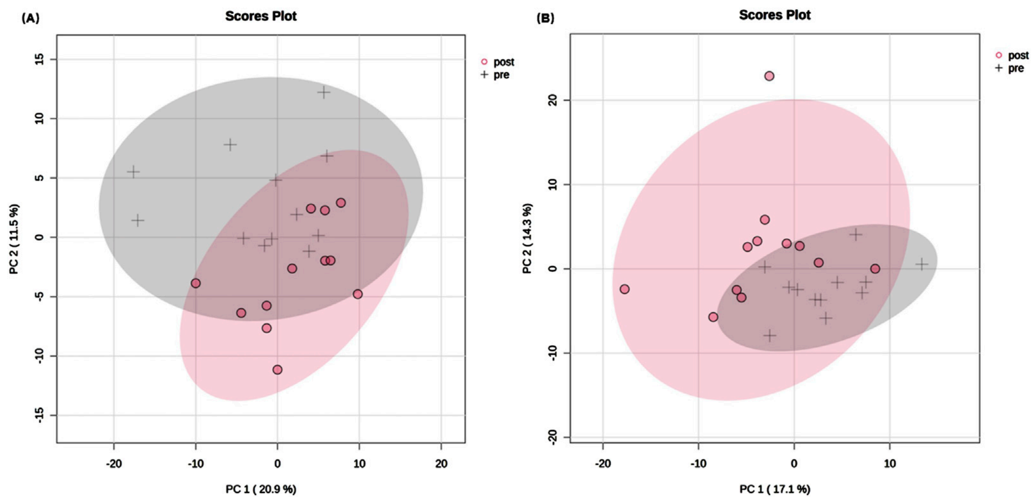

FIGURE 3
Principal component analysis plots of serum lipids pre- and post-training. **(A)** SIT, **(B)** MICT. In total, 276 lipids were identified in the serum samples of both MICT and SIT. Principal component analysis (PCA) revealed the degree of sample dispersion. PCA on 24 samples and 276 lipids resulted in a model with 2 principal components in each group, which accounted for 31.4% and 32.4% of the total variation after MICT and SIT, respectively. Only the first two principal components and their proportions are displayed in the scores plot. The grey cross represents pre-training sample and the red dot represents post-training sample. The shaded part indicates the 95% confidence interval range.

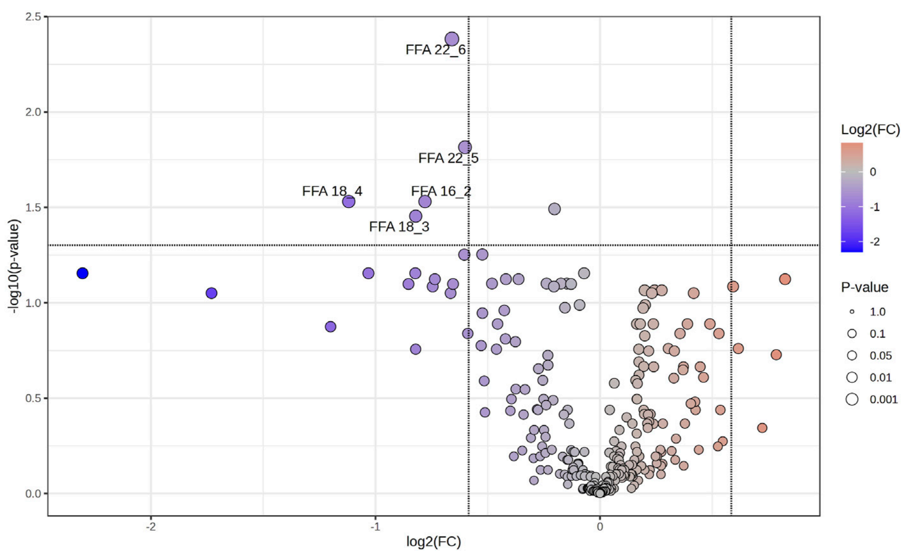

FIGURE 4
Volcano plot showing the significantly changed serum lipids in SIT. The 6 weeks of training induced significant decrease in 5 serum lipids (blue dots). The volcano plot summarizes both fold-change and *t*-test criteria for all lipids. Lipids with labeling indicate FC < 1/1.5 and FDR <0.05. Specifically, FFA 16: 2; 18:3; 18:4; 22:5; 22:6 were decreased.

3 Results

3.1 Physiological measurements

Results of biometric data and body composition as well as VO_2peak are presented in Table 1. Two-way repeated measures ANOVA revealed no significant differences in any of the anthropometric parameters at baseline or after the 6-week training between the two groups. However, analysis of VO_2peak results showed a significant effect of time [F (1, 44) = 14.75, $p < 0.001$], but no significant effect of group [F (1, 44) = 0.20, $p = 0.65$] or interaction between time and group [F (1, 44) = 0.0017, $p = 0.97$]. Tukey's multiple comparisons test showed that both MICT and SIT resulted in significant improvements in VO_2peak (from 39.05 ± 8.17 to 47.52 ± 8.51 for MICT and from 40.13 ± 6.37 to 48.42 ± 7.01 for SIT, $p < 0.05$ for both), with no significant difference between the groups.

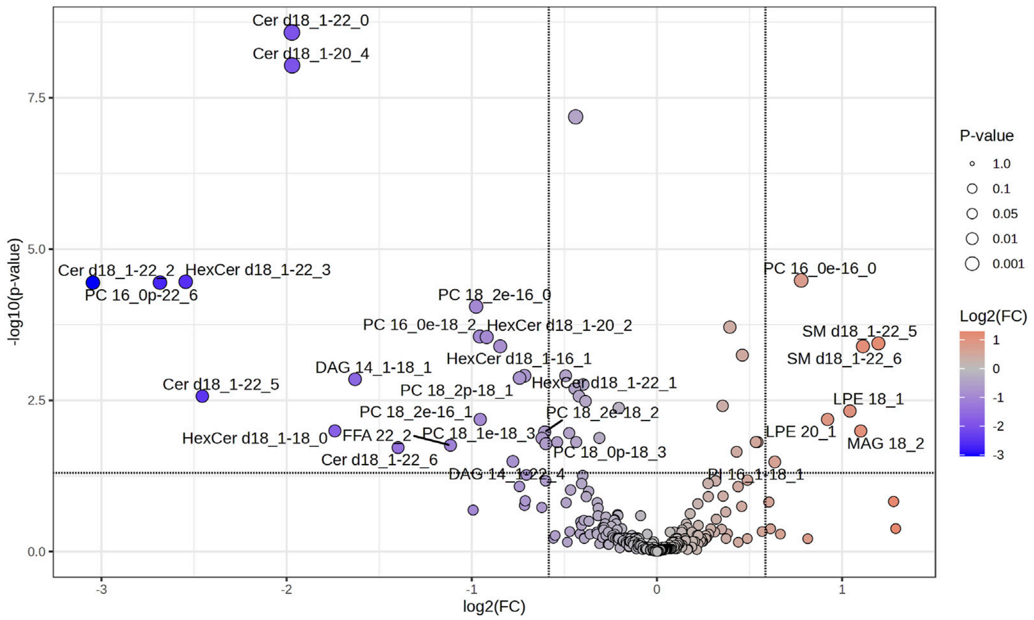

FIGURE 5
Volcano plot showing the significantly changed serum lipids in MICT. The 6 weeks of training induced significant changes in 28 serum lipids, of which 7 were increased (red dots) and 21 decreased (blue dots). Lipids with labeling indicate FC > 1.5 or <1/1.5, and FDR <0.05. Specifically, SM 18:1–22:5, SM 18:1–22:6, MAG 18:2, LPE 18:1, LPE 20:1, PC 16:0, and PI 16:0–18:0 were increased, while most PC, Cer and HexCer were decreased.

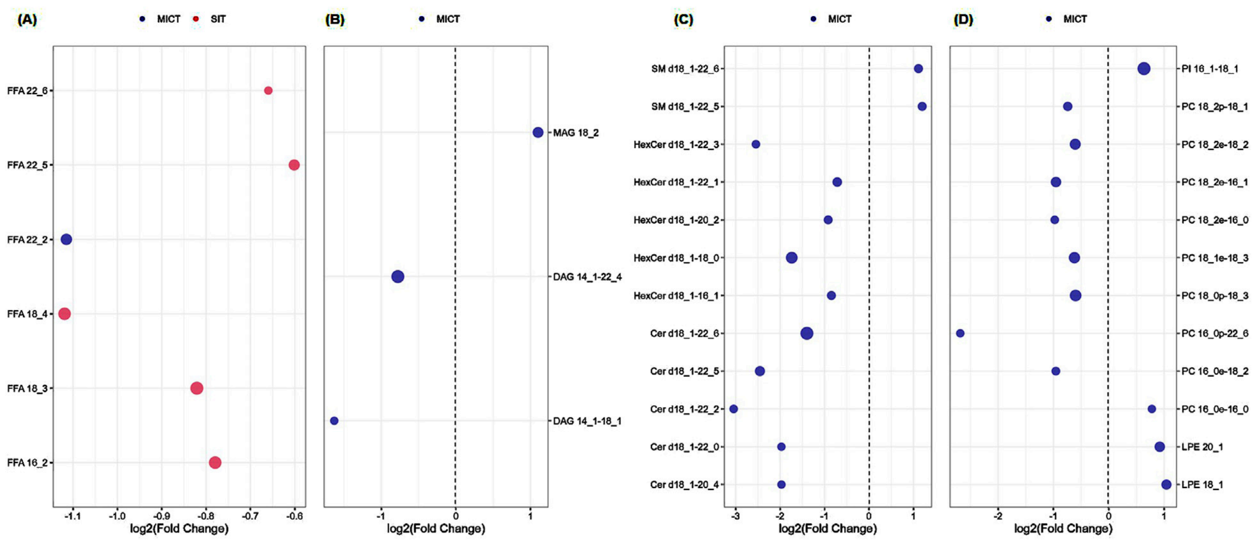

FIGURE 6
Comparison of the significantly changed serum lipids between MICT and SIT. Of the 28 and 5 lipids in MICT and SIT, respectively, four major lipid species were recognized including FFA **(A)**, glyceride (TG; **(B)**, sphingolipid (SP; **(C)**, and phospholipid (PL; **(D)**. **(A)** All the significantly changed FFAs in both SIT and MICT were decreased, and mostly in SIT (5 FFAs), only one FFA in MICT. **(B)** The significantly changed serum glycerides were only observed in MICT (totally three), of which MAG 18:2 was upregulated, and DAG 14:1–22:4 and 14:1–18:1 were downregulated. **(C)** The significantly changed serum SP was only observed in MICT, and both up- (totally two) and downregulated (totally 10). **(D)** The significantly changed serum phospholipids focused on MICT in which four were increased and eight were decreased. Note: Blue and red dots represent MICT and SIT groups, respectively. The dot size represents FDR-adjusted p value.

3.2 Serum lipoprotein profiles

Results of serum lipoprotein analysis are presented in Table 2. Two-way repeated measures ANOVA revealed that none of the parameters including total cholesterol, triglycerides, HDL-C, LDL-C, and FBG, was significantly changed within or between the two groups.

3.3 Serum lipidomic profiles

Using targeted lipidomic analyses, 276 lipids were identified in the serum samples of each group (Supplementary Table S1). The overall class distribution of lipids measured in serum was shown in Figure 2. PCA was conducted on the 276 lipids of each group to detect the degree of dispersion of serum samples taken pre- and post-training of SIT and MICT. For SIT, a model with the first two principal components of 20.9% and 11.5% was revealed, accounting for 32.4% of the total variation (Figure 3A). For MICT, a model with the first two principal components of 17.1% and 14.3% was revealed, accounting for 31.4% of the total variation (Figure 3B). For both SIT and MICT, PCA revealed a partial separation of the serum samples between pre- and post-training.

Volcano plots were further conducted to highlight the lipids species altered by the training. Paired-sample *t*-test was applied to the 276 lipids of each group to determine the relative changes of the lipids with significant levels being set at a FC < 1/1.5 or >1.5 (Supplementary Table S2). Among the 276 lipids identified in SIT, 5 lipids (2%) were significantly decreased after training (FDR <0.05, FC < 1/1.5; Figure 4), all of which were FFA (16:2; 18:3; 18:4; 22:5; 22:6). Of the 276 lipids identified in MICT, 28 lipids (10%) were significantly changed, with 7 increased (FDR <0.05, FC > 1.5) and 21 decreased (FDR <0.05, FC < 1/1.5; Figure 5). The increased lipids could be briefly classified into phosphoinositide (PI), phosphatidylcholine (PC) (16:0e-16:0), lysophosphatidylethanolamine (LPE), monoacylglycerol (MAG) (18:2), and sphingomyelin (SM), whereas the decreased lipids were categorized into Cer, hexosylceramide (HexCer), diacylglycerol (DAG), PC (16:0e-18:2; 16:0p-22:6; 18:0p-18:3; 18:1e-18:3; 18:2e-16:0; 18:2e-16:1; 18:2e-18:2; 18:2p-18:1), and FFA (22:2).

The significantly changed lipids in MICT and SIT were compared between the two groups (Figure 6). Of the 28 and 5 differential lipids in MICT and SIT, respectively, four major lipid species were recognized: FFA, glyceride (TG), sphingolipid, and phospholipid (PL). In SIT, all five differential lipids were FFA and all showed a decrease (Figure 6A). In MICT, the differential lipids were observed across all four categories, with the majority (24 out of 28) falling into the SP and PL categories (Figures 6C,D), where most (18 out of 24) showed a decrease. Furthermore, one lipid in the category of FFA was also decreased. In MICT, a total of seven lipids were increased, including MAG 18:2, SM d18:1–22:5, SM d18:1–22:6, PI 16:1–18:1, PC 16:0e-16:0, LPE 20:1, and LPE 18:1 (Figures 6B–D). Notably, none of the seven increased lipids in MICT belonged to the FFA category. In contrast, in SIT, all the decreased lipids were FFAs (Figure 6A), whereas in MICT, most of the decreased lipids were from the SP and PL categories (Figures 6C,D).

4 Discussion

The study for the first time compared serum lipidomic profiles after 6-week MICT with those of SIT and the results showed significant difference in serum lipid metabolism, despite both training inducing significant but similar improvement in VO_2peak. In general, both training induced significant reductions in serum lipids. Specifically, SIT had the greatest impact on FFA, while MICT primarily affected SP and PL.

4.1 Adaptations in aerobic capacity and serum lipoproteins

The present study reveals that both SIT and MICT markedly improved VO_2peak, without any significant difference between the groups. Several meta-analyses have clearly demonstrated that VO_2peak can be improved through continuous aerobic exercise at moderate intensities, as well as high-intensity interval training performed at workloads below or above VO_2peak. The enhancement of VO_2peak can be also influenced by various factors, such as an individual's initial VO_2peak level, the duration and frequency of training sessions, and genetic factors (Gist et al., 2014c; Milanović et al., 2015; Wen et al., 2019).

The study revealed that none of the serum lipoproteins presented significant change in either SIT or MICT, nor significant difference in any parameter between the two groups. The findings align with previous results showing a significant increase in VO_2peak but no significant change in serum lipid in overweight/obese men after a 6-week MICT and SIT (Petrick et al., 2021). As suggested, this might be due to the 6-week training period being too short to induce detectable changes in lipid metabolism (Mc et al., 2023). Anyhow, as all the adolescents in the study were healthy with normal serum lipid levels (Elkins et al., 2019), we could not expect the 6-week physical training to further improve or change these parameters. Given that the training programs are different and the adolescents are undergoing continuous growth and development with considerable variations in hormone levels (Chycki et al., 2019), the conventional clinical serum testing method is obviously not sensitive enough to detect the variations in serum lipoprotein adaptation to the different trainings.

4.2 SIT and adaptations in serum lipids

The 6-week SIT induced a significant reduction in 5 FFAs, which could be further classified as polyunsaturated fatty acid (PUFA). Physical training, especially endurance exercise, has been shown to enhance the ability of skeletal muscles to oxidize fatty acids, including medium- and long-chain fatty acids, for energy (Van Zyl et al., 1985; Holloszy and Coyle, 1984). Similarly, improved fat oxidation capacity has also been observed after long-term SIT (Bagley et al., 2016). Therefore, the significant reduction in serum FFAs might be attributed to enhanced utilization of FFAs in skeletal muscles.

The effects of physical training on PUFAs are less extensively studied compared to saturated fatty acids (SFAs) and monounsaturated fatty acids (MUFAs). Generally, studies have suggested that increased circulating SFAs and MUFAs, along with decreased PUFAs, were associated with unfavorable cardiometabolic outcomes in adults (Borges et al., 2020; Kaikkonen et al., 2021; Xiao et al., 2024; Jin et al., 2023). However, high serum levels of some specific FAs have also been linked to adverse health risks. For example, γ-linolenic acid (FFA 18:3) has been positively associated with obesity (Kaikkonen et al., 2021). Since physical training generally improves overall lipid metabolism and insulin sensitivity (Jeukendrup, 2010), and the serum lipidomic profile reflects the status of lipid metabolism, the significant reductions in serum PUFAs observed in this study were most likely due to the efficient utilization of these PUFAs.

4.3 MICT and adaptations in serum lipids

In MICT, a majority of significantly changed serum lipids were decreased (21 out of 28), particularly in the categories of SP (10 total) and PL (8 total). The ten serum lipids, belonging to SP, could be classified further into two categories: ceramides (Cers; totally 5) and hexosylceramides (HexCers; totally 5). Both Cer and HexCer have been shown to affect cell-signaling and metabolic pathways related with insulin resistance, hepatic steatosis, and major adverse cardiac events (Torretta et al., 2019).

The present study for the first time observed that MICT induced significant reduction in serum Cer levels (totally five Cers) in healthy adolescents. Similar results, however, have been observed in serum of obese and diabetic persons (Bergman et al., 2015; Kasumov et al., 2015) and in muscles of obese male humans (Shepherd et al., 2017) and mice (Mardare et al., 2016) after moderate-intensity exercise training. Cers are composed of sphingosine and a fatty acid and have multifunctional roles in many crucial cellular pathways, such as inflammatory processes and apoptosis (Gaggini et al., 2021). In addition, metabolites involved in ceramide metabolism were negatively associated with VO_2peak, fasting glucose concentrations and total LDLs, and VLDL cholesterol (Johnson Lawrence et al., 2018).

Five HexCers were significantly decreased in MICT. Currently, there is a lack of research on the impact of physical activity on serum HexCer levels. Nonetheless, hexosylceramides have been reported to be potential biomarkers for the diagnosis of epilepticus (Dickens et al., 2023), colorectal cancer (Elmallah et al., 2022) and chronic multiple sclerosis lesions (Podbielska et al., 2020). Moreover, higher level of HexCer d18:1–20:1 was significantly associated with elevated incidence of type 2 diabetes, probably mediated through β-cell dysfunction (Yun et al., 2020).

In MICT, eight serum lipids belonging to the PL category were significantly decreased, all of which were classified as phosphatidylcholine (PC). PC is the most abundant glycerophospholipids and comprises 40%–50% of total cellular phospholipids (van der Veen et al., 2017). PC plays a crucial role in various biological functions, including cell signaling, lipid metabolism, and the maintenance of cell membrane integrity (Cole et al., 2012). Circulating PC level has been suggested to be associated with running performance (Høeg et al., 2020), and PC supplementation might be beneficial for endurance athletes (Jäger et al., 2007; von Allwörden et al., 1993). Evidence has shown that both acute exercise and long-term exercise training could result in reduction in overall PC levels in muscle (Chorell et al., 2021) and serum (Lin et al., 2023; Beckner et al., 2023); yet compared with untrained persons, well-trained persons generally had relatively higher serum PCs levels (Pikó et al., 2021; Carayol et al., 2017).

PI forms a minor component of the cell membrane compared with other phosphatidylglycerides and is essential for diverse cellular processes, including signaling transduction, membrane dynamics and cellular trafficking (Phan et al., 2019; Viaud et al., 2016). In this study, only one PI, 16:1–18:1, was significantly increased in MICT. Currently, there are no reports on the effects of physical exercise on serum PI level; however, serum levels of PI have been reported to be significantly lower in obese-than in non-obese adults (Yin et al., 2021). Therefore, the increased PI 16:1–18:1 might reflect the beneficial effects of long-term MICT.

5 Limitations

It should be noted that the adolescents undergo critical periods of growth and development, which may compound the interpretation of the results based only on blood samples, rather than tissues. Given that serum circulating factors may directly regulate complex processes such as metabolism and the development of chronic diseases, our findings obtained from the blood samples reveal the dissimilar intensities of exercise-induced changes in lipidic metabolites. However, the deep physiological phenotyping of lipidomic still needs further research. Due to the high cost of the lipidomic analyses, the sample size was limited. Despite that we carefully controlled confounders such as diet, stress, sleep patterns, and study environment, future studies with nutrition and food intake tracking might be helpful to draw a more convincing conclusion.

Regarding the lipid class quantification, we acknowledge that there was potential technical limitation when quantitating the PI in the negative ion mode based on fatty acyl transitions, which may lead to potential distortion in summed PI abundances. This limitation may apply to other phospholipid classes quantification. Thus, it needs to be cautious in interpreting the data and comparing the data when different methodology is applied.

The results of the study are expected to provide potential guidelines for healthcare organizations in developing recommendations for adolescents. Additionally, the findings may offer insights into the characteristics of physical training that improve physical fitness in adolescents. However, as this study focused solely on male adolescents, future research on female adolescents is clearly necessary.

6 Conclusion

In summary, 6 weeks of MICT and SIT significantly improved aerobic capacity to a similar extent in adolescents. Although conventional serum clinical analysis showed no significant difference in any parameter such as total cholesterol, HDL-C, LDL-C, or triglycerides between the two groups, targeted lipidomic analysis indeed revealed significant differences in serum lipidomic profiles between SIT and MICT. Specifically, while both types of training predominantly reduced serum lipids, MICT induced changes in a broader range of lipid species, including HexCer, Cer, and PC, whereas SIT primarily affected FFA.

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.

Ethics statement

The studies involving humans were approved by the Sports Science Experimental Ethics Committee at Beijing Sport University (2020139H). 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

WS: Formal Analysis, Investigation, Methodology, Software, Visualization, Writing–original draft, Writing–review and editing. JL: Data curation, Investigation, Methodology, Project administration, Resources, Writing–review and editing. AW: Formal Analysis, Investigation, Methodology, Software, Visualization, Writing–review and editing. HZ: Data curation, Methodology, Resources, Software, Writing–review and editing. YS: Investigation, Writing–review and editing. ZY: Investigation, Writing–review and editing. MS: Writing–review and editing. J-GY: Validation, Writing–review and editing. LZ: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, 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.2025.1475391/full#supplementary-material

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Effects of 6-week sprint interval training compared to traditional training on the running performance of distance runners: a randomized controlled trail

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Introduction: This study aimed to compare the effects of sprint interval training *versus* traditional training on running performance in well-trained male distance runners.

Methods: Twenty male distance runners (VO2: 67.4 ± 4.5 mL/kg/min, personal best time for the 5000 m: 14′38″47 ± 00′23″46) were recruited and randomly assigned to either the intervention training (IT) group, which performed sprint interval training, or the control training (CT) group, which engaged in traditional long-distance training. Both groups completed their respective training regimens twice a week for 6 weeks. Measurements for VO2max, O2 cost, time to exhaustion (TTE), and running times for 100, 400, and 3000 m were taken before and after the intervention.

Results: The results indicated that the IT group showed significant improvements in TTE and running performance across 100, 400, and 3000 m (all $P < 0.01$), while the CT group only demonstrated improvements in 400 m time ($P < 0.01$). The IT group exhibited superior 3000 m performance compared to the CT group ($P < 0.01$). Analysis of effect sizes revealed small to moderate improvements in physiological and performance measures for the IT group, with VO2max showing a small effect size of 0.43, O2 cost a moderate effect size of 0.65, and TTE a moderate effect size of 0.77.

Conclusion: These findings suggest that sprint interval training may offer superior benefits for enhancing running performance of well-trained male distance runners, particularly in time to exhaustion and middle-to long-distance events, compared to traditional longdistance training.

KEYWORDS

sprint interval training, VO2max, running performance, distance runners, endurance

1 Introduction

Interval training is a structured form of exercise that alternates between high-intensity bursts of activity and periods of rest or lower intensity. This training method is designed to enhance both aerobic and anaerobic fitness by pushing the body to work at maximum effort during the intense phases, followed by recovery periods that allow for partial recuperation (Gist et al., 2014; Gibala, 2021). Research has demonstrated that interval training can induce physiological adaptations comparable to those achieved through traditional endurance or strength training, effectively combining the benefits of both (Burgomaster et al., 2008; MacInnis and Gibala, 2017; Boullosa et al., 2022). For example, a study by McRae et al. compared the effects of whole-body interval training with traditional endurance training in active females, revealing that interval training offered significant additional benefits in enhancing aerobic fitness and muscular endurance (McRae et al., 2012). Interval training is designed to surpass the adaptations achieved through traditional long-duration, steady-intensity training by incorporating short bursts of high-intensity effort followed by recovery periods. These high-intensity intervals push the body to work at or near maximum effort, stimulating both aerobic and anaerobic systems more effectively than continuous steady-state exercise. Recent studies have demonstrated that this training method not only improves cardiovascular endurance and aerobic capacity (Milanović et al., 2015), but also enhances muscle oxidative capacity and metabolic flexibility, leading to greater overall performance (Hood et al., 2011; Callahan et al., 2021). Furthermore, interval training allows for greater time efficiency while yielding comparable or superior benefits to longer, moderate-intensity training protocols (Billat et al., 2000; Gillen and Gibala, 2014). This is particularly relevant for elite endurance athletes, who typically engage in extensive training and therefore need to effectively manage their total training duration while enhancing training efficiency. Research indicates that interval training has become a central component of training for athletes in endurance sports such as middle-distance running, long-distance swimming, and cycling (Hellard et al., 2019; Leo et al., 2020; Casado et al., 2022). Thus, given its proven benefits, interval training, particularly sprint interval training (SIT), has become an essential component of training for endurance athletes, as it offers a time-efficient alternative to traditional endurance training while enhancing both aerobic and muscular performance.

Sprint interval training (SIT) is a specialized form of high-intensity exercise that involves short bursts of maximum effort followed by longer rest periods. This training method is characterized by short bursts of activity and extended recovery (Mølmen and Rønnestad, 2024; Usher and Babraj, 2024). The sprints are repeated multiple times and the recovery period is interspersed between every two sprints. SIT offers the same benefits as other interval training methods, enhancing aerobic capacity and muscular performance when implemented in a well-structured training protocol (Skovgaard et al., 2018). For instance, a study by Gibala et al. investigated the effects of low-volume SIT compared to high-volume endurance training in active males, revealing similar improvements in muscle oxidative capacity, muscle buffering capacity, and muscle glycogen content for both training methods (Gibala et al., 2006). SIT is particularly beneficial for endurance athletes, and developing targeted SIT protocols is essential for effective training management among elite athletes. Research demonstrates that multiple all-out sprints lasting no more than 40 s, with recovery periods 5 times longer than the sprint duration, can significantly improve the performance of endurance athletes (Bangsbo, 2015).

Additionally, training intensity—specifically, all-out sprints of varying durations—emerges as a key loading parameter in SIT (Boullosa et al., 2022). The most commonly used SIT protocol involves performing 4 to 6 repetitions of 30-s all-out sprints, with numerous studies confirming the positive effects of this approach (Vollaard and Metcalfe, 2017; Vollaard et al., 2017). However, despite the proven value of SIT, existing research is still insufficient. There is relatively little research on other parameters of the SIT protocol, such as repetition rate, training frequency, and training period (Vollaard and Metcalfe, 2017). Meanwhile, most SIT studies have been conducted in controlled laboratory environments, typically using equipment such as power bicycles or treadmills, which are both expensive and time-consuming, and not conducive to simultaneous training of multiple subjects (Astorino et al., 2012; Jakeman et al., 2012; Willoughby et al., 2016). As a result, there is a notable lack of field-based studies that assess the efficacy of SIT in real-world settings, with only a few exceptions (Koral et al., 2018), highlighting the need for further research in this area to better understand the practical implications of SIT for athletes in natural training environments.

Therefore, the primary aim of this study is to compare the effects of a carefully designed SIT protocol with traditional endurance training methods on the aerobic capacity and athletic performance of well-trained long-distance runners. This protocol conducts onsite and includes parameters such as sprint repetition frequency, training frequency, training cycle, sprint duration, and interval time. The hypothesis of this study posits that 12 sessions of maximum sprint training—each consisting of 10 sets of 30 s with 3.5 min of rest in between—over a period of 6 weeks, can significantly improve the VO2max, O2 cost (an index of running economy), time to exhaustion (TTE), and timed running performance in the 100, 400, and 3,000 m for long-distance runners.

2 Methods

2.1 Subjects

Twenty well-trained male distance runners were recruited for this study, with a mean VO2 max of 67.4 ± 4.5 mL/kg/min and an official personal best time for the 5000 m of 14′38″47 ± 00′23″46. The subjects were randomly divided into two groups using computer randomization: the intervention training group (IT group, n = 10, age: 19 ± 1 year, height: 173.3 ± 5.5 cm, weight: 59.5 ± 4.4 kg) and the control training group (CT group, n = 10, age: 20 ± 1 year, height: 175.8 ± 6.4 cm, weight: 58.6 ± 6.3 kg). Before the experiment commenced, the purpose of the study, its procedures, and poten-tial risks were thoroughly explained to all subjects, and written informed consent was obtained. The study was performed in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of Sports Science Experiment (TJUS2024-046).

2.2 Research design

A randomized controlled trail (RCT) was conducted for this study. Subjects in both the IT group and the CT group performed high-intensity training twice per week for 6 weeks (12 sessions in total). The IT group engaged in sprint interval training for their high-intensity sessions, while the CT group participated in traditional long-distance training. Before the intervention, All subjects followed identical training regiments. Both groups engaged in regular aerobic endurance training, consisting of moderate-intensity jogging for 40–60 min, 4 days a week. Additionally, both groups took 1 day off per week. On the remaining days of the week, both the IT group and the CT groupjogged for 40–60 min on 4 days and took 1 day off. Before the tests, subjects were instructed to rest for at least 24 h after their last training session to minimize fatigue and ensure consistent test results. Post-intervention testing was performed 48 h following the final training session to allow for adequate recovery and avoid residual fatigue from the training sessions. Subjects were provided with general dietary guidelines before the test sessions to ensure that nutritional factors did not influence the results. They were instructed to consume a balanced meal consisting of complex carbohydrates, lean protein, and vegetables at least 3–4 h before each test session. Additionally, participants were advised to avoid heavy meals or caffeine intake within 2 h of the test. Before and after the 6-week training periods, VO2max, O2 cost, and TTE during submaximal running were assessed using a laboratory treadmill test. Additionally, sprinting times for 100 and 400 m, as well as the 3,000 m running time, were measured through field tests. The tests were scheduled before the intervention (baseline tests) and after the intervention (post-test) at specific intervals. Baseline tests were conducted within 1–2 days of the beginning of the intervention. Post-intervention tests were conducted 48 h after the final training session. For the field tests, the 100m and 400 m sprint tests were conducted on 1 day, and the 3000 m running test was conducted on a separate day within 5 days following the last training session.

2.3 Training protocols

The IT protocol was designed based on the research of Skovgaard et al. (Skovgaard et al., 2018). The protocol consisted of 10 sets of 30-s maximal sprint runs, with a 3.5-min recovery period between sets. During the recovery periods, subjects' heart rates were maintained below 70% of their maximum. The starting workload for the first set was determined based on each subject's average workload from their 100-m performance. Within each training session, the intensity was gradually reduced from interval to interval, as sustaining the high intensity of a 30-s maximal sprint is not feasible for 10 consecutive bouts. The average interval intensity during a training session was approximately 175% of the maximal aerobic speed (MAS). During all intervals, each subject received one-on-one follow-up and verbal encouragement to ensure maximum intensity during each sprint. At the end of each session, a 3-min cooldown was added, with an intensity corresponding to ≤70% of HRmax, resulting in a total duration of 50 min. Additionally, the CT protocol included various traditional endurance training programs over 12 sessions, was based on established endurance training methods that focus on improving aerobic capacity through sustained, moderate-intensity exercise, featuring 10-km running, 2 repetitions of 3000-m running, three repetitions of 2000-m running, 4 repetitions of 1500-m running, five repetitions of 1000-m running, and 12 repetitions of 400-m running (Campos et al., 2022). This protocol aimed to simulate a more traditional long-distance running approach commonly used by endurance athletes. The intensity of these sessions was prescribed based on a heart rate zone corresponding to 70%–85% of each subject's maximum heart rate, which is typical for endurance training aimed at improving aerobic capacity. Each of these program was conducted twice.

2.4 Testing procedure and measures

2.4.1 Treadmill running tests

VO2max, O2 cost, and TTE were measured using step and graded exercise tests conducted on a treadmill. The tests began with a 5-min warm-up at a speed of 200 m/min. Following the warm-up, subjects engaged in the step exercise test, which consisted of running at five different step speeds (230, 250, 270, 290, and 310 m/min) on a flat treadmill (0% slope). Each step lasted 3 min, followed by a 1-min rest period between steps. This approach has been shown to effectively reflect the running performance of long-distance runners (Tanji et al., 2017). After completing the step exercise test, subjects underwent a 3-min rest period before performing the graded exercise test. This test initiated at a speed of 290 m/min, with an increase of 10 m/min each minute (290, 300, 310, 320, 330, 340, 350, 360, 370 m/min, etc.), allowing subjects to reach their speed until exhaustion on the flat treadmill. During both exercise tests, a respiratory gas analyzer (AE-310S; Minato Medical Science), calibrated with a standard injector and precision reference gases prior to each test, was used to measure the expired levels of O2 and CO2 for each subject. VO2max was defined as the highest oxygen intake of the two tests. O2 cost was calculated as the average oxygen uptake during the final 60 s of steps 4 (290 m/min) and 5 (310 m/min) of the step exercise test. TTE was recorded as the duration of the graded exercise test. These treadmill running tests were conducted both before and after the intervention, with post-intervention tests per-formed within 2 days following the final session of the intervention.

2.4.2 Field track running tests

The 100-m and 400-m running tests were conducted on an all-weather track utilizing a wireless phototube timing system (Brower TCi Timing Systems, HaB International Ltd.). The times

TABLE 1 Intra-group comparisons of variables before (pre-test) and after (post-test) training program.

Variables	IT group (n = 10)				CT group (n = 10)			
	Pre	Post	Mean changes	P-values	Pre	Post	Mean changes	P-values
VO_2 max	4.00 ± 0.31	4.17 ± 0.34	0.17 ± 0.23	0.055	4.03 ± 0.23	4.04 ± 0.25	0.01 ± 0.03	0.366
O_2 cost	3.34 ± 0.09	3.22 ± 0.15	−0.11 ± 0.18	0.077	3.32 ± 0.10	3.30 ± 0.06	−0.02 ± 0.05	0.365
TTE	8.30 ± 0.22	8.42 ± 0.18**	0.12 ± 0.08	<0.01	8.27 ± 0.23	8.26 ± 0.23	−0.01 ± 0.02	0.423
100 m-time	13.49 ± 0.75	13.29 ± 0.68**	−0.20 ± 0.10	<0.01	13.22 ± 0.67	13.23 ± 0.69	0.01 ± 0.02	0.471
400 m-time	56.10 ± 2.12	55.44 ± 2.14**	−0.67 ± 0.50	<0.01	55.51 ± 3.28	55.23 ± 3.21**	−0.28 ± 0.19	<0.01
3000 m-time	527.48 ± 4.44	522.61 ± 3.52**	−4.86 ± 1.36	<0.01	528.23 ± 4.12	527.93 ± 3.44	−0.30 ± 1.12	0.414

*$p < 0.05$; **$p < 0.01$; VO2 max, maximal oxygen uptake; O2 cost, Oxygen Cost; TTE, time to exhaustion.

TABLE 2 Pairwise comparisons between groups of variables before (pre-test) and after (post-test) training program.

Variables	Pre-test			Post-test		
	Mean changes	P-values	Cohen's d	Mean changes	P-values	Cohen's d
VO_2 max	−0.03 ± 0.12	0.803	0.11	0.13 ± 0.13	0.353	0.43
O_2 cost	0.02 ± 0.04	0.619	0.23	−0.08 ± 0.05	0.162	0.65
TTE	0.03 ± 0.10	0.762	0.14	0.16 ± 0.09	0.102	0.77
100 m-time	0.27 ± 0.32	0.400	0.39	0.07 ± 0.31	0.834	0.09
400 m-time	0.59 ± 1.23	0.639	0.21	0.21 ± 1.22	0.867	0.08
3000 m-time	−0.75 ± 1.91	0.699	0.18	−5.31 ± 1.56**	<0.01	1.53

*$p < 0.05$; **$p < 0.01$; VO2 max, maximal oxygen uptake; O2 cost, Oxygen Cost; TTE, time to exhaustion.

were recorded between two timing gates, with a starting cue provided by the tester. During the tests, subjects were required to wear spikes and complete two 100-m sprints from a standing position, following a warm-up. A 5-min rest period was taken between the two sprints. The shorter of the two times was used for analyses. Subsequently, after a 10-min rest period, subjects proceeded to perform a 400-m sprint test from a standing start. To minimize the influence of external factors such as wind speed, we implemented a rigorous testing protocol that ensured all 20 subjects were tested within a 3-h timeframe. Additionally, the 3000-m timed run was conducted on the same all-weather track. To prevent subjects from adjusting their pace during the test, each subject completed the run individually. A tester used a stopwatch to record lap times at 1,000 and 2000 m, as well as the final completion time. All tests were conducted both before and after the intervention, with the post-intervention assessments for the 100-m and 400-m sprints taking place on the third day following the final session, and the post-intervention 3000-m run conducted within 5 days thereafter.

2.5 Statistical analyses

The test data were analyzed using IBM SPSS statistical software package (version 24.0). Descriptive statistics are presented as means ± standard deviation (M±SD). The normality of all variables was confirmed using the Shapiro-Wilk test. Inter-group dif-ferences between the IT group and CT group across various indicators (VO2max, O2 cost, TTE, 100 m-time, 400 m-time, and 3000 m-time) were evaluated using independent t-tests, while intra-group differences were assessed using paired t-tests, with Bonferroni adjustment applied for multiple comparisons. Cohen's d was used to assess the effect size (ES) according to the following thresholds: <0.2 as trivial, 0.2–0.6 as small, 0.6–1.2 as moderate, 1.2–2.0 as large, and >2.0 as very large (Hopkins et al., 2009). The level of significance was set at $P < 0.05$ for all tests.

3 Results

The M ± SDs and performance changes are presented in Tables 1, 2. The Shapiro-Wilk tests confirmed that all data followed a normal distribution. Intra-group comparisons revealed that the IT group demonstrated significant improvements in TTE and performance for the 100m, 400m, 3000 m running following training, all with statistical significance ($P < 0.01$). In contrast, VO2max and O2 cost did not exhibit sta-tistically significant changes in the IT group, with P-values of 0.055 and 0.077, respectively. Within the CT group, only the 400 m time showed a significant change com-pared to pre-training ($P < 0.01$), while no statistically significant differences were ob-served found in the other variables (Table 1).

Baseline comparisons revealed no significant differences in any variables between the IT and CT groups prior to the training program (Table 2). Post-training inter-group comparisons indicated that the IT group achieved a significant reduction in 3000 m time compared to the CT group ($P < 0.01$). However, no statistically significant differ-ences were found for VO2max, O2 cost, TTE, 100 m time, or 400 m time. Further analysis of ESs revealed that VO2max had a small ES (0.43), while O2 cost and TTE have moderate ESs (0.65 and 0.77, respectively). The 3000 m time had a large ES (1.53) (Table 2).

4 Discussion

This study demonstrated that SIT, consisting of 10 sets of 30-s maximum sprint runs with a 3.5-min recovery period, can significantly enhance the TTE of male long-distance runners, as well as their performance in the 100m, 400m, and 3000 m events. In comparison to CT, SIT shows a small effect size on VO2max, a moderate effect size on O2 cost and TTE, and a large effect size on 3000 m performance. These findings contribute to the expanding body of literature that supports SIT as an effective training modality for endurance athletes.

Our study used VO2max, O2 cost, and TTE to assess the athletic performance and endurance of long-distance runners. VO2max is widely regarded as the best indicator of cardiovascular endurance (Jansson and Kaijser, 1987; Millet et al., 2023), and O2 cost is used to evaluate exercise economy (Scheer et al., 2018). VO2max represents the maximal capacity of an individual's cardiovascular system to transport and utilize oxygen during intense exercise. It is a crucial determinant of aerobic endurance, as higher VO2max values are associated with improved performance in endurance-based events, such as long-distance running (Broxterman et al., 2024). Lower O2 cost indicates greater exercise economy, reflecting the efficiency with which the body utilizes oxygen at a given intensity, thereby reducing energy expenditure and enhancing performance over prolonged periods (Jones et al., 2021). In this study, although no significant improvements in VO2max and O2 cost were observed with high-intensity SIT, which contradicts previous research (Buchheit and Laursen, 2013; Thurlow et al., 2024), the results with P-values close to 0.05 suggest a potential effect may exist. This lack of significant improvement could be attributed to several factors, including the short duration of the training program and the possibility that SIT might preferentially target other physiological adaptations, such as muscle oxidative capacity or neuromuscular function, which may not immediately impact VO2max and O2 cost. Additionally, the intergroup differences in this study revealed that the VO2max of the IT group was higher than that of the CT group, and the O2 cost was lower in the IT group, indicating an advantage in cardiovascular endurance and exercise economy for the IT group. This trend aligns with the notion that high-intensity interval training can enhance muscle oxidative capacity, which indirectly improves VO2max, although these changes may not be immediately observable in a short intervention (Wang and Wang, 2024). While the statistical differences did not achieve significance, the small to medium effect sizes underscore the need for further research. Studies comparing SIT to traditional training have shown conflicting results regarding VO2max and O2 cost. Some studies suggest that while SIT may lead to improvements in other performance markers such as TTE, it may not always produce the same magnitude of change in VO2max or O2 cost compared to traditional endurance training (Buchheit and Laursen, 2013). However, the current study's small sample size and short intervention period may limit the detection of such changes, suggesting that longer training periods or larger sample sizes might be necessary for clearer insights. Future studies could consider increasing the sample size or extending the intervention duration to obtain more definitive results.

For TTE, it is a key metric in exercise physiology that measures an individual's endurance capacity (Amann et al., 2008). TTE evaluates aerobic capacity, muscular endurance, and overall fitness; a longer TTE suggests better endurance performance (Chen et al., 2022; Sitko et al., 2022). In this study, the significant increase in TTE was observed, suggesting that SIT may effectively enhance both muscular endurance and aerobic capacity in long-distance runners. These findings are consistent with previous studies comparing SIT to traditional endurance training, which also found that SIT can significantly improve TTE, potentially by promoting both aerobic and anaerobic adaptations (Buchheit and Laursen, 2013). However, it is important to note that while SIT has demonstrated improvements in TTE, its effects may vary depending on the training parameters, such as work-to-rest ratios and the intensity of the sprints. For example, shorter recovery periods may yield more pronounced anaerobic adaptations, while longer recovery periods, as used in this study, may favor aerobic improvements (MacInnis and Gibala, 2017). The mechanism behind this improvement could be attributed to various physiological adaptations, including increased muscle oxidative capacity and enhanced neuromuscular function (Burgomaster et al., 2005; Little et al., 2010), both of which are essential for sustaining prolonged exercise efforts. This supports the view that SIT may enhance aerobic capacity through increased mitochondrial density and oxidative enzyme activity in the muscles, allowing athletes to sustain higher intensities for longer durations. Specifically, SIT can enhance the ability of muscles to produce more energy through aerobic pathways, allowing athletes to maintain high-intensity exercise for extended periods and effectively delay the onset of fatigue (Burgomaster et al., 2005; Gibala et al., 2006; Little et al., 2010; Gibala et al., 2012; MacInnis and Gibala, 2017; Gonzalez Rojas et al., 2024). Additionally, SIT can improve the coordination between the nervous system and muscles, increasing the efficiency with which the nervous system activates the muscles involved in running (Bertschinger et al., 2020), which helps athletes achieve better performance in endurance events.

Another critical outcome of this study is the significant enhancement in running performance across various distances. The improvements observed in the 100m and 400 m events indicate that SIT not only enhances anaerobic capacity but also positively influences speed and power output. For long-distance runners, speed and power output are essential components of overall performance, as they contribute to the ability to sustain fast paces over long periods and recover from surges in race intensity (Beattie et al., 2014). In particular, speed helps runners maintain competitive paces during race segments, while power output enables better acceleration and efficient use of energy, which are critical when running up hills or during sprint finishes (Bazyler et al., 2015). These results align with previous research high-lighting the benefits of high-intensity training for neuromuscular adaptations and sprint mechanics (Buchheit and Laursen, 2013). Specifically, these neuromuscular adaptations include increased muscle fiber recruitment and faster muscle contraction rates, which help athletes maintain more efficient movement patterns, reduce energy expenditure, and enhance sprint performance (Du and Sim, 2021; Van der Stede et al., 2024). By improving neuromuscular coordination, SIT helps athletes produce greater force with less effort, which improves running economy and reduces fatigue. The sprint mechanics associated with SIT suggest that it improves the anaerobic energy systems critical for 100m and 400 m sprints. By en-hancing the muscles' ability to generate energy anaerobically, SIT helps athletes manage lactate accumulation more effectively and delay the onset of fatigue (Fiorenza et al., 2019; Thom et al., 2020).

In this study, the significant improvements in the 3000 m event indicate that SIT can also enhance aerobic performance. This is particularly significant, as the 3000 m race requires a balance between both aerobic and anaerobic energy systems. These results align with several studies that have compared the effects of SIT *versus* traditional endurance training on long-distance performance. Research has shown that, while traditional endurance training primarily enhances aerobic capacity and improves performance in sustained, moderate-intensity events, SIT may offer additional benefits by improving both anaerobic capacity and overall race performance, especially in middle- and long-distance events (Buchheit and Laursen, 2013). The physiological adaptations associated with SIT, such as enhanced muscle oxidative capacity and improved lactate threshold, likely play a crucial role in maintaining higher intensities over extended periods (MacInnis and Gibala, 2017). Additionally, SIT's ability to improve neuromuscular function and running economy has been suggested to allow athletes to maintain faster paces and recover more effectively from surges in pace, which is crucial for 3000 m races that require both aerobic endurance and intermittent anaerobic efforts (Laursen and Jenkins, 2002). This interval format ensures that athletes can sustain anaerobic efforts during the sprints while still benefiting from the aerobic adaptations that occur during the recovery phase between bouts of high-intensity exercise (Jones and Carter, 2000). This recovery period is also sufficient to prevent complete depletion of phosphocreatine stores, allowing athletes to perform repeated high-intensity efforts with reduced fatigue compared to continuous endurance training (Bishop et al., 2011).

This study has several limitations. First, the sample size was relatively small, consisting of only 20 participants, which may increase the influence of individual variations on the results. To enhance the robustness and generalizability of the findings, future research should aim to include a larger sample. Additionally, the study population was limited in terms of gender and age range, as all participants were male and within a specific age group (e.g., 18–30 years). This homogeneity may reduce the generalizability of the results to other populations, such as female athletes or older individuals. Future studies should consider including a more diverse sample, encompassing both genders and a wider age range, to determine if the effects of SIT on endurance performance differ across these variables. Second, the duration of the intervention was limited to 6 weeks. Although this timeframe is adequate for observing short-term effects, it is insufficient for evaluating the long-term impact of SIT on ath-letic performance. Furthermore, the level of trainability of participants, which may vary depending on their training history and experience, was not considered. This variability could influence the responsiveness to SIT. In future studies, the training background of participants should be documented and analyzed to assess how different levels of baseline fitness might affect the outcomes of SIT. Future studies could benefit from extending the intervention period to better assess the enduring effects of the training regimen.

5 Conclusion

Our findings suggest that SIT is a time-efficient and effective alternative to traditional continuous training for long-distance runners. As athletes seek to optimize training while minimizing time commitment, SIT could be a practical addition to training programs. For coaches and athletes, it is recommended to incorporate two to three sessions of SIT per week, focusing on high-intensity sprints followed by adequate recovery, as a way to complement traditional endurance training. This approach can enhance both aerobic and anaerobic capacity while reducing the overall training time required. Future research should explore the long-term effects of SIT on performance and its underlying physiological mechanisms, as well as the optimal integra-tion of SIT with traditional endurance training. Additionally, it would be beneficial to investigate how SIT can be tailored to different athlete populations, such as those with varying fitness levels or training backgrounds, to maximize its impact. Overall, our results support the inclusion of SIT as a valuable tool for enhancing performance in male long-distance runners.

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 Tianjin University of Sport. 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.

Author contributions

KJ: Writing–original draft, Conceptualization, Data curation, Formal Analysis, Investigation. MC: Writing–original draft, Writing–review and editing, Conceptualization, Data curation, Formal Analysis, Investigation. YZ: Writing–review and editing. BW: Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–review and editing. YY: Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft.

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The effect of 12-week combined balance and plyometric training on dynamic balance and lower extremity injury risk in college dancers

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Background: Dancers face significant physical demands and are at high risk for lower extremity injuries due to the complexity and intensity of their movements, which require strong dynamic balance. Improving dynamic balance through training can potentially enhance performance and reduce injury risk.

Objective: This study aimed to investigate the effects of a 12-week combined balance and plyometric training program (BP) compared to plyometric training alone (PL) on dynamic balance and lower extremity injury risk among college dancers.

Methods: A total of 30 female college dancers were randomly assigned to either the BP group (n = 15) or the PL group (n = 15). Both groups participated in a 12-week training program, with the BP group engaging in both balance and plyometric exercises, and the PL group performing only plyometric exercises. Dynamic balance was assessed using the Dynamic Posture Stability Index (DPSI). Lower extremity injury risk was evaluated using the Limb Symmetry Index (LSI) and Center of Pressure (COP) measurements, pre- and post-intervention.

Results: The BP group showed significant improvements in dynamic balance compared to the PL group, with a reduction in DPSI values (DF-DPSI: $p < 0.001$, partial $\eta^2 = 0.625$; DL-DPSI: $p < 0.001$, partial $\eta^2 = 0.559$). Additionally, the BP group showed significant reductions in COP displacements, particularly in the anterior-posterior direction (DF-COPAP: $p < 0.015$, partial $\eta^2 = 0.101$; DL-COPAP: $p = 0.019$, partial $\eta^2 = 0.094$). The BP group also demonstrated greater improvements in LSI-3C and LSI-6, which reflect dynamic stability (LSI-3C: $p < 0.001$, partial $\eta^2 = 0.229$; LSI-6: $p = 0.006$, partial $\eta^2 = 0.128$).

Conclusion: The 12-week combined balance and plyometric training program was more effective than plyometric training alone in improving dynamic balance and reducing lower extremity injury risk in college dancers. This combined training approach is recommended for improving performance and preventing injuries in dancers.

KEYWORDS

dynamic balance, plyometric training, balance training, lower extremity injury risk, college dancers dynamic balance, college dancers

Introduction

Professional dancers are not only artists but also athletes. Dance performance is not a single art activity, but it is a complex phenomenon depending on multiple elements with both direct and indirect effects during dance performance, such as physically fitness. The intense physical demands of dancing expose dancer's feet to a high risk of injuries such as hallux valgus, metatarsal injury, and subsequent ankle pain (Furia et al., 2010). Additionally, "dance injury" is common among dancers because of the high-intensity training required and the technical discipline and rigour needed for dance performance (Shah et al., 2012). Unlike athletes in other sports, dancers engage in more fluid and complex movements that require superior dynamic balance, with an injury incidence of up to 95% over a dancer's lifetime (Byhring and Bø, 2002). Dancing involves many quick and slow motions, including acceleration, deceleration, rotation, and single leg support (Clarke et al., 2021), making dynamic balance a key component of dance performance (Koutedakis and Jamurtas, 2004). This unique demand for balance in dance—different from that in sports such as football or basketball—requires a more specific training approach. Moreover, dynamic balance ability is linked to lower-limb injuries. Therefore, strategies aiming to improve dynamic balance hold great promise to improve dance performance and reduce injury risk among dancers.

Plyometric training (PT) is one such strategy, which consists of motions related to the eccentric-concentric contraction cycle of muscles, also known as the stretch-shortening cycle (SSC) (Markovic and Mikulic, 2010) (e.g., depth jump and continuous jump (Stojanović et al., 2017)). PT is widely used in the training of athletes, as it can improve strength and power performance. Several studies have examined the effects of PT on strength. Recent studies have shown that compared to traditional resistance training (RT), PT can lead to comparable or even better enhancement of the performance of athletes (Ziv and Lidor, 2010a; Asadi et al., 2016) by improving their power and strength. The PT has also shown positive effects in enhancing dynamic balance and proprioception in athletes. For instance, Alikhani et al. (2019) observed that a 6-week PT could significantly improve dynamic balance and knee proprioception in female badminton players, which can ultimately prevent injury among participants. These findings suggest that PT could also be beneficial for dancers, whose lower limbs are constantly subjected to dynamic loads and high-impact movements.

However, while PT has been widely studied, the combined effects of PT and balance training specifically in dancers remain unclear. Recently, a combined intervention has been developed by concurrently implementing two types of training programs. The combined training can simultaneously improve multiple underlying domains contributing to dynamic balance, thereby inducing greater effects on performance compared to the intervention using only one training type. Studies demonstrated that combined training can significantly improve the strength, balance, and change of direction (COD) ability of basketball, football, and badminton players (Makhlouf et al., 2018; Muehlbauer et al., 2019) compared to the intervention using only one type of training. For instance, Guo et al. implemented the combined training of PT and balance (PB) in badminton players. This PB training consisted of depth and continuous jumps with balance exercises on unstable platforms. The results of this study showed that PB can significantly improve COD performance compared to PT only (Guo et al., 2021a). However, this combined approach has not been tested in dancers, who face a unique set of biomechanical challenges.

Therefore, the present study aimed to examine the effects of a 12-week combined training on dynamic balance and lower extremity injury risk among college dancers. This study is novel because it focuses on dancers' specific movement patterns and biomechanical needs, exploring how combined PT and balance training could uniquely enhance their dynamic balance. We hypothesized that a combined training protocol would induce a greater increase in parameters pertaining to dynamic balance and decrease the injury risk compared to PT.

Materials and methods

Subjects

The sample size of this study was 30 participants, determined using GPower (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). A total of 30 female college dancers volunteered to participate in this study considering 15%–20% attrition rate during the test and intervention. Participants were randomly assigned into a BP group (n = 15, age: 22.51 ± 3.92 years, height: 167.41 ± 6.12 cm, weight: 52.87 ± 6.45 kg, and training experience: 5.4 ± 1.4 years) and a PL group (n = 15, age: 22.90 ± 3.85 years, height: 168.82 ± 4.69 cm, weight: 51.29 ± 5.91 kg, and training experience: 4.4 ± 1.3 years) using a RAND function (1 and 2) (Microsoft Excel 2019) (Figure 1).

Study participants were recruited from April 1 to 30 April 2024, and the experiment was conducted from May 1 to August 1. The inclusion criteria were college dancers (1) who were female, (2) were versed in resistance and plyometric training skills, and (3) had the capability and intention to complete the 12-week training program including the exercise and testing. The exclusion criteria were participants (1) who had sustained serious injuries to their lower limbs, such as the anterior cruciate ligament, hamstring, meniscus, and ankle, or had developed any medical or orthopedic problems in the last 3 years and (2) were unable to perform plyometric training. Participants provided written informed consent after being informed about the potential benefits and risks associated with data collection. They were instructed to maintain their regular diet, avoid additional nutritional supplements, and consume caffeine-free beverages during the study. The study received approval from the Shandong Normal University Institutional Research Commission (Approval number: 2023105) and adhered to the guidelines of the Declaration of Helsinki.

Procedures

All experimental training programs were conducted along with a weekly technical training routine. Participants from the BP and PL groups followed a balance training combined with a plyometric

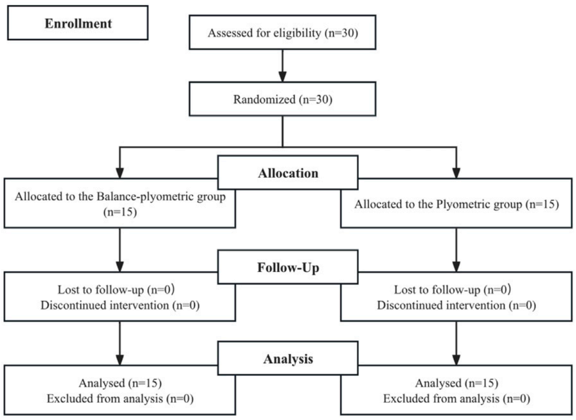

FIGURE 1
Flow chart of the progress through the phases of the study according to the CONSORT statements.

training program (40 min of plyometrics and 20 min of balance training) three times per week with 24–48 h of recovery between each training session (Guo et al., 2021a). To control the 20-min balance training protocol, the PL group was required to perform the same drills as the BP group. However, unlike the BP group that undertook all the exercises under unstable conditions (i.e., BOSU ball, Swiss ball, and Balance pad), the PL group practiced on the floor. Before the commencement of the study and the initiation of testing, all players completed a 2-week trial period (three sessions/week) to become acquainted with the physical training programs during the formal experimental course of the study. A detailed description of the balance and plyometric training protocols and the biweekly progression are presented in Tables 1, 2. During each session, players received consistent instructions from certified strength and conditioning coaches on proper techniques for agility drills, balance exercises, plyometric exercises, and landing. All the protocols were designed and supervised by one of the authors, who is an experienced researcher in strength and conditioning, and a fitness trainer with a master degree in strength and conditioning.

Assessment of dynamic balance and quickness

The dynamic balance and lower extremity injury risk were assessed at baseline and within 3 days after the last session of the 12-week training. The tests consisted of dynamic posture stability test and single-legged hop test. All tests were completed within a day. Before each testing session, participants finished warming-up, including a 5-min dynamic stretch, 8-min movement integration, and 2-min neural activation. A 5–10-min rest was given between each test. Each type of test was conducted at the same time and place across different visits, and the participants were asked to wear the same preferred sporting shoes through all the assessments. The players maintained their normal routine of diet and were prohibited from consuming beverages containing caffeine or alcohol during the whole period. The detailed assessments were as described below.

Dynamic posture stability test

The test was used to assess the dynamic balance of players through the dynamic posture stability index and center of pressure (Sell, 2012) and is a reliable and sensitive measure of dynamic postural control test (Kiers et al., 2022). Participants stood on an in-ground force plate (Kistler 9281CA, KISTLER, Winterthur, Switzerland, 1,000 Hz) and then jumped anteriorly or laterally with a dominant leg standing for 10 s. The distance between the jumping line and the center of the force plate was 40% of the players' height (cm) (Sell, 2012; Bourgeois et al., 2017). The fence was placed at the midpoint of the connection between these. The fence height in the forward jump and lateral jump was 30 cm and 15 cm, respectively. All players were asked to complete two types of jumps three times, and the average was considered for data analysis. Matlab software (r2014b, MathWorks, Natick, Massachusetts, USA) was used to calculate the dynamic postural stability index (*DPSI*) and center of pressure (COP). Time-series data for ground reaction force (*GRF*) and center of pressure (COP) were collected within 10 s after the players landed on the force plate

TABLE 1 The balance training program for the BP (combined training) group.

Exercises	The first stage (1–4 weeks)	The second stage (5–8 weeks)	The third stage (9–12 weeks)
Stand on the balance board exercise	Static standing on the board with two legs (3 sets: 30s/set)	Static standing on the board with two legs and eyes closed (3 sets: 30s/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 (3 sets: 30s/set)	Isometric supine single-leg bending bridge on Swiss Ball (3 sets: 30s/set)	Dynamic supine single-leg bending bridge on Swiss (3 sets: 10 reps/set)
Side-plank with inflated balance disc	Side-plank with inflated balance disc with elbow (3 sets: 30s/set)	Side-plank with inflated balance disc and the non-supporting leg stretches backwards (3 sets: 10 reps/set)	Side-plank with inflated balance disc and the non-supporting leg stretches backwards with elastic band (3 sets: 10 reps/set)
Lunge squat on BOSU ball	Lunge squat on BOSU ball (3 sets: 10reps/leg/set)	Lunge squat on BOSU ball and inflated balance disc (3 sets: 10reps/leg/set)	Lunge squat on BOSU ball and inflated balance disc with 5 kg dumbbells (3 sets: 10 reps/leg/set)
Airex® Balance-pad Elite exercise	Single-leg squat with balance-pad (3 sets: 10reps/leg/set)	Single-leg standing with balance-pad and the non-supporting leg stretches backwards (3sets: 12reps/leg/sets)	Single-leg support with balance-pad elite and the non-supporting leg stretches backwards with elastic band (3sets: 12reps/leg/sets)
Rest	Between exercise: 60 s Between sets: 3 min		

TABLE 2 The plyometric training program for BP (combined training) and PL (plyometric training) group.

Exercises	The first stage (1–4 weeks)	The second stage (5–8 weeks)	The third stage (9–12 weeks)
Front barrier jump (6 hurdles)	Double-leg front barrier jump (15 cm) (3 sets: 10 reps/set)	Single-leg front barrier jump (15 cm) (3 sets: 5 reps/leg/set)	Single-leg front barrier jump (30 cm) (4 sets: 5 reps/leg/set)
Lateral high-knees with hurdles	4-hurdle (15 cm) (3 sets: 2 reps/set)	6-hurdle (30 cm) (3 sets: 4 reps/set)	6-hurdle (30 cm) (3 sets: 6 reps/set)
Lateral barrier jump	Double-leg jump (15 cm) (3 sets: 10 reps/set)	Double-leg jump (30 cm) (3 sets: 12 reps/set)	Single-leg jump (30 cm) (3 sets: 15 reps/leg/set)
Depth jump	Jump with 20 cm box (3 sets: 8 reps/set)	Jump with 30 cm box (3 sets: 8 reps/set)	Jump with 40 cm box (3 sets: 8 reps/set)
Multi-direction jumps with hurdles	Triangle jump with double-leg (3 hurdles) (3 sets: 6*3 reps/set)	Square jump with single-leg (4 hurdles) (3 sets: 8*3 reps/set)	Hexagon jump with single-leg (6 hurdles) (3 sets: 12*3reps/set)
Intensity and number of contact with ground	Low intensity 144	Middle intensity 234	High intensity 325
Rest	Between exercise: 60 s Between sets: 3 min		

with a single leg. All data were smoothed through low-pass filtering, and the truncation frequency was set to 13.33 Hz.

DPSI was calculated from the *GRF* curve within 3 s after touchdown (the time when the *GRF* value exceeded 5% of body weight) (Wikstrom et al., 2005). Where *BW* is the body weight, GRF_x, GRF_y, and GRF_z are the back and forth, left and right, and vertical ground reaction forces. The dynamic posture stability indexes of forward jump (DF-DPSI) and lateral jump (DL-DPSI).

$$DPSI = \frac{\left(\frac{\sqrt{\sum(0-GRF_x)^2+\sum\left(0-GRF_y\right)^2+\sum(BW-GRF_z)^2}}{\text{number of data points}}\right)}{BW}$$

COP was calculated from the time series within 10 s after landing, and the back and forth displacement difference (COP_{AP}), left-to-right displacement difference (COP_{ML}), and total displacement distance (COP_{PL}) of the forward jump (DF) and lateral jump (DL) were calculated (Ziv and Lidor, 2010b). X_T and Y_T are the back and forth, and left and right displacements at T seconds, and the value of T is 1–10 s.

$$COP_{AP} = \sum_{1}^{10}(x_t - \bar{x})^2$$

$$COP_{PL} = \sum_{0}^{9}\sqrt{(x_{t+1} - x_t)^2 + (y_{t+1} - y_t)^2}$$

Lower extremity injury risk test

Single-legged hop tests can serve as a predictive factor of knee function in individuals to evaluate the risk of ACL injury and discriminate between individuals who return to their previous activity level after ACL injury or reconstruction (Figure 2). The single hop for distance, triple hop for distance, cross-over hop for distance, and time for the 6 m hop were measured. Smart Speed device (Fusion Sport, Coopers Plains, Australia) was set to record the time for the 6 m hop. After hopping, participants needed to stand with a single leg for 2 s to make the results effective. Participants were asked to jump three times on every leg in each test, and the longest distance and the shortest time in the three tests were taken as the final data when the four tests' lower LSI was calculated. LSI was counted as the ratio between the non-dominant leg (N) and the dominant leg (D), while the 6 m hop time was calculated from the dominant and non-dominant leg in the division. Four types of LSI were defined, including LSIO (Single Hop for Distance), LSIT (Triple Hop for distance), LSIC (Cross-over for distance), and LSIS (Time for 6 m Hop) in this study. When LSI ≥85%, there is no risk of ACL injury; and when LSI <85%, ACL is at risk of injury (Noyes et al., 1991).

Statistical analysis

Experimental data were processed using IBM SPSS statistical software package (version 25.0, IBM, Chicago, IL, United States). All data were presented as means and SD. The level of significance was set at $p < 0.05$ for all tests. To examine the effects of the combined

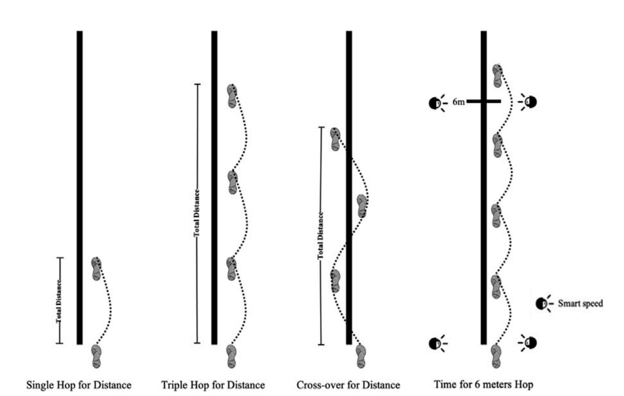

FIGURE 2
Single-legged hop tests.

TABLE 3 The assessment results for BP (combined training) and PL (plyometric training) before and after the 8-week training.

	PB group		PL group		Time effect		Time × Group interaction effect	
	Pre	Post	Pre	Post	*P* value	Partial η^2	*P* value	Partial η^2
LSI 1 (%)	95.44 ± 2.83	95.83 ± 1.92	95.41 ± 3.01	97.30 ± 1.72[a]	0.076	0.055	0.236	0.025
LSI 3 (%)	96.70 ± 1.23	98.67 ± 1.71	95.98 ± 1.82	97.32 ± 2.22	<0.001	0.189	0.493	0.008
LSI 3C (%)	94.13 ± 1.77	98.32 ± 1.54#	94.61 ± 2.26	95.49 ± 3.56	<0.001	0.229	0.010	0.112
LSI 6 (%)	95.13 ± 1.40	98.54 ± 1.19#	96.70 ± 2.09	97.93 ± 1.00	<0.001	0.398	0.006	0.128
DF-DPSI	0.387 ± 0.001	0.378 ± 0.005#	0.387 ± 0.002	0.383 ± 0.002	<0.001	0.625	<0.001	0.224
DL-DPSI	0.385 ± 0.002	0.376 ± 0.005#	0.385 ± 0.001	0.382 ± 0.002	<0.001	0.559	<0.001	0.264
NF-DPSI	0.389 ± 0.002	0.374 ± 0.007#	0.388 ± 0.002	0.384 ± 0.002	<0.001	0.626	<0.001	0.312
NL-DPSI	0.386 ± 0.002	0.374 ± 0.007#	0.386 ± 0.001	0.380 ± 0.005	<0.001	0.552	0.009	0.114

[a]Statistically significant difference between pre-and post-test, p < 0.05; # Statistically significant difference between group, p < 0.05.

training on the performance of single-legged hop tests and proprioception tests, we first performed two-way repeated-measure ANOVA (group × time). The dependent variable for each model was LSIO, LSIT, LSIC, LSIS, D-(AP, ML, LSI), and N-(AP, ML, LSI). The model factors were group, time, and their interaction. When a significant interaction was observed, LSD post-hoc correction was performed to identify the location of the significance. Secondly, we examined the effects of CT on the performance within each group, as well as the percentage changes from pre-to post-intervention between CT and PT by using separate one-way ANOVA models. The model factor was time. Partial η^2 was used to assess the effect size (ES) where significance was observed, with its strength being interpreted as the following: <0.06 as small, <0.14 as moderate, and ≥0.14 as large.

Results

All participants completed this study and were included in the analysis. All the data were normally distributed ($p > 0.207$). There were no significant differences in demographic characteristics (i.e., age, body weight, and height), primary outcomes (i.e., LSI and DPSI), and secondary outcomes (i.e., COP) between the PB and PL groups ($p > 0.947$).

Primary two-way repeated-measures ANOVA models showed significant time effect and interactions between group and time on LSI3C ($p < 0.001$) and LSI6 ($p = 0.006$). Post hoc analysis revealed that LSI3C ($p < 0.003$) and LSI6 ($p < 0.027$) were significantly greater after the PB intervention compared to all the other pre- and post-interventions. Additionally, primary two-way repeated-measures ANOVA models also showed significant time effect on LSI3 ($p < 0.001$). The exploratory ANOVA model showed that within both the PB and PL groups, LSI3 (PB: $p = 0.004$; PL: $p = 0.043$) was significantly improved after the intervention as compared to baseline (Table 3; Figure 3).

The primary two-way repeated-measures ANOVA models showed significant time effect and interactions between group and time on DF-DPSI ($p < 0.001$), DL-DPSI ($p < 0.001$), NF-DPSI ($p < 0.001$), and NL-DPSI ($p = 0.009$). Post hoc analysis revealed that DF-DPSI ($p < 0.001$), DL-DPSI ($p < 0.007$), NF-DPSI ($p < 0.002$), and NL-DPSI ($p < 0.001$) were significantly greater after the PB intervention compared to all the other pre- and post-interventions (Table 3; Figure 4).

The primary two-way repeated-measures ANOVA models showed significant time effect and interactions between group and time on DF-COP_{AP} ($p = 0.015$), DL-COP_{AP} ($p = 0.019$), NF-COP_{AP} ($p < 0.001$), NL-COP_{AP} ($p = 0.006$), DF-COP_{PL} ($p = 0.029$), DL-COP_{PL} ($p = 0.028$), NF-COP_{PL} ($p = 0.013$), and NL-COP_{PL} ($p = 0.015$). Post hoc analysis revealed that DF-COP_{AP} ($p < 0.038$), DL-COP_{AP} ($p < 0.017$), NF-COP_{AP} ($p < 0.001$), NL-COP_{AP} ($p = 0.007$), DF-COP_{PL} ($p < 0.001$), DL-COP_{PL} ($p < 0.007$), NF-COP_{PL} ($p < 0.001$), and NL-COP_{PL} ($p < 0.015$) were significantly greater after the PB intervention compared to all the other pre- and post-interventions (Table 4; Figure 5).

The primary two-way repeated-measures ANOVA models showed significant time effect on DF-COP_{ML}, DL-COP_{ML}, NF-COP_{ML}, and NL-COP_{ML}. The exploratory ANOVA model showed that within both the PB and PL groups, DF-COP_{ML} (PB: $p < 0.001$; PL: $p = 0.034$), DL-COP_{ML} (PB: $p = 0.008$; PL: $p = 0.016$), NF-COP_{ML} (PB: $p < 0.001$; PL: $p = 0.016$), and NL-COP_{ML} (PB: $p < 0.001$; PL: $p = 0.009$) were significantly improved after the intervention as compared to baseline (Table 4; Figure 6).

Discussion

The aim of the present study was to investigate the effect of combined balance and plyometric training on dynamic balance ability and injury risk in college dancers. To our knowledge, this is the first study to explore the effect of BP in dancers. The results of the present study showed that BP significantly enhanced the LSI-3C, LSI-6, and indicts of DPSI, indicating that BP is more effective in improving the dynamic balance ability and reducing lower limb injury risk.

At a competitive level, dance performance is not a single art activity, but it is rather a complex phenomenon that relies on various elements with both direct and indirect effects, such as physically fitness. Dancing involves a lot of quick and slow motions, including

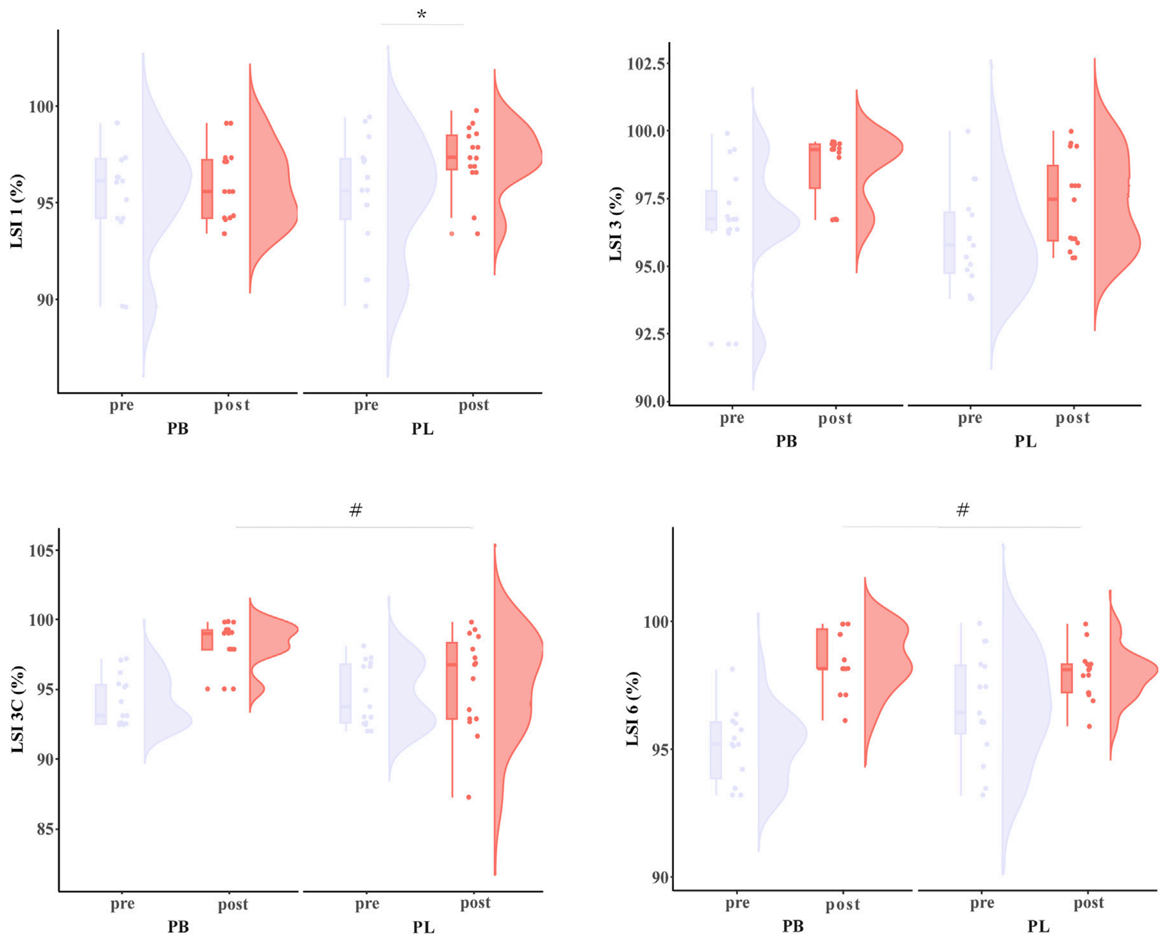

FIGURE 3
The LSI results for BP (combined training) and PL (plyometric training) before and after the 8-week training. * Statistically significant difference between pre-and post-test, $p < 0.05$; # Statistically significant difference between group, $p < 0.05$.

acceleration, deceleration, rotation, and single leg support (Clarke et al., 2021), and this makes dynamic balance a key component of fitness training (Koutedakis and Jamurtas, 2004). Previous studies have demonstrated the effectiveness of BP in improving dynamic balance among athletes in different sports, such as basketball (Guo et al., 2021b), badminton (Lu et al., 2022), and taekwondo (Shen, 2024). Our study further confirms the effectiveness of BP in improving the balance ability of dancers.

The results of this study indicated that BP induced a significant improvement in the DPST performance compared with PL. BP significantly improved all DPSI indices, whereas PL did not. In a previous study, participants with functional ankle instability exhibited poor ankle joint reposition sense (Cho and Park, 2019). Both balance training on an unstable surface and plyometric training could activate the mechanical or proprioception receptor on foot or tendon ligaments around the ankle joint (Docherty et al., 1998; Lin et al., 2021). This may explain the improved dynamic balance observed in our study due to enhanced ankle joint reposition sense. The lack of significant improvement in DPSI with PL training alone may be attributed to the dancers' relatively weak strength, suggesting that additional strength training is necessary to achieve the benefits of PL training.

Additionally, our findings reveal that BP significantly reduced COP displacement in the anterior-posterior direction during single-leg landing (DF-COP_{AP}, DL-COP_{AP}, NF-COP_{AP}, and NL-COP_{AP} all showed significant improvements compared to PL). This finding is inconsistent with a previous study which showed that the integration of plyometric and core stability training reduced the COP displacement in the medial-lateral direction (Lin et al., 2021). This discrepancy may be due to differences in testing methods. The present study used a dynamic postural stability test, whereas the other study employed specific ballet movements. The direction and distance of the jumps in these studies could have contributed to the varying results. The balance training program in our study included numerous core stability training, particularly performed on unstable surfaces (such as BOSU balls and Swiss ball). A previous study demonstrated that improved core stability could reduce the range of COP displacements (Kaji et al., 2010). This likely resulted in enhanced co-contraction of the hip and core muscles, thereby improving the dynamic balance capabilities. Additionally, the plyometric training could effectively stimulate the neural reflexes of the ankle joint, thereby enhancing postural adjustments in the anterior-posterior direction (Winter et al., 1996). The improved postural control may also be due to an enhanced reposition sense of

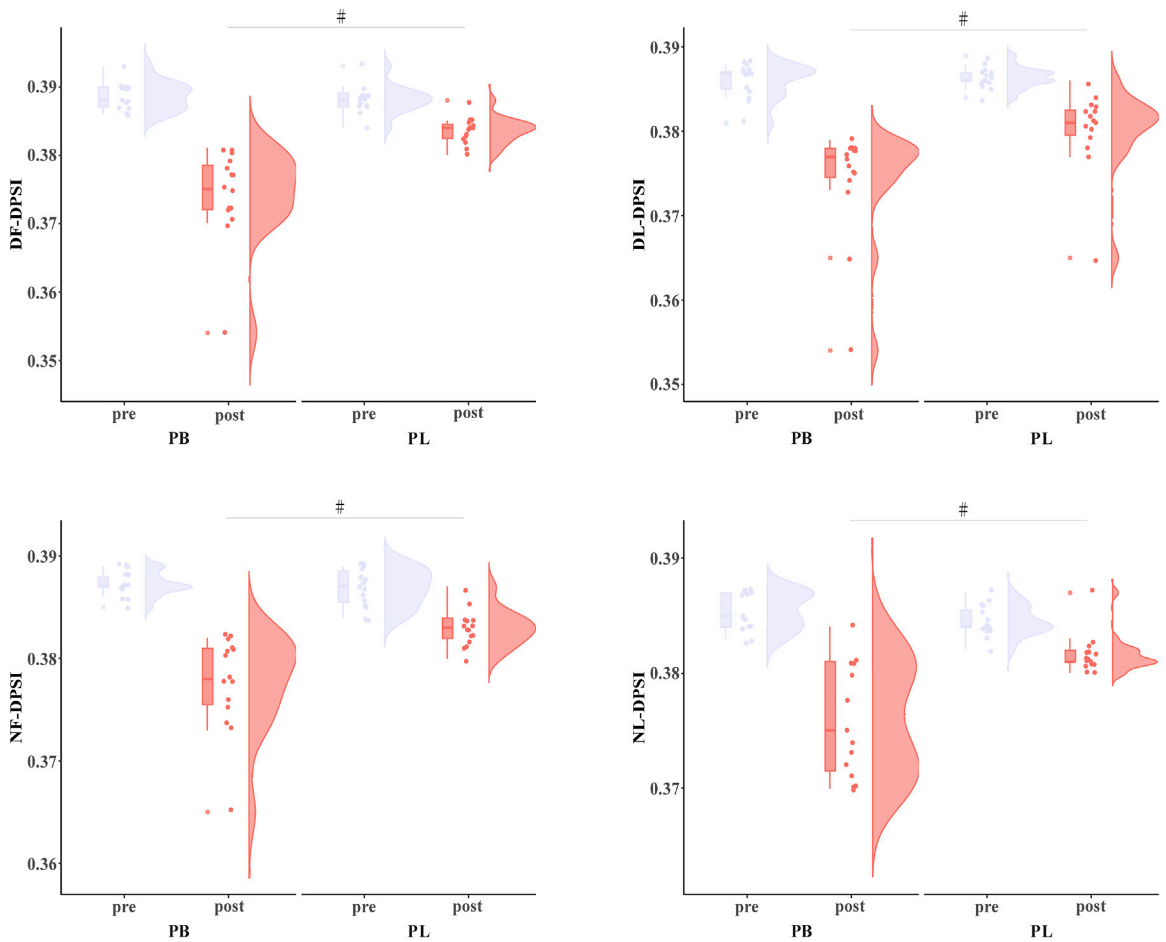

FIGURE 4
The DPDI results for BP (combined training) and PL (plyometric training) before and after the 8-week training. * Statistically significant difference between pre-and post-test, $p < 0.05$; # Statistically significant difference between group, $p < 0.05$.

the ankle joint and core stability. Compared with PL, BP significantly improved LSI 3C and LSI 6, while PL significantly improved LSI 1. LSI-3C reflects the capacity to generate forces in the frontal and transverse planes with multiple hops in the sagittal plane (Logerstedt et al., 2012). It requires a high level of stretch-shortening cycle (SSC) function and good postural control, both of which are crucial skills in dance performance. Traditional plyometric training focuses solely on enhancing SSC function and does not address improvements in balance, particularly trunk dynamic balance, during rapid lateral movements. The BP training could integrate both balance training and plyometric training, and our result demonstrated that this combination could reduce the limb asymmetry during continuous lateral movement. Besides, LSI 6 was also improved in our study. LSI 6 can be used to identify the dynamic stability of knees in ACL injury rehabilitation (Zwolski et al., 2016). Unlike LSI 3, LSI 6 represents a greater number of consecutive hops, where balance may play a more significant role in the later hops. Dance often involves continuous, rapid forward and backward movements (Bird, 2016), which closely resemble the movement pattern assessed by LSI-6. A previous study demonstrated that there was greater instability on the non-dominant side and more stability on the dominant side (Kilroy et al., 2016), leading to high injury risk during high technical demand movement. The present study showed that BP could significantly reduce the asymmetry between the dominant and non-dominant limb, thereby reducing the injury risk in dance performance.

The findings of this study suggest that incorporating BP training into dance training programs can significantly improve dynamic balance and reduce the risk of lower limb injuries. Dance instructors and physical trainers should consider integrating balance and plyometric exercises to enhance the performance and safety of dancers. Future research should aim for larger sample sizes and longer training durations to validate these findings. Additionally, exploring the effects of BP training on other aspects of dance performance, such as agility and muscle strength, can provide a more comprehensive understanding of its benefits. We believe that the incorporation of this training protocol into a dancer's regular training routine over the course of their career could significantly reduce injury risk, which should be investigated in future longitudinal studies. Furthermore, given that the balance demands for dancers are generally higher than those required in many other sports, such as team sports like soccer and basketball, or racket sports like badminton and tennis, the findings of this study

TABLE 4 The assessment results for BP (combined training) and PL (plyometric training) before and after the 8-week training.

	PB group		PL group		Time effect		Time × Group Interaction effect	
	Pre	Post	Pre	Post	*P* value	Partial η^2	*P* value	Partial η^2
DF-COP_{AP}	90.29 ± 12.2	72.19 ± 7.39#	95.06 ± 8.63	88.27 ± 5.24	<0.001	0.352	0.015	0.101
DF-COP_{ML}	72.76 ± 11.35	60.55 ± 7.09	81.94 ± 8.75	74.81 ± 8.13	<0.001	0.238	0.277	0.021
DF-COP_{PL}	131.56 ± 15.27	109.66 ± 16.64#	137.27 ± 13.8	132.19 ± 12.05	<0.001	0.187	0.029	0.082
DL-COP_{AP}	79.29 ± 9.97	61.23 ± 4.40#	82.45 ± 9.41	74.88 ± 8.79[a]	<0.001	0.382	0.019	0.094
DL-COP_{ML}	90.71 ± 9.68	81.37 ± 9.63	93.66 ± 10.07	85.17 ± 7.77	<0.001	0.196	0.859	0.001
DL-COP_{PL}	131.25 ± 15.18	104.72 ± 9.28#	139.82 ± 12.39	127.44 ± 11.09	<0.001	0.406	0.028	0.083
NF-COP_{AP}	95.58 ± 10.92	72.09 ± 7.23#	93.80 ± 9.04	90.89 ± 7.03	<0.001	0.382	<0.001	0.273
NF-COP_{ML}	76.93 ± 10.18	61.40 ± 6.25	81.94 ± 8.75	74.52 ± 6.88	<0.001	0.346	0.060	0.062
NF-COP_{PL}	131.54 ± 12.43	107.09 ± 15.76#	137.27 ± 13.80	130.79 ± 11.90	<0.001	0.258	0.013	0.105
NL-COP_{AP}	82.26 ± 9.62	62.25 ± 4.44#	82.45 ± 9.41	74.30 ± 7.24	<0.001	0.456	0.006	0.130
NL-COP_{ML}	93.74 ± 9.07	77.12 ± 9.07	93.66 ± 10.07	84.74 ± 7.68	<0.001	0.350	0.103	0.047
NL-COP_{PL}	135.19 ± 14.69	108.64 ± 9.64#	139.82 ± 12.39	128.87 ± 10.59	<0.001	0.396	<0.001	0.102

[a]Statistically significant difference between pre-and post-test, $p < 0.05$; # Statistically significant difference between group, $p < 0.05$.

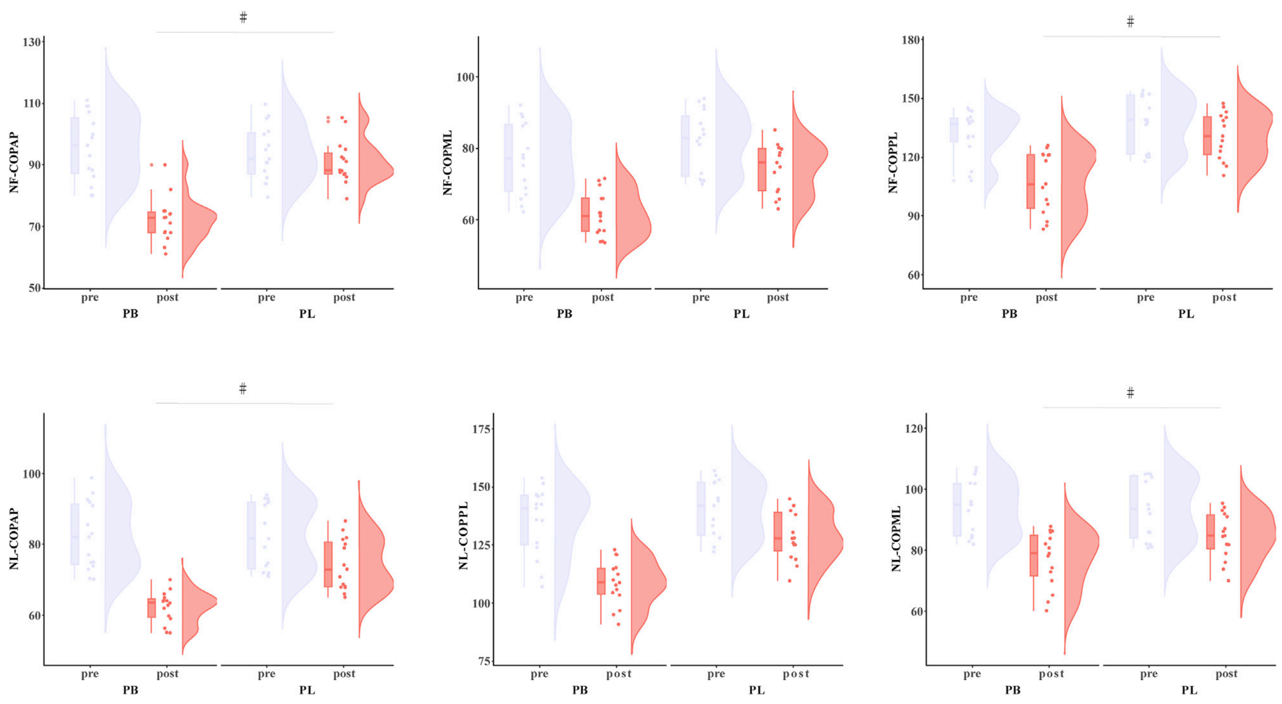

FIGURE 5
The NF-COP results for BP (combined training) and PL (plyometric training) before and after the 8-week training. * Statistically significant difference between pre-and post-test, $p < 0.05$; # Statistically significant difference between group, $p < 0.05$.

may also have potential applications in these areas. However, the specific effects in these contexts still require further investigation. Several limitations of this study should be noted. First, the assessment metrics used in this study primarily reflect general balance and injury risk indicators, rather than tests directly related to specific dance activities. Second, the injury risk in this study was predicted using LSI, which does not directly reflect the actual risk of lower limb injuries. Longer-term observations are needed to obtain real injury data and validate the predictive power of LSI in this context.

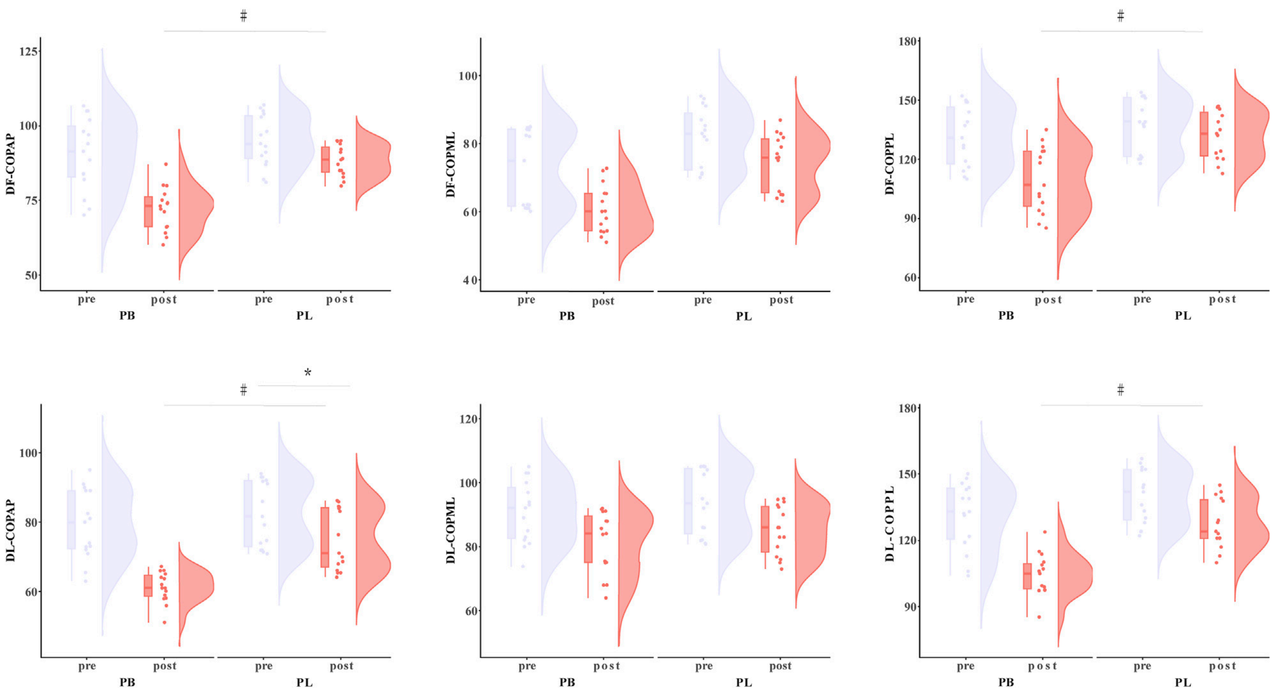

FIGURE 6
The DF-COP results for BP (combined training) and PL (plyometric training) before and after the 8-week training. * Statistically significant difference between pre-and post-test, $p < 0.05$; # Statistically significant difference between group, $p < 0.05$.

Conclusion

The 12-week combined balance and plyometric training program was more effective than plyometric training alone in improving dynamic balance and reducing lower extremity injury risk in college dancers. This combined training approach is recommended for improving performance and preventing injuries in dancers.

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.

Ethics statement

The studies involving humans were approved by Shandong Normal University Institutional Research Commission (Approval number: 2023105). 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.

Author contributions

YY: Formal Analysis, Investigation, Methodology, Resources, Writing–original draft. PS: Conceptualization, Data curation, Supervision, Validation, Writing–review and editing. HS: Conceptualization, Methodology, Writing–review and editing. YZ: Formal Analysis, Methodology, Writing–original draft.

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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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Corrigendum: The effect of 12-week combined balance and plyometric training on dynamic balance and lower extremity injury risk in college dancers

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KEYWORDS

dynamic balance, plyometric training, balance training, lower extremity injury risk, college dancers dynamic balance, college dancers

A Corrigendum on
The effect of 12-week combined balance and plyometric training on dynamic balance and lower extremity injury risk in college dancers

by Yan Y, Seoyoung P, Seomyeong H and Zhao Y (2025). Front. Physiol. 16:1501828. doi: 10.3389/fphys.2025.1501828

In the published article, there was an error in affiliation 1. Instead of "School of Dance, Sichuan Normal University, Chengdu, China", it should be "Dance College, Sichuan Normal University, Chengdu, China."

In the published article, there was an error. The **Conclusion** included incorrect text.

A correction has been made to **Conclusion**, paragraph 1. This sentence previously stated:

"This pilot study showed that CT is of great promise to induce significantly greater improvements in strength and power of firefighters compared to RT, thereby better enhancing their capabilities for occupational activity. The knowledge obtained from this study will ultimately help inform the design of future larger-scale studies to confirm the findings in this study and help firefighter agencies to develop more appropriate fitness training and management programs for firefighters in their daily routine."

The corrected sentence appears below:

"The 12-week combined balance and plyometric training program was more effective than plyometric training alone in improving dynamic balance and reducing lower extremity injury risk in college dancers. This combined training approach is recommended for improving performance and preventing injuries in dancers."

The authors apologize for this error and state that this does not change the scientific conclusions of the article in any way. The original article has been updated.

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The physiological responses to volume-matched high-intensity functional training protocols with varied time domains

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Background: High-intensity functional training (HIFT) is typically performed with minimal or no rest periods, including "rounds for time" (RFT) or "as many rounds or repetitions as possible" (AMRAP) design. Alternatively, some HIFT workouts can be performed with prescribed rest intervals (e.g., "every minute on the minute" [EMOM]) that may have significant effects on physiological responses.

Purpose: To compare the physiological responses between two different HIFT workouts (EMOM and RFT) that were matched for total work volume (TWV).

Methods: Twelve trained individuals (six males and six females) performed two HIFT protocols, EMOM and RFT. Both the EMOM and RFT included five rounds of five power cleans, eight kipping pull-ups, six dumbbell thrusters, and ten burpees performed in this order. Measurements of heart rate (HR), oxygen consumption (VO_2), rating of perceived exertion (RPE) (1–10 scale), blood lactate (BLA), creatine kinase (CK), excess post-exercise oxygen consumption (EPOC), and muscle oxygen saturation (SmO_2) were performed.

Results: Time domains were significantly different for the EMOM and RFT workouts (20 vs. 12 min ± 3 min, $p < 0.00$). There were significant differences between the EMOM and RFT for HR (153 ± 19 bpm vs. 171 ± 12 bpm, $p < 0.01$), VO_2 (30.8 ± 3 mL/kg/min vs. 38.1 ± 5 mL/kg/min, $p < 0.00$), RPE (4 ± 1 vs. 7 ± 1, $p < 0.00$), and EPOC-AUC (3.5 ± 1.2 mL/kg/min vs. 5.0 ± 1.3 mL/kg/min, $p < 0.00$); however, there were no significant differences in mean SmO_2 ($p = 0.44$). An interaction effect revealed that BLA was lower for the EMOM (6.5 ± 2.7 mmol/L) than the RFT (11.2 ± 2.1 mmol/L) post-exercise ($p < 0.00$). Conversely, there was no interaction effect for CK ($p < 0.16$), yet a significant increase was observed from pre- to post-exercise for both the EMOM and the RFT ($p < 0.01$).

Conclusion: The RFT induced greater physiological stress than the EMOM, indicating that prescribed rest intervals significantly affect the metabolic, cardiovascular, and perceptual responses during high-intensity functional exercise. Furthermore, the RFT may provide a greater cardiorespiratory stimulus, while the EMOM may be more suitable for technique development and recovery in trained individuals.

KEYWORDS

cardiorespiratory fitness, muscular fitness, resistance training, high-intensity interval training, cross-training, CrossFit

Introduction

The fitness industry has evolved from traditional resistance and endurance exercise programs to combined, time-efficient programs that address cardiorespiratory and muscular fitness components in a single exercise session (Cosgrove et al., 2019; Kliszczewicz et al., 2021). One example is high-intensity functional training (HIFT), which involves functional, multi-joint exercises performed at high intensity that are designed to improve health- and skill-related components of fitness (Feito et al., 2018). This type of functional training incorporates endurance and resistance exercises that engage whole-body motor recruitment patterns across multiple planes of movement, such as running, biking, rowing, squats, deadlifts, pull-ups, cleans, snatches, and jumps (Feito et al., 2018). The level of exercise intensity or metabolic stress is determined by the combination of work volume, load, set duration, rest interval duration, and exercise selection, which will influence the magnitude of physiological responses (Haltom et al., 1999). More specifically, HIFT sessions performed with short rest periods are potent stimuli for metabolic and cardiovascular responses (Feito et al., 2018; Jacob et al., 2020).

High-intensity functional training incorporates multi-joint movements and improves ten fitness domains, including cardiorespiratory endurance, stamina, strength, flexibility, power, speed, coordination, agility, balance, and accuracy (Feito et al., 2019). A HIFT workout may include elements of gymnastics (e.g., handstand and ring exercises), weightlifting derivatives (e.g., barbell squats and presses), and cardiovascular endurance exercises (e.g., running or rowing) (Fisker et al., 2017; Feito et al., 2018), generally performed in quick, successive repetition, with little to no recovery (Glassman, 2007). Typically, workouts are designed to perform the exercises continuously with the goal to complete a set volume in the shortest duration possible, "rounds for time" (RFT), or to perform "as many rounds or repetitions as possible" (AMRAP) in a set time domain (Jacob et al., 2020). Other workouts may be designed in an interval format (prescribed rest periods) for a set time with varied volume or a set volume with varied time to completion.

Research has demonstrated significant differences among various HIFT workouts, all of which are generally characterized as high intensity (McDougle et al., 2023). However, few studies have directly compared HIFT protocols that are matched for either volume or time domain. A study by Toledo et al. (2021) compared blood lactate, heart rate (HR), and training load (session rating of perceived exertion [RPE] + total training time) in two different HIFT workouts, RFT and AMRAP, with similar total volumes in trained men and women. Heart rate response was not different between workouts. The greatest responses were found in the RFT compared to the AMRAP for RPE, training load, and maximum repetitions completed for prescribed exercises in women and lactate in men. In another study, Hernández-Lougedo et al. (2021) compared two protocols that both included an RFT component. One of the protocols was adapted to include a 1-min rest interval after each round of exercise. The final HR and average HR were not different between the workouts; however, lower RPE and lactate were observed in the adapted protocol. Regarding time domains, Butcher et al. (2015) compared HR and RPE responses to two different CrossFit® sessions (interval-based and AMRAP) with matched time domains. They found that RPE was similar in both exercise sessions; however, HR responses to the interval-based session were approximately 10% lower than during the AMRAP session, despite the work during the interval-based session being conducted at an "all-out" effort.

HIFT is implemented by novice trainees seeking health and fitness improvements, as well as trained athletes who utilize HIFT as a cross-training program or for competition in functional fitness events. With the worldwide rise in popularity over the past decade, HIFT has established itself as a significant niche within the fitness industry (Feito et al., 2019). Thus, further research characterizing different workout designs within HIFT is necessary to understand the specific physiological responses and associated adaptations, which will provide valuable insights for future exercise prescription and program design. Currently, no studies have compared volume-matched, "every minute on the minute" (EMOM) and RFT designs. Therefore, the first aim of the present study was to compare the differences in the physiological responses between two HIFT workouts that are identical for exercise selection, repetition scheme, and volume yet differ in design: continuous-based (RFT) with varied time domain and interval-based with set time domain (EMOM). We hypothesized that the RFT would induce greater metabolic, cardiovascular, and perceptual responses than the EMOM.

Materials and methods

Study design

Baseline visit 1 was held at the University of New Mexico's (UNM) Exercise Physiology Laboratory. Baseline visit 2 was followed by two randomized, balanced crossover HIFT trials (visits three and five), separated by at least 1 week, and were held at Big Barn CrossFit® affiliate supervised by a CrossFit Level 2 (CF-L2) Trainer who is also an NSCA Certified Strength & Conditioning Specialist (CSCS). The order in which participants completed the HIFT trials was determined by a random number generator. Baseline visit one included anthropometrics and cardiorespiratory fitness (VO_{2max} measurement). Baseline visit

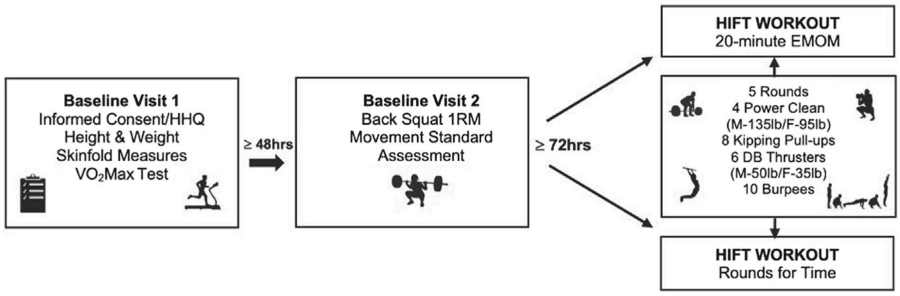

FIGURE 1
Summary of study design. Note: HHQ, health history questionnaire; HIFT, high-intensity functional training; M, male; F, female; EMOM, every minute on the minute; lb, pounds; DB, dumbbell; 1RM, one repetition maximum.

TABLE 1 Individual data between CrossFit® trained men (n = 6) and women (n = 6).

Variable	Men (mean ± SD)	Women (mean ± SD)	*p*-value
Age (yr)	34 ± 4	29 ± 5	0.12
Height (cm)	180.6 ± 3.7	171.5 ± 6.4	0.01*
Body weight (kg)	88.4 ± 9.4	68.8 ± 10.4	0.01*
Body fat (%)	18.1 ± 5.8	17.4 ± 3.5	0.80
VO_{2max} (mL/kg/min)	48.3 ± 6.4	47.3 ± 5.7	0.77
HR_{max} (bpm)	184 ± 7	189 ± 12	0.46
Back squat 1RM (kg)	148.6 ± 32.3	99.9 ± 14.8	0.01*
Relative back squat 1RM (kg)	1.5 ± 0.1	1.7 ± 0.3	0.12

*Significant difference between men and women ($p < 0.05$); yr, year; cm, centimeters; kg, kilograms; VO_{2max}, maximal oxygen consumption; mL, milliliters; min, minutes; HR, heart rate; bpm, beats per minute; RM, repetition maximum.

two included a one-repetition maximum (1RM) lower body strength test (e.g., back squat) and an assessment of the movements of the prescribed exercises in the HIFT trials. For the HIFT trials, subjects performed two volume-matched HIFT workouts: (1) every minute on the minute (EMOM) and (2) "rounds for time" (RFT). Participants had pre- and post-exercise blood samples taken for measurement of blood lactate and creatine kinase (CK), a marker of muscle damage. Gas exchange was measured pre- and post-exercise to calculate excess post-exercise oxygen consumption (EPOC). HR, VO_2, and RPE were measured during exercise (Figure 1).

Participants

Participants were men (n = 6) and women (n = 6), 18–40 years of age, who had performed HIFT training for the last 12 months, with a minimum weekly frequency of 3 days per week. All participants completed a health history questionnaire, and individuals with any musculoskeletal injuries or limitations were excluded from the study. In the baseline visits, participants demonstrated their ability to meet the movement standards of the HIFT exercises and to perform the exercise protocols using the prescribed absolute loads. Participants were instructed to refrain from vigorous exercise for 24 h and caffeine and food for 4 h before baseline visits 1 and 2. In addition, participants were advised to abstain from caffeine and food for 4 h, alcohol for 24 h, and exercise for 48 h before the HIFT trials, and to maintain their regular daily diet during the study. The *a priori* sample size was calculated using G-power software (version 3.1.9.4) with an alpha level of 0.05 and power (1 – beta) of 0.80, and the number of participants required to make a valid analysis was N = 12. The variable with the lowest effect size (average heart rate) from a study using a similar methodology was used to guide the power analysis (Fernández-Fernández et al., 2015). Independent sample t-tests showed significant differences between women and men for body mass and height, but not for age, VO_{2max}, HR_{max}, relative back squat (BS) 1RM, and %BF (Table 1).

Baseline visit 1

Upon arrival at UNM's Exercise Physiology Laboratory, participants completed an informed consent and health history questionnaire. Then, participants' heights (cm) were measured using a stadiometer (Holtain Limited, Crymych, Dyfed, Great Britain), and body weight (kg) was recorded using a digital weight scale (MedWeight MS-3900, Itin Scale Company, Brooklyn, NY, United States). Next, body composition was assessed via 3-site skinfold (SKF) measurements using a Lange skinfold caliper (Cambridge Scientific Industries, INC., Cambridge, Maryland). Two measurements within 1–2 mm were averaged. Three sites were measured: triceps, suprailiac, and thigh, and three sites were measured for men: chest, abdomen, and thigh (Jackson et al., 1980; Jackson and Pollock, 1978). Respective gender-specific equations were used to calculate body density (Jackson et al., 1980; Jackson and Pollock, 1978) and converted to a body fat percentage using the Siri equation (Siri, 1961). Finally, participants performed a maximal graded exercise test (GXT) on a treadmill (C966i, Precor Inc., Woodinville, WA, United States). In brief, treadmill speed was increased every minute by 0.5 mph, and once the top speed was reached, the percent grade was increased by 1% every minute until completion of the test. The initial speed was based on the participant's self-selected top speed in the warm-up and a stage progression that allowed the participant to reach top speed at approximately 8 min. Gas analysis, measured breath-by-breath via a portable metabolic system (K5 wearable metabolic technology, COSMED, S.r.l., Italy), was used to determine VO_{2max}. The criteria for establishing VO_{2max} were defined by reaching three of the four following parameters: reaching a plateau in VO_2 of ≤150 mL O_2/min, a maximal respiratory exchange ratio of >1.15, ±10 beats per minute (bpm) of the age-predicted maximum (220 − age), and RPE >17 (6–20 rating scale).

Baseline visit 2

At the Big Barn CrossFit® affiliate, maximal strength was tested via BS 1RM. The testing protocol included a warm-up set of 10 repetitions at 50% of BS predicted 1RM followed by 1 min rest; three repetitions with a 10%–20% increase in load followed by a 2-min rest; two repetitions with an additional 10%–20% increase followed by a 3-min rest; and a final 10%–20% increase for a one-repetition maximum attempt. Additional single repetitions, increasing in load, were performed with 3 min rest until the participant reached muscular failure (Haff and Triplett, 2016). The movement assessment included completing one round of the exercises prescribed in both HIFT protocols, including barbell power clean, kipping pull-up, dumbbell thruster, and burpee. During the performance of each exercise, the CrossFit Level 2 Coach (CF-L2)/Certified Strength & Conditioning Specialist (CSCS) professional visually inspected the participants' ability to complete full range of motion (ROM) repetitions successfully with the prescribed absolute load. A description of the exercises is provided in the Supplemental Material.

HIFT trial visits 3 and 5

The HIFT protocols were designed based on two different HIFT workouts: EMOM and RFT. Upon arrival at the Big Barn CrossFit® affiliate, participants were seated in a chair for 10 min for baseline measurements. Prior to each workout, participants performed a 3-min general warm-up of low-intensity aerobic exercise (i.e., rowing ergometer), dynamic stretching, and a specific warm-up for the movements within the workout. In the EMOM trial, participants performed the following sequence of exercises: four barbell power cleans (minute 1), eight kipping pull-ups (minute 2), six dumbbell thrusters (minute 3), and ten burpees (minute 4). This sequence was repeated for a total of 20 min (five rounds). Once the repetitions were completed within the minute, participants rested for the remaining time of that minute. The prescribed exercises were based on common movements performed in HIFT that alternate between upper- and lower-body-dominant movements to balance fatigue and include major muscle group activation. The prescribed repetition scheme and load were selected to ensure participants would have approximately 30 s of rest after each exercise. The RFT trial included five rounds of the four exercises described above and was performed "all-out." The subjects were encouraged to take minimal to no rest for the RFT. The velocity of the movements was not controlled; however, participants were asked to perform the movements as quickly as possible through the full range of motion. For both protocols, the prescribed absolute load for the barbell power clean and dumbbell thruster was 135 lb/95 lb and 50 lb/35 lb for males and females, respectively. A CF-L2/CSCS professional monitored both trials for all subjects to ensure each repetition was performed to the correct movement standards with a similar range of motion between the trials. Upon completion of the HIFT trials, participants returned to Big Barn CrossFit® for visits 4 and 6 to complete their 24 h post-exercise blood draw.

HIFT measurements

VO_2, HR, and RPE

Oxygen consumption (VO_2) was measured continuously throughout each protocol using a portable metabolic system (K5 wearable metabolic technology, COSMED, S.r.l., Italy). Participants wore a lightweight, slim-fitting vest that harnesses a sensor unit on their back to allow for proper performance of movements. A face mask, which includes a flow sensor, was attached to the sensor unit via a sampling line to collect expired gases. Participants were seated in a chair for 10 min prior to each HIFT trial for baseline VO_2 as well as 20 min after exercise for recovery VO_2. Baseline VO_2 was determined using the average of the last 2 min of seated VO_2 prior to the start of exercise (warm-up). The Polar RS800 heart rate chest strap was used to record the heart rate continuously for each trial. The VO_2 and HR were averaged for each round and then averaged for each HIFT workout to determine the mean values. Average and maximum values of relative VO_2 (mL/kg/min) were used to define participants' VO_{2peak}. EPOC was calculated from the VO_2 data extracted from the metabolic analyzer using 10 s averaging to ensure the same time comparison between HIFT protocols. To determine the slow component of EPOC, the first 2 min of recovery VO_2 data were excluded to remove data obtained during the transition from exercise to the seated position. The slow component EPOC was calculated by subtracting 18 min of the 20-min recovery VO_2 from baseline VO_2. For both HIFT trials, RPE was recorded at the end of each round using the modified category ratio 10 (CR10) RPE scale (Foster et al., 2001).

Blood sampling

Blood lactate (BLA) concentrations were determined from blood samples drawn from the earlobe and analyzed with a portable device (Lactate Plus Analyzer, Nova Biomedical, Waltham, MA) pre- and 3 min post-exercise. In addition, participants underwent venipuncture in a prominent forearm vein cleaned following standard sterile procedure, and blood serum samples were

TABLE 2 Comparison of variables between the two workouts (N = 12).

Variable	EMOM	RFT
BLA-Pre (mmol/L)	0.9 ± 0.2	0.9 ± 0.4
BLA-Post (mmol/L)	6.5 ± 2.7	11.2 ± 2.1**
VO_{2avg} (mL/kg/min)	30.8 ± 3.0	38.1 ± 5.0**
$\%VO_{2max}$	65 ± 7	80 ± 10**
VO_{2peak} (mL/kg/min)	44.4 ± 5.2	48.3 ± 5.1*
$\%VO_{2max}$	93 ± 8	102 ± 12*
HR_{avg} (bpm)	153 ± 19	171 ± 12*
$\%HR_{max}$	82 ± 7	91 ± 3*
HR_{peak} (bpm)	173 ± 13	182 ± 9*
$\%HR_{max}$	93 ± 4	98 ± 1*
Time domain (min:sec)	19:31 ± 0:09	11:48 ± 2:56**
RPE_{avg}	4 ± 1	7 ± 1**
RPE_{max}	5 ± 2	9 ± 1**

*Significant difference between workouts ($p < 0.05$), **($p < 0.001$), WOD, workout of the day; EMOM, every minute on the minute; RFT, rounds for time; BLA, blood lactate; mmol, millimole; L, liter; VO_{2avg}, average oxygen consumption; VO_{2peak}, peak oxygen consumption; mL, milliliter; kg, kilogram; min, minute; HR_{avg}, average heart rate; HR_{peak}, peak heart rate; bpm, beats per minute; SmO_2, muscle oxygen saturation; min, minutes; sec, seconds; RPE, rating of perceived exertion (modified category ratio 10 RPE scale).

collected in BD Vacutainer™ Venous Blood Collection Tubes (Fisher Scientific, Carlsbad, CA) pre- and 24 h post-exercise. After coagulation, the samples were centrifuged at 2.900 RPM. The resultant serum was divided into several aliquots and frozen at −80°C until analysis. The pre- and 24 h post-exercise blood serum samples were sent to Quest Diagnostics for analysis of CK.

Statistical analyses

All analyses were performed using GraphPad Prism Version 10.2.0 (335). The Shapiro–Wilk test was applied to verify a normal distribution of data, and Levene's test was used to assess the homogeneity of variance. Dependent sample t-tests and effect size by Cohen's *d* were used to compare time domains, mean HR, peak HR, mean HR percentage of HR_{max}, peak HR percentage of HR_{max}, mean VO_2, peak VO_2, mean VO_2 percentage of VO_{2max}, peak VO_2 percentage of VO_{2max}, mean RPE, peak RPE, and EPOC between the two workouts (EMOM and RFT). A two-way ANOVA with effect size by partial *eta* squared (ηp^2) was applied to assess differences in and between resting and post-exercise BLA and CK. Lastly, two-way ANOVAs were performed to evaluate differences in VO_2, HR, and RPE across the five rounds of exercise for both protocols. The level of statistical significance was set at $p < 0.05$.

Results

Twelve participants completed this study, and their descriptive data are presented in Table 1. The prescribed HIFT exercises were well tolerated by all participants, and no injuries were reported.

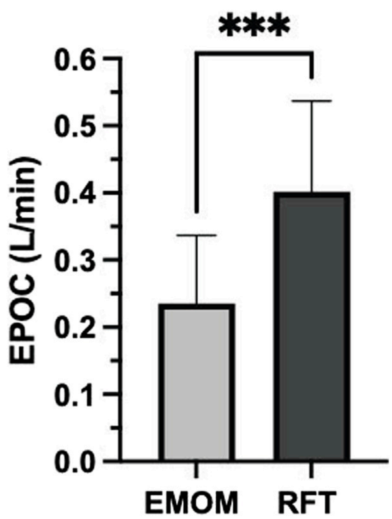

FIGURE 2
Excess post-exercise oxygen consumption (EPOC) calculated from 20 min of recovery for both conditions. L, liters; min, minute; EMOM, every minute on the minute; RFT, rounds for time. Significant differences between protocols ($p < 0.05$).

The time to complete the RFT was significantly lower than the EMOM (t (11) = 9.39, $p < 0.00$, $d_z = 2.69$), as shown in Table 2. The results showed that individuals had an average of 49 s rest following the four power cleans, 45 s rest following the eight kipping pull-ups, 46 s rest following the six dumbbell thrusters, and 30 s rest following the burpees. The assessment procedures were well tolerated by all participants, and no injuries were reported.

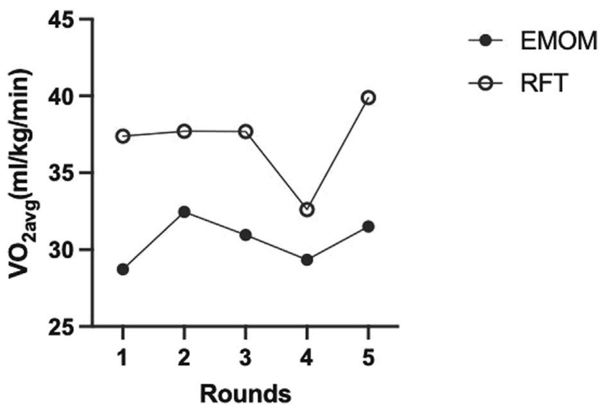

FIGURE 3
Average oxygen consumption (VO_{2avg}) of all participants (n = 12) across all rounds of exercise for both protocols. EMOM, every minute on the minute; RFT, rounds for time.

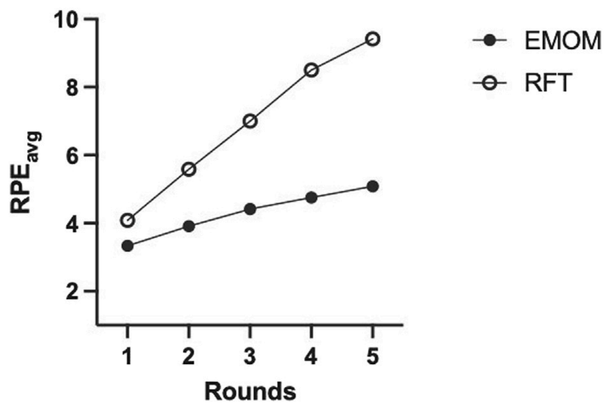

FIGURE 5
Average rating of perceived exertion (RPE_{avg}) for the full sample (n = 12) based on a modified Borg scale of 1–10 across all rounds of exercise for both protocols. EMOM, every minute on the minute; RFT, rounds for time.

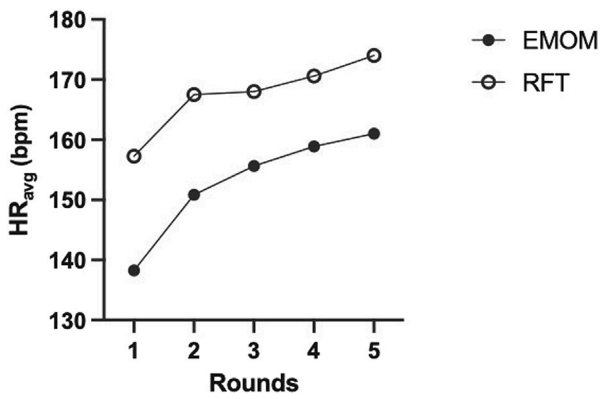

FIGURE 4
Average heart rate (HR_{avg}) for the full sample (n = 12) across all rounds of exercise for both protocols. EMOM, every minute on the minute; RFT, rounds for time.

Metabolic, cardiorespiratory, and muscle damage responses

Descriptive statistics for both workouts are presented in Table 2. There were significant differences between the EMOM and RFT for time domains (t (11) = 9.39, $p < 0.01$, $d = 2.78$), mean HR (t (11) = 4.30, $p < 0.01$, $d = 1.24$), peak HR (t (11) = 4.41, $p < 0.01$, $d = 1.27$), mean VO_2 (t (11) = 6.79, $p < 0.01$, $d = 1.79$), peak VO_2 (t (11) = 3.15, $p < 0.01$, $d = 0.76$), mean VO_2%, mean RPE (t (11) = 5.34, $p < 0.01$, $d = 1.54$), peak RPE (t (11) = 7.18, $p < 0.01$, $d = 2.07$), and EPOC (t (516) = 27.44, $p < 0.01$, $d = 1.33$) (Figure 2). The two-way ANOVA for VO_2 and HR resulted in no interaction effect for time (rounds of exercise) and protocol (EMOM and RFT) (p = 0.16 and p = 0.37); however, there was a main effect for time (p = 0.00 and $p < 0.00$) and protocol (p = 0.00 and p = 0.05) (Figures 3, 4). Conversely, the two-way ANOVA for RPE showed an interaction ($p < 0.00$) and a main effect for time and protocol ($p < 0.00$) (Figure 5).

Tukey's multiple comparisons test was conducted to examine pairwise differences between EMOM and RFT across the five rounds of exercise. For the EMOM vs. RFT comparisons, significant differences were observed across all pairs ($p < 0.05$), with the largest difference in round 5 (mean difference = −4.333, 95% CI [-5.796, −2.871], $p < 0.00$). For within-EMOM comparisons, significant differences were observed between rounds 1 vs. 4, 1 vs. 5, 2 vs. 3, 2 vs. 4, and 2 vs. 5 (mean differences ranging from −0.583 to −1.750, $p < 0.05$). For within-RFT comparisons, significant differences were observed between all rounds, with the largest mean difference between round 1 and round 5 (−5.333, 95% CI [-6.162, −4.505], $p < 0.00$). Finally, the two-way ANOVA for BLA revealed a main effect for time (F (1, 11) = 191.6, $p < 0.01$, ηp^2 = 0.95), indicating a significant increase from pre-to post-exercise across both workouts. Further, an interaction effect revealed BLA was lower for the EMOM than RFT post-exercise (F (1, 11) = 42.39, $p < 0.00$, $\eta p^2 = 0.79$). The two-way ANOVA mixed effects model for CK revealed a main effect for time (F (1, 11) = 5.14, $p = 0.04$, ηp^2 = 0.32), indicating a significant increase from pre-to post-exercise across both workouts; however, there was no interaction effect (F (1, 9) = 3.86, $p = 0.08$, $\eta p^2 = 0.30$) (Figure 6).

Discussion

In the present study, we compared the acute physiological responses of two different high-intensity functional workouts that were volume matched. One was an interval-based design with prescribed rest (EMOM), while the other was a continuous-based design performed "all-out" with self-selected rest (RFT). The main findings indicated that the RFT induced greater physiological stress, which is evident by higher values of VO_2, BLA, HR, EPOC, and RPE compared to the EMOM. Both workouts can be characterized as high-intensity exercise; however, when compared to the RFT, the EMOM may be considered more moderate intensity. Overall, both designs are comparable in intensity to other HIFT workouts reported in previous studies (Fernández-Fernández et al., 2015;

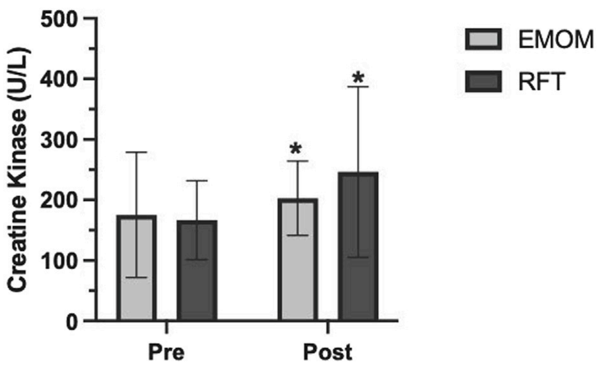

FIGURE 6
Creatine kinase pre-and 24 h post-exercise. U/L, units of enzyme activity per liter; EMOM, every minute on the minute; RFT, rounds for time. *Significantly different from baseline ($p < 0.05$).

Hernández-Lougedo et al., 2021; Maté-Muñoz et al., 2018; Toledo et al., 2021).

As previously mentioned, the workout was designed to ensure at least 30 s rest after each exercise in the EMOM, and the results showed that participants, on average, received at least 30 s of rest during the EMOM. The RFT took significantly less time (an average of 12 min) to complete the same amount of work than the 20-min EMOM. Although not statistically analyzed, it was observed that all participants were able to perform all repetitions for each movement consecutively in the EMOM, whereas some participants elected intra-set rest during the RFT. For example, the eight kipping pull-ups were performed in two sets of four repetitions with a brief rest period between. In addition, rather than performing four consecutive power cleans without releasing the bar, some participants opted to perform single repetitions. This can be attributed to the "all-out" nature of the RFT. Hernández-Lougedo et al., 2021 compared two protocols, both including a circuit of four rounds of exercises to be completed as quickly as possible (RFTstandard), but one of the protocols was adapted to include a 1-min rest interval after each round of exercise (RFTadapted). Unlike the present study, there was no significant difference in time to completion for the workouts, which may be attributed to more self-selected rest and reduced movement velocities in the RFT standard (Hernández-Lougedo et al., 2021). Relative work intensities may differ when including prescribed rest intervals for the same absolute training volume, including repetitions performed at a higher velocity, indicating a lower relative intensity for that absolute load and different ranges of effort and fatigue relevant to recovery of predominant energy systems (Hernández-Lougedo et al., 2021).

VO_2, HR, and RPE

Average VO_2, percentage of VO_{2max}, and EPOC were higher for the RFT than the EMOM protocol in the present study. Limited research has evaluated the metabolic demand of HIFT workouts via gas analyses, and no research, to our knowledge, has compared interval and continuous-based designs that are volume matched. Fernandez-Fernandez et al. (2015) characterized commonly prescribed HIFT workouts, including (1) 20-min AMRAP of five pull-ups, 10 push-ups, and 15 squats; (2) RFT of 21, 15, and 9 repetitions of barbell thrusters and pullups with an average completion time of 9 min. The 20-min AMRAP had a higher average VO_2 and $\%VO_{2max}$ (34.4 ± 3.5 and 66.2 ± 4.8 mL/kg/min, respectively) than the RFT (29.1 ± 1.1 and 56.7 ± 6.2 mL/kg/min, respectively). Both AMRAP and RFT can be characterized as high-intensity workouts similar to the workouts in the present study. Regarding the effects of rest intervals on VO_2, Haltom et al. (1999) compared two circuit weight training (CWT) protocols (matched for exercise selection and volume) that differed in rest intervals: one 20-s rest interval (20 RI) and one 60-s rest interval (60 RI). Their protocol included eight exercises: 1) leg press, 2) bench press, 3) leg extension, 4) lat-pull, 5) leg curl, 6) seated row, 7) triceps extension, and 8) biceps curl. They found that the 20 RI CWT protocol elicited a greater exercise VO_2 and EPOC than the 60 RI CWT protocol. Although both protocols were interval-based and incorporated traditional resistance exercise rather than the functional exercise used in the present study, these results demonstrate that reduced rest periods induce greater metabolic stress.

With respect to heart rate responses, we found that $\%HR_{max}$ and average HR were significantly higher during the RFT than during the EMOM. However, a smaller difference occurred in the HR response ($\%HR_{max}$ ~10% higher for RFT versus EMOM) than the VO_2 response ($\%VO_{2max}$ ~21% higher for RFT versus EMOM). The magnitude of the difference between the HR and VO_2 responses may be due to the mechanical load and intramuscular pressure induced by skeletal muscle contraction during resistance-based exercise. This high intramuscular pressure generated during muscle contraction, especially in the multi-joint exercises used in the present study, temporarily occludes flow through the active muscles, increasing afterload and decreasing stroke volume. As a result, the heart must contract more to maintain cardiac output (Kounoupis et al., 2020).

Finally, the RPE (Borg CR10 scale) for the RFT is considered vigorous intensity, while the EMOM is moderate intensity (ACSM, 2022). The RFT RPE values are similar to other studies (Fernández-Fernández et al., 2015; Maté-Muñoz et al., 2018; R. Tibana et al., 2018; Toledo et al., 2021). Conversely, the EMOM resulted in lower RPE than the limited studies evaluating the effects of rest intervals that showed RPE values characterized as vigorous intensity (Hernández-Lougedo et al., 2021; Maté-Muñoz et al., 2018; R. Tibana et al., 2018). The EMOM included ≥30 s rest after each exercise, while previous studies prescribed less rest between exercises (e.g., 10 s) (Maté-Muñoz et al., 2018) or had prescribed rest after each round of a circuit of exercises (e.g., 1 min) (Hernández-Lougedo et al., 2021; Tibana et al., 2018).

Blood lactate

Blood lactate significantly increased post-exercise for both protocols; however, the RFT elicited higher levels, suggesting a greater degree of effort, anaerobic contribution, and type II fiber recruitment during the RFT. Research has shown that continuous-based designs (RFT and AMRAP) elicit high BLA (>10 mmol/L) values in trained individuals, similar to the present study (Fernández-Fernández et al., 2015; Escobar et al., 2017;

Maté-Muñoz et al., 2018; Tibana et al., 2018). Similarly, the limited studies that have evaluated interval-based protocols have shown BLA values of >10 mmol/L (Maté-Muñoz et al., 2018; Hernández-Lougedo et al., 2021); however, in the present study, BLA for the EMOM was <10 mmol/L, which may be attributed to the differences in workout design and rest interval prescription.

Creatine kinase

The current study found an increase between CK levels pre- and 24 h post-exercise in both protocols, which is consistent with previous research (Tibana et al., 2019; Timón et al., 2019; Gomes et al., 2020). Both protocols involved a combination of upper and lower body movements performed as quickly as possible, which can significantly increase CK (Koch et al., 2014). There was no statistically significant difference in CK for the EMOM and RFT; however, CK showed an upward trend in the RFT, indicating that reduced rest periods during HIFT in trained individuals may have a greater effect on CK. While this is the first study to evaluate the effects of rest interval during HIFT on CK, research has shown CK levels are greater during resistance training performed with 1 min rest than 3 min rest between sets during traditional resistance training (Koch et al., 2014).

Limitations

The present study has limitations that readers should consider while interpreting our results. Our sample size consisted of 12 participants (six males and six females), and we did not control for the timing of our female participants' menstrual cycles. Although research suggests that exercise performance does not significantly change with menstrual cycle phases (McNulty et al., 2020), controlling for this variable would have reduced the potential impact of menstrual status on perceptual and physiologic responses. Also, it is important to acknowledge that the prescribed loads for the barbell power clean and dumbbell thrusters are common, absolute loads in HIFT and prescribed for practicality purposes rather than as a percentage of 1RM. Therefore, the prescribed weights used in the present study may have impacted individual relative effort.

Conclusion

In conclusion, both the RFT and EMOM in the present study can be considered vigorous exercise (77–95% HR_{max} and 64–90% VO_{2max}) according to ACSM's estimated intensity for cardiorespiratory exercise (ACSM, 2022). When comparing the RFT and EMOM, the RFT elicited higher levels of metabolic stress indicative of potentially greater cardiorespiratory adaptations. In addition, the increases in blood lactate and creatine kinase from both protocols support a significant anaerobic contribution, suggesting a sufficient stimulus for muscular fitness adaptations (Kraemer and Ratamess, 2005; Wackerhage et al., 2019). The results of this study may provide insight into the proper application of an RFT and EMOM design within HIFT dependent on the desired training stimulus. Future studies on various HIFT workout designs with and without rest intervals to improve exercise prescription in trained individuals are highly warranted.

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 University of New Mexico (UNM) Institutional Review Board (IRB) Main Campus. 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.

Author contributions

JS: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, resources, software, supervision, validation, visualization, writing–original draft, and writing–review and editing. GB: investigation, methodology, and writing–review and editing. FA: conceptualization, data curation, formal analysis, investigation, methodology, project administration, supervision, writing–review and editing, and validation.

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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.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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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.2024.1511961/full#supplementary-material

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The impact of the experimental "Hypoxic Boxing" training on the motor abilities and specialized fitness of national boxing champions: a randomized controlled trial

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Introduction: Among theorists and practitioners, there is a consensus regarding the significant role of optimizing sports training in high-altitude conditions. This stems from the specific combination of environmental variables that determine the dynamics of changes in broadly understood training adaptation. The aim of this study was to evaluate the impact of an experimental training program, Hypoxic Boxing (under normobaric hypoxia conditions), on the development of the functional profile (motor and specialized fitness) within a national elite group of boxers.

Methods: A randomized controlled trial was conducted with 20 elite-level boxers representing the national championship level (mean age: 23.9 ± 3.0 years; height: 181.3 ± 7.14 cm; body weight: 79.3 ± 8.84 kg; BMI: 24.15 ± 2.21; training experience: 10 ± 4.0 years). The participants were assigned to either the experimental group (Hypoxic Boxing - HB; n = 10) or the control group (Normoxic Boxing - NB; n = 10). Both groups followed the same 6-week training program, which included two daily training sessions (morning and afternoon). The afternoon training sessions for the HB group were conducted under normobaric hypoxic conditions in a hypoxic chamber, while the NB group trained in non-simulated normoxic conditions. The profile of changes was assessed before and after the intervention (pretest vs. posttest) by analyzing the results of selected motor ability tests from the Eurofit battery and specialized fitness using the Pawluk Boxing Test.

Results: The HB group (within-group analysis) demonstrated a significant improvement in test performance for strength endurance and resistance to fatigue in the abdominal, arm, and back muscles. Specifically, the number of sit-ups increased from 27.5 ± 4.0 to 28.8 ± 3.4 (p = 0.007, d_c = 0.35), and the number of pull-ups improved from 14.9 ± 4.5 to 16.4 ± 4.6 (p = 0.005, d_c = 0.33). The intervention also led to a notable enhancement in specialized fitness, including anaerobic capacity and technical efficiency, as reflected in the number of punches delivered in 20 s (72.6 ± 9.6 to 74.3 ± 9.5, p = 0.008, d_c = 0.18), post-exercise recovery (HR 1 min: 143.3 ± 6.6 to 138.4 ±

5.8 bpm, p = 0.004, d_c = 0.79), and the multidimensional Index of Specialized Performance (4.5 ± 0.5 to 4.3 ± 0.5, p = 0.005, d_c = 0.40). These changes were not observed in the NB group (p > 0.05). Additionally, the HB group showed increased homogeneity in performance outcomes during the post-test phase. The intergroup comparison of training effects after the experiment revealed significant differences in the overall dimension of special fitness (p > 0.05), with a more favorable improvement observed in the HB group.

Conclusion: Hypoxic Boxing demonstrates the benefits of an extended, combinatory training program compared to standard protocols. Our findings hold both scientific and practical significance, as Hypoxic Boxing appears effective in enhancing selected motor abilities and multidimensional specialized fitness. Further research is needed to better understand the potential benefits and limitations of hypoxic training for combat sports athletes.

KEYWORDS

combat sports, experimental intervention, IHT, Normobaric Hypoxia, motor fitness, specialized performancecombat sports, hypoxic chamber

1 Introduction

Boxing, also referred to as "the art of fencing with fists," is the flagship discipline among striking combat sports, including those classified as Olympic sports (Kelestimur et al., 2004; Litwiniuk et al., 2022). It is practiced both at an amateur and professional level, with the pairing of competitors and the duration of bouts depending on the type of boxing, weight category, age group, and gender (Obmiński et al., 2011; Karpiński, 2020). On a technical level, competitors engage in standing positions (distance, mid-distance, clinch), utilizing specialized boxing locomotion techniques (e.g., boxing stance, sidesteps, leaps). Additionally, to gain an advantage over their opponent, they execute a variety of offensive actions (single or combination attacks: straight punches, hooks, and uppercuts) and defensive maneuvers (sidesteps, dodges, blocks, and covers) (Ambroży et al., 2015). Considering these variables, a skilled boxer should possess comprehensive motor fitness, a wide range of technical and tactical skills, and excellent physical conditioning to meet the demands of training and competition (Chaabène et al., 2015; Ambroży et al., 2016). A particularly crucial aspect is the synergy of these components, or in other words, the athlete's specific ability to function effectively within their discipline, defined as multifaceted specialized fitness (Wąsacz et al., 2024). The overarching goal of sports training is for the athlete to achieve optimal per-formance (Spieszny et al., 2024). This drives the pursuit of innovative training methods and the assessment of their effectiveness, aiming to optimize the broadly understood training process, as emphasized in numerous publications (Čepulėnas et al., 2011; Ouergui et al., 2014; El-Ashker, 2018; Çakmakçı et al., 2019).

Among theorists and practitioners, there is a consensus on the significant role of optimizing sports training in high-altitude conditions (Khodaee et al., 2016; Ramchandani et al., 2024). The effectiveness of altitude training depends on several key factors, including altitude level (typically 2000–4,000 m at 760–620 hPa), the duration of exposure (2–3 weeks for significant physiological adaptations), and the time frame in which the effects persist post-training (which may last from several days to a few weeks, depending on individual adaptation levels and training intensity). This is due to the specific combination of environmental variables that influence the dynamics of changes in broad-based training adaptation. The most critical and unique factor is the reduced availability of oxygen (hypoxia), which compels the athlete's body to undergo intensified adaptations to better cope with oxygen deficiency. This includes, among other things, an increase in erythropoietin production, blood volume, and oxygen-carrying capacity. Following recovery, the physiological adaptation positively impacts exercise performance (Mujika et al., 2019).

Considering the limiting criterion, namely the lack of desired access to high-altitude terrain, an alternative may lie in anthropotechnology, interpreted as the relationship between humans and technology. More specifically, this involves the use of specialized hypoxic and thermoclimatic chambers (normobaric or hypobaric) in training. These devices enable the artificial induction of various combinations of climatic conditions (control of altitude, temperature, and humidity, as well as the ability to create environmental conditions that do not naturally occur) (Pałka et al., 2023). The literature suggests an improvement in athletes' exercise performance following hypoxic training (Wilber, 2007). To enhance athlete functionality, one training model involves living at low altitudes while training at specific high-altitude conditions (Live Low/Train High - LL/TH). A combinatory training method using normobaric hypoxic devices is Intermittent Hypoxic Training (IHT), where athletes participate in sessions lasting 30–90 min under controlled hypoxic conditions while staying in normoxic conditions before and after the session (Ambroży et al., 2020). It is important to note that while the above-mentioned IHT studies refer to conditions simulated using normobaric hypoxia, other protocols may employ hypobaric conditions achieved by actual ascent to high-altitude environments (e.g., Mujika et al., 2019). The physiological response to hypoxia is harnessed to improve exercise capacity. Scientific reports on IHT indicate enhancements in the potential for prolonged submaximal intensity exercise (evidenced by increases in maximal oxygen uptake - VO_2 max and intensity at metabolic thresholds, particularly at the second ventilatory threshold - VT_2), which is significant in competitive sports (Dufour et al., 2006; Czuba et al., 2011). However, other studies have not observed an increase in VO_2 max under IHT conditions, potentially due to insufficient duration of hypoxia exposure or inadequate training loads (Levine, 2002; Levine and Stray-Gundersen, 2007). Diving deeper into the topic, additional research reports that hypoxic training increases anaerobic power, which enhances the effectiveness of short-duration exercises at maximal and supramaximal intensities (Meeuwsen et al., 2001; Hendriksen and Meeuwsen, 2003; Faiss et al., 2013; Puype et al., 2013). In contrast, other studies suggest that such training does not significantly impact anaerobic performance or selected motor abilities (e.g., explosive lower-limb strength, maximum running speed) (Brocherie et al., 2015; Sanchez and Borrani, 2018).

Given the conflicting reports on the effectiveness of IHT and the ongoing quest to optimize the functional profile of boxing athletes, it is worth considering the experimental design of a training program incorporating IHT. Such an initiative would allow for an assessment of the impact of this application on variables that determine training functionality and athletic performance. There is a notable lack of studies verifying the application of IHT within the combat sports domain. To the best of our knowledge, we are the first to explore the diagnosis of motor and specialized fitness changes, personalized specifically for boxing athletes. Accordingly, the aim of this study was to evaluate the impact of an experimental training program conducted under normobaric hypoxia on the development of the functional profile (selected motor abilities and specialized fitness) in a group of elite-level, national-level boxing athletes.

2 Materials and methods

The project obtained approval from the Ethics Committee at the District Medical Chamber in Krakow, under the reference number No. 226/KBL/OIL/2023. In accordance with the Helsinki Declaration requirements, the participants were informed about the research objectives, methods, potential side effects, and the option to withdraw from the study at any time without providing a reason. The participants provided written con-sent to participate.

2.1 Study design

An experimental approach with repeated measurements and a randomized controlled trial design was employed. The testing procedure was conducted before and after a 6-week intervention period. For the experimental group (HB - Hypoxic Boxing), the intervention was integrated into their regular training program, with modifications to their afternoon training sessions, which were conducted under normobaric conditions in a hypoxic chamber. The control group (NB - Normoxic Boxing) followed the same training program; however, all sessions were conducted outside the chamber, exclusively under normoxic conditions interpreted as those naturally occurring in the Krakow region of Poland. It was a deliberate experimental measure aimed at reliably comparing the effect of training under simulated high-altitude conditions with that of traditional training methods, which are commonly carried out under normoxic conditions.

2.2 Participants characteristics

The study involved a purposively selected group of 20 Polish male athletes who were actively training in boxing at a national championship level. The participants' average age was 23.9 ± 3.0 years, with a mean height of 181.3 ± 7.14 cm, body weight of 79.3 ± 8.84 kg, BMI of 24.2 ± 2.2, and an average training experience of 10 ± 4.0 years. The sample size was calculated using G*Power v 3.1.9.6 (effect size f = 0.65, α = 0.05) with anactual power of 80%. Initially, 24 competitive players were recruited. Four of them were excluded from the study due to exclusion criteria (history of injuries or health status). The inclusion criteria for the study were as follows: national championship-level boxer, current medical clearance, no history of severe injuries, positive medical recommendation, abstinence from supplementation (during the study period) and doping, and active participation in competitions. Exclusion criteria included the violation of any of the above conditions, as well as current injuries or conditions that may affect participation in training or studies, lack of consent from the athlete for participation in the study, athletes with no experience in participation in sports competitions, spending more than 48 h at an altitude exceeding 2,000 m above sea level within 6 months prior to the study. All participants were active competitors in championship-level events, including international, national, and local competitions, with some achieving notable sporting successes. The study was conducted during the preparatory phase of the training cycle. The athletes were not on restrictive diets and, during the intervention period, did not participate in competitions or sparring sessions at competition-level intensity. Information on chronological age, training experience, activity level, and competitive history was gathered using a diagnostic survey method, implemented through direct interviews with the athletes and their coaching staff.

Selection of research groups (procedure): Based on purposeful subgroups defined by weight categories, the participants were divided into two groups. At this stage, the allocation was random: one participant from each weight category was randomly assigned to one of the two study groups: HB (n = 10) or NB (n = 10). The study included athletes from the following weight categories: Lightweight (n = 5), Middleweight (n = 7), Heavyweight (n = 8). Each category was evenly distributed between the experimental and control groups. Each participant was assigned a unique identification number, and group placement was determined through a random number generator. The three-stage selection process (Stages 1 and 2 purposeful, Stage 3 random) allowed for the creation of groups with similar body mass, height, and BMI values. No significant differences were found between groups (Table 1).

2.3 Characteristics of the experimental intervention

The participants in both groups (HB and NB) followed the same training program, consisting of 4 days per week with 2 training sessions per day, over a period of 6 weeks. The control group (NB) performed all training sessions in normoxic conditions outside the hypoxic chamber to prevent any potential placebo effect. The duration of 6 weeks was selected based on previous studies investigating hypoxic training, which indicate that this

TABLE 1 Statistical characteristics of basic somatic traits in the studied groups of athletes (HB vs. NB).

Variables	Group HB (n = 10); x̄ ± sd	Group NB (n = 10); x̄ ± sd	p-value
Body height [cm]	181.8 ± 4.88	180.3 ± 4.19	0.471
Body weight [kg]	80.4 ± 8.02	78.5 ± 8.22	0.607
BMI [kg/m^2]	24.3 ± 2.11	24.2 ± 2.44	0.923

HB, hypoxic boxing; NB, normoxic boxing; x̄, arithmetic mean; sd, standard deviation; *p*, level of significance.

period allows for measurable physiological adaptations, such as increased erythropoiesis and enhanced anaerobic performance (Wilber, 2007; Mujika et al., 2019). Additionally, a 6-week training cycle aligns with typical preparatory phases in elite boxing training schedules. In the morning, they performed a 60-min technical-tactical boxing training session, which included low and moderate-intensity exercises (up to 50% of maximum load). In the afternoon, they completed a 60-min session aimed at developing and enhancing endurance and motor abilities. The total weekly training time was 480 min. The difference in the applied intervention was that the boxers in the HB group carried out their afternoon training session under normobaric hypoxia. The hypoxic chamber (Wichary Technologies, Żory, Poland) measured 5 m × 5 m × 3 m and allowed for simultaneous training of up to 5 athletes. The CO_2 levels inside the chamber were maintained below 0.5%. IHT was applied in a normobaric hypoxic chamber (Wichary Technologie, Żory, Poland) at a simulated altitude of 4,000 m (FiO_2 = 12.9%), with a temperature of 21°C–22°C and air humidity between 40% and 45%. The athletes in the NB group completed their training cycle in Kraków (natural climate), exclusively in normoxic conditions (230 m above sea level). To assess the profile of changes induced by the intervention, two measurement points were used. The first measurement was taken before the start of the program (baseline diagnosis of variables: pre-test). The second measurement was taken after the completion of the 6-week training period (effectiveness assessment: post-test). The final tests were conducted 24 h after the completion of the last training session. The chosen time interval allowed for adequate athlete recovery, eliminating the influence of immediate fatigue and transient effects, while simultaneously enabling the evaluation of lasting training adaptations (Mujika et al., 2019). The impact of the experimental training was evaluated within the HB group (intra-group) and compared to the NB group (inter-group), which served as a reference point for comparison. A flow diagram of the research intervention is presented in Figure 1.

2.4 Characteristics of the applied training program

The first training session in the morning (9:00–10:00) focused on the technical and tactical aspects of boxing, with the specifics outlined in Table 2. The second training session in the afternoon (18:00–19:00) consisted of two phases (see Table 3). The first phase (a 3-week application period) was based on various functional training guidelines using bodyweight resistance exercises (Ambroży, 2008) in a circuit training format (Ambroży, 2007). The second phase (the subsequent 3-week intervention) was focused on developing and enhancing endurance abilities, utilizing the airbike Airdyne AD7 (Schwinn, Chicago, United States).

The key priorities of the program were its structure (exercise content, sequence, number of sets, and repetitions), which encompassed aspects related to technical-tactical skills, muscular fitness, and physical endurance. The exercises were designed and implemented with the aim of optimizing a broad hybrid of specialized fitness, a crucial area for the effective performance of an athlete in their specific sport discipline (Wąsacz, 2023).

2.5 Measurements of motor and specialized fitness

Each time before the measurements, both groups participated in a standard 15-min warm-up session consisting of exercises to prepare the body for physical effort. All tests were performed in normobaric conditions. Exercises were conducted in accordance with the principle of formative exercises and involved static and dynamic movements of the arm, trunk, abdomen, back, and legs. The examiner demonstrated each test according to the procedure, then provided instructions and clarifications. Effective recovery breaks (at least 15 min) were observed between trials.

Motor fitness, in the context of selected motor abilities, was assessed using standardized population tests from the EUROFIT battery (European Physical Fitness Test) (Grabowski and Szopa, 1989) and general physical fitness tests (Talaga, 2004). The selection of motor tests was based on years of athlete-coach practice (choosing those trials that are subjectively the most useful for the physical demands of elite boxers). Additionally, the EUROFIT protocol includes the bent-arm hang test, which assesses the potential for force generation in an isometric dimension, a priority plane in grappling combat sports (Wąsacz and Pociecha, 2021; Wąsacz et al., 2022; Wąsacz et al., 2023). The pull-up test (Talaga, 2004) was applied as a more appropriate measure of strength fitness in relation to the specificity of boxing. The testing procedure included the following trials:

1. Standing long jump (explosive power): the subject stands with the feet slightly apart in front of the starting line, bends the knees, and moves the arms backward at the same time, and then he or she performs the arm swing and jumps as far as they can; the landing occurs on both feet while maintaining the upright position; the test is performed twice. The longest of the two jumps measured to the closest mark left by the participant'sheel is recorded, with an accuracy of 1 cm. A tape measure, a hard surface, and two gymnastic mattresses connected lengthwise are used.
2. Static handgrip strength measurement: The participant, standing with feet slightly apart, held the dynamometer firmly in the fingers, with the arm positioned along the torso, ensuring the hand did not touch the body. The participant performed a brief maximal grip, while the other arm rested alongside the body. The best result of two maximal static strength tests of the dominant hand (HGSmax) was recorded using a dynamometer

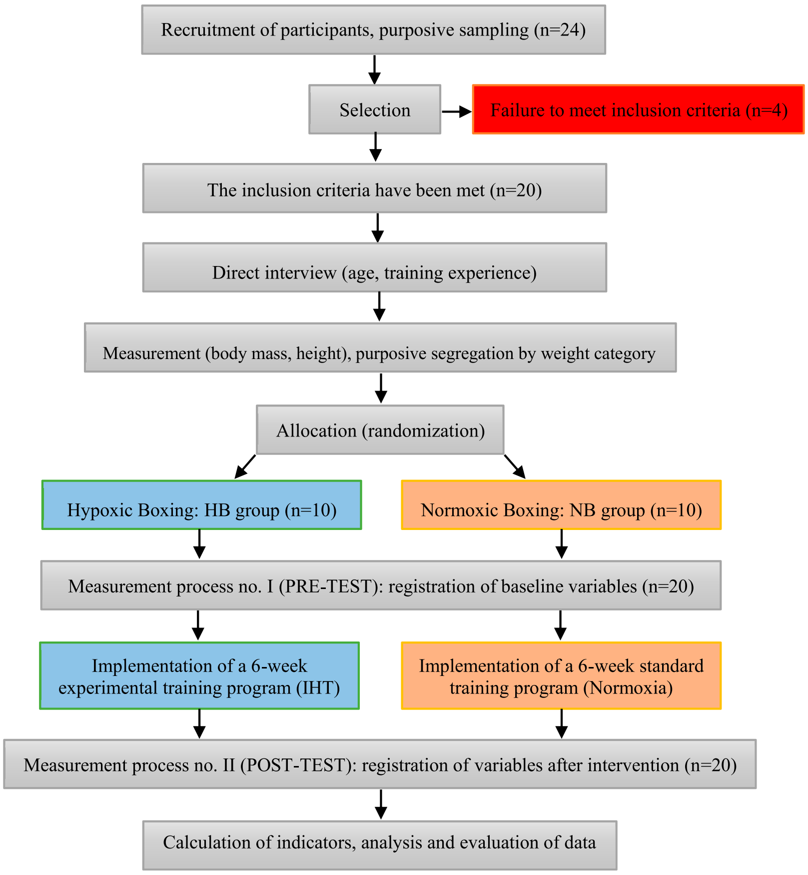

FIGURE 1
Flowchart of the research intervention.

(MG 4800, Charder, Taichung, Taiwan) with an accuracy of 1 kg. The rest interval between tests was 5 min.

3. Sit-ups (strength endurance of the abdominal muscles): The participant lay on a mat with feet 30 cm apart and knees bent at a 90-degree angle. Hands were clasped behind the neck, and a partner held the participant's feet. At the start signal, the participant sat up, touched the knees with elbows, and returned to the starting position. The duration was 30 s, and the result was the number of repetitions completed.
4. Pull-ups on the bar (arm strength): evaluation of the strength of the shoulder girdle based on the number of repetitions: the subject catches the bar using a pronated grip and hangs; at the signal, the subject bends arms in elbows and pulls the body up so high that the chin is above the bar and then, without rest, returns to a simple hanging; the exercise is repeated as many times as possible without rest; the result is the number of complete pull-ups (chin over the bar).

To diagnose specialized fitness, the Pawluk Boxing Test (Fidziński, 1982) was used. While high-altitude training is primarily associated with improvements in aerobic endurance, the present study focused on anaerobic capacity and sport-specific performance. Therefore, a traditional aerobic test such as the 20 m shuttle run was not included. Instead, the Pawluk Boxing Test was selected as a more relevant measure of short-duration high-intensity effort. The posttest assessments were conducted 24 h after the last training session to minimize the impact of acute fatigue and ensure reliable performance measurements. This is a specific and specialized research tool for assessing and monitoring the level of this variable in boxing activity (Adamczyk et al., 2013; Szot et al., 2017). According to the test protocol, the test involved performing the maximum number of punches on a punching bag within 20 s. The participant assumed a fighting distance, directly and frontally in front of the punching bag, adopting a boxing stance with a guard on their dominant side. Upon the “box” command, the participant began the trial, executing any punches (straight, hook, or uppercut). The procedure required performing the punches with maximum speed under supramaximal effort conditions. The “stop” command signified the end of the trial. The evaluation focused on: the number of correctly landed punches. This was assessed retrospectively based on a video recording played in slow motion. The heart rate (HR bpm) was also measured immediately after the test (HR final), and 1 minute after completing the test (HR 1min) (see Figure 2). Following Sterkowicz's method developed for judo (Sterkowicz, 1995), the Special Endurance Indexes of the Pawluk Test were calculated according to the following formula:

$$\text{Index Pawluk's Boxing Test} = \frac{HR\ final\,(bpm) + HR\,1\ min\,.(bpm)}{The\ total\ number\ of\ punches\ thrown}$$

TABLE 2 Structure of the technical-tactical training unit in a morning session.

Preliminary part (10 min)	Main part (40 min)	Final part (10 min)
7 min general segment: light jog; shaping exercises according to the gymnastic routine	First 2 weeks of the training period: 15 min column-based technical exercises: single punches or combinations (straight-hooks-uppercuts) performed together with steps (forward-backward-left-right)	7 min flexibility and mobility exercises
3 min specialized segment: shadow boxing	25 min technical exercises in pairs: one trainee delivers punches alternately single or in combinations (straight-hooks-uppercuts) together with steps (forward-backward-left-right), while the other trainee performs alternating defenses (block-parry-slip-lean-back-step-backside-step-ducking).	3 min relaxation exercises, calming the body
	Next 4 weeks of the training period: Same training content performed from the opposite boxing stance to the usual one	

TABLE 3 Structure of the motor and effort training unit in an afternoon session.

Preliminary part (10 min)	Main part (40 min)	Final part (10 min)
7 min general segment: light jog; shaping exercises according to the gymnastic routine	First 3 weeks of the training period (strength endurance): 5 min dynamic stretching exercises 5 min free work with a jump rope 30 min station-based circuit: Resistance – body weight Number of exercises per circuit – 6 Number of circuit repetitions – 4 Exercise duration – 30 s Tempo – fast Passive rest between circuits – 180 s No breaks between exercises within a circuit 1st station: Squat jump 2nd station: Push-ups 3rd station: Russian twists 4th station: Lunges 5th station: Plank 6th station: Mountain climbers	6 min flexibility and mobility exercises
3 min specialized segment: shadow boxing or coordination ladder exercises	Subsequent 3 weeks of the training period (effort abilities): 5 min dynamic stretching exercises 5 min free work with a jump rope 30 min interval effort (airbike): Interval program 20/50: 8 rounds, 20 s work at maximum subjective intensity/interspersed with 50 s recovery interval performed at four times lower intensity, program performed twice	4 min relaxation exercises, calming the body

Where:

HR final - heart rate recorded immediately after completion of the test.

HR 1min - heart rate recorded 1 min after the completion of the test.

The total number of punches thrown - The number of punches delivered in 20 s.

The index reflects the level of a boxer's special endurance, which signifies the effective collaboration of the body's exertional capabilities, overall fitness, and technical skills. The interpretation of the test result is inversely proportional–the higher the level of special endurance, the lower the value of the index (Ambroży et al., 2021; Chwała et al., 2023; Wąsacz, 2023; Wąsacz et al., 2024).

2.6 Statistical analysis

In the analysis of the research results, basic statistical methods were used, including the calculation of the arithmetic mean, median, standard deviation, minimum and maximum values, and the coefficient of variation. To assess the significance of differences between groups, the independent samples t-test or the non-parametric Mann–Whitney U test was used. To evaluate the significance of within-group changes (differences in the progression of a given group), the paired samples t-test or the non-parametric Wilcoxon signed-rank test for paired observations was applied. Furthermore, the effectsize was calculated using Cohen's d index (d = 0.20, weak effect; d = 0.50, moderate effect; d = 0.80, strong effect). The choice of tests was preceded by checking the normality of variable distributions using the Shapiro–Wilk test, which confirmed normality for some variables (NB: standing long jump p = 0.221, pull-ups p = 0.334, final HR p = 0.341, HR 1 min p = 0.061, index p = 0.622. HB: grip strength p = 0.212, sit-ups p = 0.324, number of punches p = 0.287, final HR p = 0.075, HR 1 min p

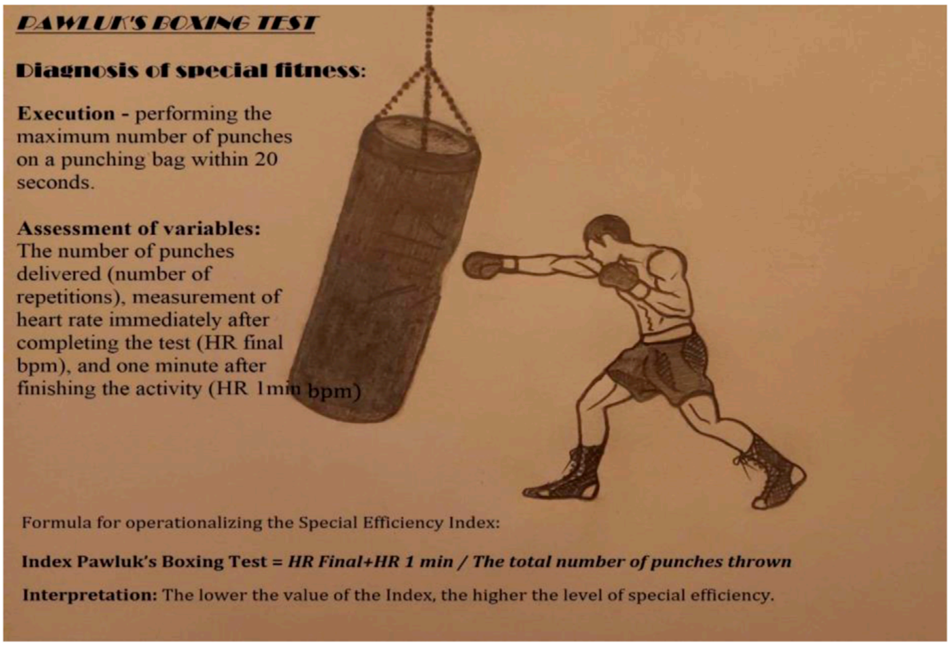

FIGURE 2
Graphical diagram of the Pawluk's Boxing Test execution. Source: Authors' own elaboration.

= 0.201, index p = 0.124), while indicating a significant deviation from normality for others (NB: grip strength p = 0.043, sit-ups p = 0.012, number of punches p = 0.016. HB: standing long jump p = 0.031, pull-ups p = 0.023. The degree of intragroup diversity was as-sessed by interpreting the coefficient of variation values according to the classification: CV < 25% indicates low variability; 25%–45% indicates moderate variability, 45%–100% indi-cates high variability; >100% indicates very high variability (Cohen, 2013). The collected data were analyzed using Statistica software, version 13.3 (Statsoft, Krakow, Poland). The threshold for statistical significance was set at $p < 0.05$.

3 Results

3.1 Results of the assessment of the profile of changes in selected motor abilities

The test effects of the studied groups and their level of intergroup (HB vs NB) and intragroup differentiation are presented in Table 4.

With respect to the baseline assessment (first measurement–pretest), the groups exhibited a similar level of selected components of motor fitness, as measured by population tests, with no significant differentiation observed (p > 0.05). However, significant effect sizes were noted for the results of the long jump and sit-ups from a lying position, both favoring the HB group, with the effect sizes being strong and moderate, respectively. An opposite trend was observed for pull-ups on a bar, where the NB group performed better, with a moderate effect size.

After 6 weeks of applying the experimental stimulus (second measurement–posttest), intergroup comparisons did not reveal significant differences in the levels of the test variables (p > 0.05). However, in order to isolate the initial level of variables in the groups, the analysis of the mean difference comparison showed a significant variation for the standing long jump (p = 0.002), where a more favorable progress was observed in the NB group. The HB group demonstrated better abdominal muscle endurance in the sit-ups test, with a strong effect size noted.

Comparative analysis of intragroup progression revealed significant differentiation for improvements in the efficiency of sit-ups (p = 0.007) and pull-ups (p = 0.005) within the HB group. For the NB group, such an effect was observed only for explosive strength, as measured by the standing long jump (p = 0.005).

The variability coefficients indicate that internal differentiation of the analyzed test variables within both groups (HB vs NB) was very low (CV = 4–24%). Regarding the efficiency of strength endurance in arm and back muscles, as assessed by the pull-up test, moderate internal differentiation bordering on very low was observed in both measurement points (CV = 24.4–30.1%).

3.2 Results of the assessment of the profile of changes in specific fitness variables

Table 5 presents the profile of changes in the components of special fitness as-sessed using the Pawluk Boxing Test, as well as the degree of intergroup and intragroup differentiation within the studied groups of boxers (HB vs NB).

The baseline assessment (pretest) revealed a similar intergroup level for all test variables (p > 0.05).

In the HB group, following 6 weeks of experimental training (pretest vs posttest), improved results were observed

TABLE 4 The statistical characterization of the profile of selected motor abilities and their variability (intergroup and intragroup) in the studied groups (HB vs. NB) of boxers (n = 20).

Measurement	Group HB (n = 10)			Group NB (n = 10)			d_1	p_1	d_{c1}
	x̄	sd	CV(%)	x̄	sd	CV(%)			
Standing long jump - explosive power [cm]									
I pre-test	234.6	13.3	5.7	226.2	12.5	5.5	8.2	0.162	0.65*
II post-test	235.4	13.4	5.7	231.4	9.7	4.2	4.0	0.455	0.35
d_2	0.8	1.6	202.4	5.2	3.0	57.2	−4.4	**0.002**	1.91*
p_2	0.153			**0.005**			-	-	-
d_{c2}	0.06			0.47**			-	-	-
Static handgrip strength measurement [kG]									
I pre-test	54.3	6.1	11.2	54.0	6.5	12.1	0.3	0.894	0.05
II post-test	54.7	6.2	11.3	54.4	5.7	10.4	0.3	0.938	0.05
d_2	0.38	1.2	302.6	0.37	1.5	402.9	0.01	0.762	0.01
p_2	0.150			0.479			-	-	-
d_{c2}	0.07			0.07			-	-	-
Sit-ups - strength endurance of the abdominal muscles [Number of repetitions]									
I pre-test	27.5	4.0	14.4	26.1	2.9	10.9	1.4	0.375	0.41**
II post-test	28.8	3.4	11.8	26.7	2.8	10.6	2.1	0.150	0.68*
d_2	1.3	1.2	89.2	0.6	1.0	161.0	0.7	0.151	0.64**
p_2	**0.007**			0.081			-	-	-
d_{c2}	0.35**			0.21			-	-	-
Pull-ups on the bar - arm strength [Number of repetitions]									
I pre-test	14.9	4.5	30.1	16.5	4.4	26.8	−1.6	0.433	0.36**
II post-test	16.4	4.6	28.1	17.8	4.3	24.4	−1.4	0.493	0.31
d_2	1.5	1.5	100.6	1.3	1.2	89.2	0.2	0.521	0.15
p_2	**0.005**			0.074			-	-	-
d_{c2}	0.33			0.30			-	-	-

HB, hypoxic boxing; NB, normoxic boxing; x̄, arithmetic mean; sd, standard deviation; CV%, coefficient of variation; I, first measurement period (pre-test); II, second measurement period (post-test).
d, difference between means (delta); *p*, level of significance; level of significance statistically significant values are shown in bold (p < 0.05); d_C, effect size expressed using Cohen's *d* coefficient (intergroup);*strong effect;**moderate effect; $_1$, data concerning inter-group variability; $_2$, data concerning intra-group variability.

across all aspects of special fitness. The observed intergroup variation for the averaged results (HB vs NB groups) was characterized by a lack of significant differences (p > 0.05). However, in the analysis of mean differences, significant differences were noted for the number of punches (p = 0.034), post-exercise recovery–HR 1 min (p = 0.009), and the multidimensional Special Performance Index (p = 0.010), with a more favorable training effect observed in the HB group.

The comparative analysis (within-group) of test efficiency gains showed significant variation for quantitative technical performance–number of punches delivered (p = 0.008), post-exercise recovery–HR 1 min (p = 0.004), and the multidimensional Special Performance Index (p = 0.005) in the HB group, where

TABLE 5 The statistical characterization of variables related to specific fitness and their variability (intergroup and intragroup) in the studied groups (HB vs NB) of boxers (n = 20).

Measurement	Group HB (n = 10)			Group NB (n = 10)			d_1	p_1	d_{c1}
	x̄	sd	CV(%)	x̄	sd	CV(%)			
The total number of punches thrown [number of repetitions]									
I pre-test	72.6	9.6	13.2	71.9	9.8	13.6	0.7	0.762	0.07
II post-test	74.3	9.5	12.7	72.4	10.5	14.6	1.9	0.496	0.19
d_2	1.7	1.0	55.8	0.5	1.2	235.7	1.2	**0.034**	1.09*
p_2	**0.008**			0.236			-	-	-
d_{c2}	0.18			0.05			-	-	-
HR final [bpm]									
I pre-test	178.9	5.9	3.3	180.2	5.8	3.2	−1.3	0.624	0.22
II post-test	179.5	5.9	3.3	181.3	7.4	4.1	−1.8	0.554	0.27
d_2	0.6	4.2	699.2	1.1	3.0	275.9	−0.5	0.764	0.14
p_2	0.662			0.281			-	-	-
d_{c2}	0.10			0.17			-	-	-
HR 1 min [bpm]									
I pre-test	143.3	6.6	4.6	142.2	7.7	5.5	1.1	0.736	0.15
II post-test	138.4	5.8	4.2	141.4	7.3	5.2	−3.0	0.323	0.46**
d_2	−4.9	4.0	−81.9	−0.8	1.9	−241.5	−4.1	**0.009**	1.39*
p_2	**0.004**			0.223			-	-	-
d_{c2}	0.79*			0.11			-	-	-
Index Pawluk's Boxing Test									
I pre-test	4.5	0.5	11.2	4.5	0.5	12.0	0.0	0.829	0.00
II post-test	4.3	0.5	10.9	4.5	0.6	12.6	−0.2	0.411	0.36**
d_2	−0.2	0.1	−84.9	0.0	0.1	−435.8	−0.2	**0.010**	2.00*
p_2	**0.005**			0.487			-	-	-
d_{c2}	0.40**			0.00			-	-	-

HB, hypoxic boxing; NB, normoxic boxing; x̄, arithmetic mean; sd, standard deviation; CV%, coefficient of variation; I, first measurement period (pre-test); II, second measurement period (post-test).
d, difference between means (delta); *p*, level of significance; level of significance statistically significant values are shown in bold ($p < 0.05$); d_C, effect size expressed using Cohen's *d* coefficient; *strong effect; **moderate effect; $_1$, data concerning inter-group variability; $_2$, data concerning intra-group variability.

significantly more favorable results were observed. Such cause-and-effect relationships were not found in the NB group ($p > 0.05$).

The variability coefficients demonstrated that the internal variability of the analyzed test variables was very low in both groups (CV = 3.2–14.6%). The averaged CV% values from the two measurement sessions indicate greater homogeneity in the HB group, with progressive improvement in homogeneity during each subsequent measurement in the experimental procedure (average test variability index for the HB group: pretest = 8.08%; posttest = 7.78% vs. the NB group: pretest = 8.58%; posttest = 9.13%).

4 Discussion

The aim of this study was to investigate the impact of a 6-week targeted training program, "Hypoxic Boxing," designed to optimize selected aspects of motor abilities and broadly defined special fitness—key determinants of performance outcomes in this sport activity (Chwała et al., 2023). The experimental intervention incorporated intermittent simulated high-altitude conditions (LL/TH + IHT) combined with resistance, endurance, and boxing-specific exercises. According to theorists and discussions within the practical sports community, training under hypoxic conditions is gaining significance in the context of optimizing training processes, especially for endurance sports (Czuba et al., 2011), but also for specific areas of combat sports (Arabaci, 2015), including boxing (Ambroży et al., 2020). A thorough analysis of the relevant literature identified a research gap concerning the evaluation of IHT interventions' effectiveness in the boxing environment on general and special fitness profiles. This study aimed to address this scientific and practical gap to further develop the dis-cipline. Our findings demonstrated that this approach was effective for the HB (experimental) group, leading to improvements in some motor abilities and, essentially, all verified variables that constitute the profile of special fitness, which is crucial for combat sports (Szot et al., 2017).

The analysis of intragroup differentiation revealed significant progressions in the strength endurance of the abdominal (p = 0.007), arm, and back muscles (p = 0.005), as assessed through the sit-ups and pull-ups tests. Posttest results indicated an average improvement of 1.3 repetitions in sit-ups and 1.5 repetitions in pull-ups, indicating a moderately significant improvement (d_c = 0.35 and 0.33). This suggests enhanced muscle fatigue resistance and an associated improvement in the body's tolerance to acidification, which can be critical during prolonged sessions of intermittent high-intensity efforts commonly observed in boxing (Slimani et al., 2017). This improvement is also significant from a technical perspective, as nearly every technical action in boxing relies on the efficient muscular and energetic function of these areas (Sharkey and Gaskill, 2013). Motor abilities related to generating maximum force in short bursts (2–10 s), assessed through hand dynamometry and the standing long jump, also showed improvement, although the changes were not statistically significant ($p > 0.05$). In contrast, Hagiwara et al., in their case study of two international-level fencers, reported an increase in explosive power after 3 weeks of sprint training under hypoxic conditions (Hagiwara et al., 2023). The differing outcomes might be attributed to methodological differences, as their training content specifically targeted the improvement of this variable. Interestingly, in the NB (control) group, a significant increase (p = 0.005) was observed for explosive strength, as assessed by the standing long jump. Participants in this group improved their posttest results by an average of 5.2 cm (moderately significant improvement d_c = 0.47). For other variables within this group, no significant improvement was noted.

General motor tests do not always correlate directly with sports performance (Ambroży et al., 2021). Therefore, it is highly appropriate to use specific research tools to diagnose and monitor the unique hybrid of an athlete's abilities required for effective performance in their discipline (Wąsacz et al., 2024). It is crucial that these tools are designed based on the technical-tactical aspects of the sport and simulate the conditions of real competitive confrontations (Wąsacz, 2023). In this study, a trend of overall improvement was also observed for multidimensional special fitness, as assessed by the Pawluk Boxing Test. The HB group demonstrated significant intragroup progress in the number of punches delivered in 20 s (p = 0.008), with an average posttest improvement of 1.7 punches. This indicates enhanced ability to deliver punches at full speed and suggests improved anaerobic performance (Zatoń and Jastrzębska, 2020). Similar findings were reported by Ran Wang et al., who observed improvements in anaerobic capacity among amateur female boxers following a short-term Live Low-Exercise High training period (21 days) (Wang et al., 2015). Likewise, Ambroży et al. found a similar trend of improvement in anaerobic performance among elite national-level boxers after a 6-week intervention (Ambroży et al., 2020). Significantly better results were also recorded for post-exercise recovery during the first minute (HR 1 min) (p = 0.004), with an average posttest reduction of 4.9 bpm. This indicates strong progression (d_c = 0.79). This improvement is particularly relevant for recovery between rounds during a bout, as well as during tournaments where athletes may need to compete multiple times in 1 day. As a result of these progressions, a marked improvement (p = 0.005; d_c = 0.40)) was observed in the operationalized indicator of broad special fitness (Index). This effect was not seen in the NB group ($p > 0.05$), confirming the more effective and comprehensive training adaptation of the HB group subjected to intermittent hypoxic training. These results highlight the potential of such innovative training stimuli, utilizing advanced anthropotechnics like hypoxic chambers. When analyzing the global results (motor and special fitness), a functional improvement trend can be noted for high-intensity efforts lasting 20–60 s. Qualitatively, this appears related to the improved efficiency of the glycolytic system (anaerobic glycolysis) (Sharkey and Gaskill, 2013). However, no similar improvements were observed in the HB group for short-duration efforts of 2–5 s (maximum isometric static strength in handgrip dynamometry or explosive strength in the standing long jump). This suggests that the participants' phosphagen system (ATP-PCr) did not significantly respond to the experimental intervention. Based on these observations, it can also be qualitatively inferred (Grabowski, 2022) that appropriately applying diverse training stimuli during sensitive periods (Szopa et al., 1996) is crucial for effective periodization of the training process (e.g., a macrocycle—a long-term training plan for preparation for an Olympic form or high-level competition).

A comparison between groups with a randomized control trial did not reveal the significant nature of these changes ($p > 0.05$). The HB group demonstrated more favorable final test outcomes, except for the pull-up test, where the NB group excelled. In order to isolate the baseline level (pretest) for each variable, an analysis of the training effects was conducted, revealing significant differentiation in the number of strikes (p = 0.034; dc = 1.09), post-exercise recovery (p = 0.009; dc = 1.39), and the special performance index (p = 0.010; dc = 2.00), with a stronger, more favorable training effect observed in the HB group. In the NB group, a similar trend was noted for the standing long jump (p = 0.002; d = 1.91). This confirms the high effectiveness of Hypoxic Boxing in the broad optimization of the training process. Future explorations should consider the proportions of exercise content, their intensity, training period, and exposure under IHT conditions. Arabaci, in his research, reported improvements in anaerobic power, 1-RM strength, and aerobic capacity in elite freestyle wrestlers after 8 weeks of intermittent hypoxic training (Arabaci, 2015). It is recommended that future interventions incorporate longer periods of the discussed stimulus to verify the potential for generating even stronger training adaptations (Škarabot et al., 2020) with more pronounced changes.

4.1 Limitations of the study

At this stage, the sample size can be considered a limitation of the presented study, although the participants were elite athletes in their field. Additionally, the specific profile of participants (boxers) may limit the generalizability of the results to other populations of athletes. Another limitation is the inclusion of different weight categories, as physiological demands may differ between lightweight and heavyweight athletes. To capture the multifaceted context of the problem, future studies should consider extending the intervention duration, increasing the number of participants, including female athletes, and involving representatives of other combat sports. Such measures would help confirm the findings presented in this study and provide broader insights into the effects of the training protocols examined.

5 Conclusion

Our findings hold scientific and cognitive significance in understanding the causal relationships between the Hypoxic Boxing training program and the dependent motor and special fitness profiles of boxing athletes. The proposed intervention in the HB group appears effective in improving selected motor abilities and overall special fitness. Despite the absence of significant changes in test outcomes measuring the potential to generate maximal force over short periods (hand dynamometry, standing long jump), the implemented program, augmented with intermittent hypoxic training (IHT), led to improved test performance in muscular endurance and fatigue resistance of the ab-dominal, arm, and back muscles (sit-ups, pull-ups) within the HB group. The experi-mental stimulus applied to the HB group significantly enhanced special fitness com-ponents, including anaerobic capacity, technical efficiency (number of punches in 20 s), post-exercise recovery (HR 1 min), and, ultimately, the multidimensional Index of Special Fitness. These improvements were not observed in the NB group. Furthermore, the progressive homogeneity of results in the HB group across subsequent stages of the experiment highlights the beneficial global impact of the program on the HB cohort. This approach underscores the advantages of adopting an extended, com-bined training program compared to standard protocols. It also emphasizes the neces-sity for ongoing exploration of innovative training interventions to optimize the func-tional profiles of athletes in this field to their maximum potential.

5.1 Practical implications

The 6-week Hypoxic Boxing training program can be considered an effective practical approach for shaping and enhancing the motor and special fitness profiles of elite-level boxers. The results have valuable practical implications for coaches and athletes in this sport. Hypoxic Boxing is recommended for inclusion in training practices and its evaluation in other athletic categories, including different competitive levels, age groups, and female athletes. Moreover, the potential exists to adapt the modified training program using the combined IHT method to other combat sports disciplines, where a strong motor fitness base and multidimensional special fitness are essential and determinative of athletic success.

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 at the District Medical Chamber in Krakow, under the reference number No. 226/KBL/OIL/2023. 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.

Author contributions

TA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. PS: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Writing–original draft, Writing–review and editing. ŁR: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Validation, Writing–original draft, Writing–review and editing. AK: Data curation, Project administration, Supervision, Writing–original draft, Writing–review and editing. WW: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Bajiquan martial arts training as physical activity for enhancing physical fitness, body composition, and perceived exercise benefits: a quasi-experimental study

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Background: Martial arts are a traditional aspect of Chinese culture, and with the diverse development of recreational activities, they have gained widespread acceptance not only for self-defense but also as a popular recreational activity. Physical activity and fitness characteristics associated with different martial arts vary depending on developmental backgrounds. Bajiquan is a traditional Chinese martial art known for its explosive power in close combat, emphasizing quick elbow and shoulder strikes over a short range. However, research on the application of Bajiquan to physical activity, health promotion, and its perceived benefits remains relatively limited. This study aimed to investigate the effects of a programmed 8-week Bajiquan training intervention on physical fitness, body composition, and perceived benefits of exercise.

Methods: This quasi-experimental study enrolled participants and allocated them to the experimental ($n = 15$; 27.4 ± 2.6 years; female = 13.3%) and control groups ($n = 15$; 26.0 ± 3.1 years; female = 13.3%). The experimental group participated in an 8-week Bajiquan program, whereas the control group engaged in regular exercise with the same intervention frequency. Pre- and post-tests were conducted to assess the effects on physical fitness and body composition. Additionally, participants' subjective perceptions of the benefits of martial arts exercise were evaluated using an exercise perceived benefit questionnaire.

Results: The experimental group demonstrated significantly higher social relationships ($\Delta = 17.2\%$; $\delta = 0.586$, $p < 0.05$) and personal benefits ($\Delta = 19.8\%$; $\delta = 0.431$, $p < 0.05$) than the control group ($p < 0.05$). Changes in pre- and post-test measurements within the experimental group were significantly different from those in the control group in terms of body weight ($p = 0.008$, $d = 1.05$), body mass index ($p = 0.003$, $d = 1.17$), and body fat percentage ($p = 0.004$, $d = 1.13$). The experimental group exhibited significant differences in changes in muscle explosive power ($p = 0.003$, $d = 1.27$), cardiorespiratory fitness ($p = 0.004$, $d = 1.14$), and core muscle strength ($p = 0.009$, $d = 1.10$) compared with the control group. Core muscle strength also significantly increased in the experimental group compared to that in the control group in the post-test ($\Delta = 17.0\%$; $p = 0.003$, $d = 1.21$).

Conclusions: The Bajiquan martial arts exercise intervention demonstrated beneficial effects on physical and mental development, making it a viable option for physical activity programs. In the future, program adjustments and applications can be tailored for different populations, such as children or the elderly, to promote health and disseminate the practice of martial arts.

KEYWORDS

traditional martial arts, physical fitness, recreation activity, health promotion, Bajiquan

1 Introduction

Bajiquan is a traditional Chinese martial art originating in Hebei Province, northern China. It is characterized by explosive power and short-range force, with a focus on elbow strikes and close-quarter combat. Bajiquan has gained popularity in recent decades in northern China and Taiwan due to its self-defense applications and unique martial arts characteristics. It has since expanded to Japan, South Korea, and various Western countries. The essence of Bajiquan lies in the application of explosive power, which is achieved through instantaneous acceleration from the waist to the limbs during attacks. Its primary techniques include elbow strikes, arm punches, fist strikes, hip strikes, and shoulder strikes, with a strong emphasis on lower-body training and footwork coordination (1). Martial arts training, which emphasizes full-body movement patterns, philosophy, interpersonal interactions, and self-defense, positively affects physical activity, mental health, and cognitive well-being in adults and children. Martial arts are a form of exercise therapy that can be provided to people of all ages to promote holistic health (2). In the elderly population, Judo practice may have positive effects on three main areas: physiological health (including bone health, anthropometric measures, and quality of life), functional fitness (such as balance, strength, and walking speed), and psychosocial well-being (including fear of falling, cognitive function, and self-efficacy) (3). In recent years, the number of people participating in martial arts has increased steadily. A report on martial arts participation in Australia indicates that 1.2% of the adult 15+ population engages in martial arts, with 85% of participation being organized. The total annual spending on martial arts reaches $87 million. Additionally, there is a 49% potential market growth, with strong interest across all age groups, particularly among older adults (65+) considering participation (4). This indicates a growing trend in using martial arts as a form of exercise or physical activity.

The application of martial arts in health promotion is particularly beneficial for older adults as it can improve strength, mobility, aerobic endurance, flexibility, and balance (5). For adults, the positive effects of martial arts practice include improvements in balance, cognitive function, and mental health. However, further investigation and long-term follow-up are required to fully understand these benefits (6). Previous studies on young adults have also examined the modulation of hormones, such as oxytocin, in relation to martial arts training, highlighting that its effects may vary across different populations. Additionally, martial arts experience has been associated with enhanced selective attention (7, 8). Evidence also demonstrates a positive correlation between practicing martial arts and health behaviors and higher scores in quality of life (9). These studies demonstrated that martial arts can be used as a form of physical activity and therapeutic intervention, offering health and developmental benefits across different populations.

Globally, one-third of the age-standardized adult population (31.3%) is physically inactive, as indicated by population-based surveys (10). Sedentary behavior has numerous detrimental effects on health including increased risks of all-cause mortality, cardiovascular disease mortality, cancer, metabolic disorders, mental health issues, and cognitive impairment. Reducing sedentary behaviors and increasing physical activity are crucial for promoting public health (11). Increasing physical activity is effective in preventing chronic diseases and premature mortality, with a positive relationship observed between physical activity and health outcomes (12). In addition to improving obesity and physical fitness, increased physical activity plays a vital role in emotional stability and mental health (13). Previous research has shown that martial arts such as Taekwondo positively influences body composition and reduces obesity (14). In addition, findings from the literature review indicate that Judo positively impacts children and adolescents by improving body fat composition, modulating bone mineralization, and enhancing the cardiorespiratory system (15). However, owing to the limitations of existing studies, such as a lack of research, heterogeneity, short intervention periods, small sample sizes, and methodological constraints, whether martial arts are effective in improving anthropometric measures and body composition in individuals with overweight and obesity remains unclear (16). Therefore, whether martial arts can be considered suitable for weight control requires further evaluation.

The impact of martial arts on health has been studied primarily in specific disciplines. Tai Chi is the most extensively studied form of martial arts, followed by Judo, Karate, and Taekwondo. Although further standardized research is needed, existing evidence suggests that traditional martial arts can serve as exercise prescriptions for various populations (17). In recent years, martial arts research has primarily focused on mixed martial arts, such as Tai Chi, Judo, Karate, and Taekwondo. Martial arts emphasize not only self-defense but also movement patterns and interpersonal interactions. They can be considered a form of exercise therapy that benefits physical activity, psychological well-being, and cognitive health across all age groups (2, 6). However, empirical research on Bajiquan is lacking. Therefore, this study aims to examine the effects of a

Bajiquan training program on body composition and physical fitness. Additionally, the perceived benefits of martial arts will be assessed through the development of a Martial Arts Perceived Benefits Questionnaire, ensuring validated reliability and validity. The findings of this study hold significant implications for the future application and promotion of Bajiquan as a means to achieve health promotion objectives.

2 Materials and methods

2.1 Experimental design

Participants were recruited from fitness centers and screened based on the following eligibility criteria. The study groups (experimental and control) were selected using convenience sampling for an exploratory study in present study. The experiment was based on quasi-experimental design with a parallel control group for pretest–posttest evaluations following the martial intervention (duration: 2023.4.3 to 2023.7.3). The inclusion criteria were as follows: no experience of any musculoskeletal injuries within the past month and ability to engage in normal training activities; without cognitive impairment; capability to understand the questionnaire; and ability to complete it online. The exclusion criteria were as follows: diagnosis of musculoskeletal disorders, joint diseases, unstable cardiovascular conditions, or cognitive impairments; deemed unfit for physical activity by a physician; and inability to understand or complete the questionnaire online. All participants provided written informed consent. This study implemented an 8-week Bajiquan Martial Arts Training Program as an intervention. Pre- and post-intervention assessments were conducted to evaluate the effects of martial arts training on body composition, functional fitness, and the perceived benefits of exercise. This study was reviewed and approved by the Fu Jen Catholic University Institutional Review Board (New Taipei City, Taiwan; C111137) (valid duration: 2023.3.29 to 2024.3.28).

2.2 Bajiquan martial arts training program

Certified martial arts instructors led the experimental group in Bajiquan training. The instructor possessed the following certifications: Bajiquan Instructor Certification from Wu Tan Bajiquan, Coaching Certification from the Chinese Wushu Sanda Association, and Level C Martial Arts Coach Certification from the Taipei City Sports Federation. The training followed a systematic and progressive approach to physical and physiological adaptations. The course began with fundamental training in stance work, hand form, and footwork. This was followed by practicing five forms of routine, starting with "Xiao Baji" to establish the foundation, "Da Baji" to advance techniques, and "Liu Da Kai" to master specific skills. "Lian Huan Quan", created by Master Liu Yunqiao, was a comprehensive adaptation of the first three forms. Finally, participants practiced "Pigua Zhang", focusing on long-range strikes and balancing weaknesses and strengths. Each section of the curriculum was taught for 10–12 h per week, with an additional 12 h for comprehensive review, totaling 84 h. Training sessions were implemented 5–6 times per week, with each session lasting 2 h, for a total duration of 8 weeks (Table 1). The control group participated in general fitness training including swimming, yoga, running, and fitness exercises. Specific examples of the training included 50-meter freestyle or breaststroke swimming, 3,000-meter running, beginner-level yoga, and basic fitness routines. The overall exercise duration and frequency were the same as those of the experimental group.

2.2.1 The forms of routine in Bajiquan

These four forms represent essential routines in present Bajiquan program, each emphasizing distinct techniques and applications. A brief overview is presented as follows.

2.2.1.1 Xiao Baji

Characteristics: An introductory routine featuring compact and powerful movements that focus on fundamental skills and force emission.

Techniques: Emphasizes close-range strikes, explosive short-power (peng jin), elbow strikes (ding xin zhou), and a stable, grounded stance.

Application: Develops footwork stability, enhances close-combat abilities, and establishes the foundation for force generation in Bajiquan.

2.2.1.2 Da Baji

Characteristics: Involves broader movements and a wider attack range, incorporating the full range of Bajiquan techniques.

Techniques: Introduces long-range offensive methods such as lateral palm strikes (cheng zhang), upward elbow strikes (tiao da ding zhou), and continuous kicking techniques.

TABLE 1 Bajiquan martial arts training program.

Weeks	Training topics	Hours	Frequency
1st	fundamental training[a]	10	5 times/week
2ed	fundamental training[a]	2	5 times/week
	Xiao Baji	8	
3ed	Xiao Baji	4	5 times/week
	Da Baji	6	
4th	Da Baji	6	6 times/week
	Liu Da Kai	6	
5th	Liu Da Kai	6	6 times/week
	Lian Huan Quan	6	
6th	Lian Huan Quan	6	5 times/week
	Pigua Zhang	4	
7th	Pigua Zhang	8	5 times/week
	General review	2	
8th	General review	10	5 times/week
Bajiquan demonstration video (Da Baji, Lian Huan Quan)[b]: https://www.youtube.com/watch?v=C4xblWK6e9Y&t=49s			

[a]Fundamental training includes six basic movements (arm raise and circle, arm swing and waist twist, arm lift and back stretch, left and right palm press, left and right leg thrust, and horse stance and bow punch).
[b]Martial art was demonstrated by the author.

Application: Enhances full-body coordination and explosive power while balancing offense and defense in combat scenarios.

2.2.1.3 Liu Da Kai

Characteristics: The core combat techniques of Bajiquan, emphasizing breaking through an opponent's defense.

Techniques: Incorporates six primary offensive methods—body collision (tie shan kao), spiraling punch (chan si beng chui), aggressive upward strike (meng hu ying pa shan), lateral palm strikes (zuo you ta zhang), blocking punches (zuo you lan chui), and continuous tiger pounce punches (hu pu lian huan quan).

Application: Designed for breaking an opponent's guard and swiftly engaging in close combat, making it highly applicable in practical combat and Sanda (Chinese kickboxing).

2.2.1.4 Lian Huan Quan

Characteristics: Focuses on seamless, relentless attacks with constant forward pressure.

Techniques: Features uninterrupted punches, elbow strikes, and shoulder thrusts, emphasizing rhythm and aggression.

Application: Trains the ability to sustain consecutive attacks, preventing the opponent from regaining control—an embodiment of Bajiquan's offensive nature.

These forms complement one another, progressing from foundational skills (Xiao Baji) to a complete technical framework (Da Baji), and further into advanced combat applications (Liu Da Kai and Lian Huan Quan). Bajiquan is characterized by close-range combat, explosive short-power, and dynamic force application, and each of these routines is structured around these core principles.

2.3 Body composition

Body composition was measured using four-point bioelectrical impedance of the hands and feet. This method reduces measurement errors caused by uneven body posture or fluid distribution between the upper and lower bodies, providing a more accurate assessment of whole-body composition. Body composition including body fat percentage (BFP), visceral fat (VF), and muscle mass was measured before and after the intervention using portable bioelectrical impedance analysis devices (InBody H20B; Seoul, South Korea).

2.4 Functional fitness tests

Cardiovascular endurance, explosive power, and core strength endurance were evaluated using a 3 min step, horizontal jumps, and bent-knee sit-up tests, respectively.

2.4.1 Cardiovascular endurance

The step test was used to assess heart rate recovery over a three-minute period following a standardized stepping exercise. Participants stepped onto a 35 cm-high wooden crate at a consistent pace of 24 cycles per minute for three minutes, with each cycle consisting of two steps up and two steps down, synchronized to a metronome set at 96 beats per minute. A stopwatch recorded the actual exercise duration. Regardless of whether participants completed the full three-minute exercise or stopped prematurely, their heart rates were measured while seated at three intervals: 1:00–1:30 min, 2:00–2:30 min, and 3:00–3:30 min post-exercise. The following formula was used to calculate the stepping cardiovascular function index: (exercise duration × 100)/(2 × sum of the three pulse rates) (18).

2.4.2 Explosive leg power

Lower body explosive strength was evaluated through standing long jump and standing triple jump tests, which are widely used to assess leg power. In the standing long jump, participants positioned their feet slightly apart behind a marked line on a calibrated landing mat. They executed a simultaneous two-foot takeoff and landing, using arm swings and knee flexion to maximize jump distance. The distance from the starting line to the nearest landing point (heel position) was recorded and rounded down to the nearest centimeter for analysis (18).

2.4.3 Muscular endurance

Muscular endurance was assessed using the 1 min bent-knee sit-up test. Participants lay on a mat with their arms crossed over their chests and hands resting lightly on their shoulders. Each sit-up required them to curl up until both elbows touched their knees, then return to the starting position with both shoulder blades touching the mat before initiating the next repetition. The total number of correctly performed sit-ups within 60 s was recorded as a measure of core endurance. The detailed procedures, devices, and manipulations have been described previously (18).

2.5 Martial arts exercise perceived benefits questionnaire

In this study, reliability and validity of the questionnaire were analyzed. A pilot survey was conducted online, which yielded 449 valid responses. The original questionnaire contained 30 items; however, two items were excluded because of inadequate decision values and correlation coefficients. After applying factor analysis using the orthogonal rotation method with maximum variance, items 13 and 27 were removed as the fifth factor contained only these two items. Thus, a total of 26 items were retained. A 5-point Likert scale was used for the questionnaire. The reliability analysis of the questionnaire yielded a Cronbach's α coefficient of 0.938, indicating high internal consistency. The Kaiser–Meyer–Olkin value for the factor analysis was 0.943, and Bartlett's test of sphericity produced a significant chi-square value ($p < 0.05$), confirming the suitability of the data for the factor analysis (Table 2). Factor analysis divided the questionnaire into four dimensions as follows: "personal", "social", "psychological", and "physiological barriers to exercise". The procedures of reliability, validity, and factor analysis for this questionnaire were provided as complementary files for reference.

TABLE 2 The factor analysis for martial arts exercise perceived benefit questionnaire.

Factor analysis/ dimensions	Personal benefits	Social relationship benefits	Psychological barriers	Barriers to exercise
Eigenvalues	6.05	5.05	3.30	2.62
Retained question number	11	7	4	4
% of variance	23.26%	19.41%	12.68%	10.10%
Cumulative %	65.44%			
Individual Cronbach's α	.940	.893	.854	.819
Overall Cronbach's α	.938			
KMO	.943			
Bartlett's test	χ^2 (325, $N = 449$) = 7587.56, $p < .001$			

KMO, Kaiser–Meyer–Olkin.

2.6 Power analysis

The repeated measures design equation implemented in G*Power software (version 3.1.9.6) was used to calculate the required statistical power of 80%. The sample size estimation was based on an effect size of 0.4, a Type I error probability of 0.05, and the *t*-test family. The analysis determined that a total of 50 participants would be necessary to proceed with the intervention. While the present study had limited statistical power to detect significant effects, it was expected to be sufficient for identifying trends in improvements, which could be further explored in a larger follow-up study.

2.7 Statistical analysis

The anthropometric and sociodemographic characteristics of the participants were analyzed using descriptive statistics and a chi-squared test. The normality of all dependent variables was assessed using the Kolmogorov–Smirnov test to determine the appropriateness of parametric and non-parametric analyses. Non-parametric tests, including the Wilcoxon signed-rank test and the Mann–Whitney *U*-test, were employed for the analysis of questionnaire assessments. In contrast, parametric methods, such as mixed two-way analysis of variance (ANOVA) and unpaired and paired *t*-tests, were utilized to evaluate body composition, physical fitness, and baseline anthropometric variables. The gain score (delta value) and effect sizes (ES), such like Cohen's d or Cliff's δ, were calculated for all significant findings. These statistical methods were applied to identify significant differences in the dependent variables both between and within groups. SPSS version 22 (IBM, Armonk, NY, USA) was used for all the statistical analyses. The probability of a type I error ($p < 0.05$) was considered significant.

3 Results

3.1 Anthropometric and sociodemographic characteristics of participants

In the Table 3, no significant differences in age or weight were observed between the two groups, although the participants in the control group were significantly taller than those in the experimental group. The chi-square tests showed no significant differences in categorical variables such as sex, marital status, education level, and occupation between the groups (Table 3).

3.2 Effects of Bajiquan martial arts training on exercise perceived benefits

The martial arts exercise perceived benefit questionnaire encompasses four dimensions: personal, social, psychological, and physiological barriers to exercising. This scale demonstrated effective reliability and validity in evaluating the psychological effects of Bajiquan training (Table 4). Among the personal benefits, improvements in physical fitness, coordination, explosiveness, and lower body strength were ranked as the most significant. Following the intervention, improvements in physical fitness (Cliff's δ = 0.484) and explosiveness (Cliff's δ = 0.466) as

TABLE 3 Baseline anthropometric and sociodemographic characteristics of participants.

Characteristics	Experimental group ($N = 15$)	Control group ($N = 15$)
Sex (male/female)	13/2	13/2
Age (years)	27.4 ± 2.61	26.0 ± 3.09
Height (cm)	170.13 ± 5.71	176.87 ± 7.28
Weight (kg)	72.7 ± 11	74.1 ± 11
BMI	25.0 ± 2.9	23.4 ± 2.2
Marital status^{+}		
Married	12	12
Single	3	3
Academic qualification^{+}		
Senior high school	4	3
College	10	10
Graduate school	1	2
Occupation^{+}		
Student	10	13
Public office	3	2
Freelance	2	0
Regular exercise^{+}		
None	0	0
3 or less times/week	12	11
4 or more times/week	3	4

$^{+}$Was indicated as number distribution.

TABLE 4 Effects of Bajiquan martial arts training on perceived exercise benefits.

Dimension	Items	Experimental group		Control group	
		Pre-test	Post-test	Pre-test	Post-test
Personal benefits	Significant improvement in physical fitness	4.00 ± 0.76	4.27 ± 0.80[a]	3.6 ± 0.7	3.33 ± 1.1
	Better body coordination	4.20 ± 0.86	4.27 ± 0.70	3.5 ± 0.9	3.53 ± 1.1
	Sufficient explosiveness	4.07 ± 0.88	4.07 ± 0.88[a]	3.5 ± 0.8	3.33 ± 0.8
	Strong lower body strength	4.27 ± 0.88	4.33 ± 0.72	3.9 ± 1.2	3.53 ± 1.2
	Improvement in flexibility	4.13 ± 0.74	3.93 ± 0.96	3.7 ± 1.1	3.53 ± 1.2
	Developed a regular martial art practice routine	3.73 ± 0.88	3.67 ± 0.82	3.3 ± 0.9	3.00 ± 1.3
	Reduced work stress	3.73 ± 1.10	3.47 ± 0.92	3.2 ± 0.9	2.87 ± 1.3
	Feeling happy	3.67 ± 1.05	3.60 ± 0.99	3.1 ± 1.1	3.00 ± 1.0
	Inner calmness	3.73 ± 0.88	3.67 ± 0.90	3.3 ± 1.1	3.27 ± 1.1
	Increased focus	3.93 ± 0.96	3.87 ± 0.83	3.4 ± 0.8	3.27 ± 1.2
	More self-confidence	3.93 ± 0.88[a]	3.80 ± 0.94	3.1 ± 1.0	3.13 ± 1.1
	Dimension sum	43.4 ± 8.2	42.9 ± 7.4[a]	37.8 ± 8.6	35.8 ± 10.7
Social relationship benefits	Made like-minded friends	3.73 ± 1.03	3.87 ± 0.99	3.27 ± 1.03	3.13 ± 1.13
	Strengthened friendships	3.80 ± 1.01	3.87 ± 0.83	3.20 ± 1.21	3.27 ± 0.96
	Martial art cannot help others	2.60 ± 1.55	2.53 ± 0.99	2.87 ± 1.13	3.13 ± 1.06
	Motivations to each other	4.13 ± 0.99	4.13 ± 0.74[a]	3.33 ± 1.29	3.33 ± 1.05
	Sharing martial art experiences together	4.07 ± 0.96	4.27 ± 0.70[a]	3.60 ± 1.06	3.27 ± 1.10
	Strengthened family bonds	3.27 ± 0.96	3.20 ± 0.41	2.47 ± 1.25	2.67 ± 1.18
	Learning different perspectives and ideas	4.13 ± 0.83	4.07 ± 0.80[a]	3.60 ± 1.06	3.27 ± 0.88
	Dimension sum	25.7 ± 5.01	25.9 ± 2.91[a]	22.3 ± 4.53	22.1 ± 5.16
Psychological barriers	Feel pressure during each martial art session	2.60 ± 1.18	2.20 ± 0.94[a]	2.93 ± 1.49	3.27 ± 1.16
	Afraid of making mistakes while practicing	3.27 ± 1.22	2.87 ± 1.19	3.07 ± 1.49	3.20 ± 1.26
	Feeling like still not improving	2.33 ± 1.05	2.27 ± 1.03	2.73 ± 1.44	2.87 ± 1.30
	Always struggle to keep up with others	2.67 ± 1.11	1.87 ± 0.92	2.67 ± 1.45	2.73 ± 1.44
	Dimension sum	10.9 ± 3.48	9.20 ± 3.21	11.4 ± 5.50	12.1 ± 4.86
Barriers to exercise	Feeling physically fatigued	3.13 ± 0.99	2.20 ± 1.01	2.67 ± 1.29	2.67 ± 1.29
	Frequent discomfort in joints	3.40 ± 1.18	3.33 ± 1.23	3.33 ± 1.29	3.13 ± 1.30
	Unable to execute movements precisely	2.73 ± 0.88	2.13 ± 0.99	3.07 ± 1.44	3.00 ± 1.31
	Feeling stiff and unable to relax	2.87 ± 0.92	2.27 ± 1.10	3.13 ± 1.46	3.07 ± 1.39
	Dimension sum	12.1 ± 3.41	9.93 ± 3.43	12.2 ± 4.63	11.9 ± 4.47

[a]Significant differences between groups.

well as in the overall personal benefit dimension (Cliff's δ = 0.431) were significantly higher in the experimental group than in the control group. In addition, motivation (Cliff's δ = 0.435), shared experiences (Cliff's δ = 0.537), and learning different perspectives (Cliff's δ = 0.480), along with the overall Social Relationship Benefits dimension (Cliff's δ = 0.586), showed significant improvements compared to the control group. In the barrier dimension, perceived pressure during martial arts sessions (Cliff's δ = 0.484) demonstrated a significant decrease following the implementation of martial arts training.

3.3 Effects of Bajiquan martial arts training on body composition

The body composition of the participants was assessed before and after the intervention, which involved martial arts and general fitness training. The interaction between treatment and time demonstrated significant differences in body weight, body mass index (BMI), and BFP [F(1, 28) = 8.271, 10.44, and 9.686, $p < 0.05$, $\eta p^2 = 0.228$, 0.272, and 0.257, respectively]. Within the experimental group, significant differences in BMI [t(14) = 3.872, $p = 0.002$, $d = 0.99$], BFP [t(14) = 3.832, $p = 0.002$, $d = 0.98$], and VF [t(14) = 2.646, $p = 0.019$, $d = 0.68$] were observed. Meanwhile, no significant differences were observed in the control group. A difference-in-differences analysis, based on gain scores in body weight [t(28) = 2.876, $p = 0.008$, $d = 1.05$], BMI [t(28) = 3.231, $p = 0.003$, $d = 1.17$], and BFP [t(28) = 3.112, $p = 0.004$, $d = 1.13$], revealed that participants in the Bajiquan training group experienced significantly greater improvements than those in the control group (Table 5).

3.4 Effects of Bajiquan martial arts training on functional fitness

Cardiovascular endurance, explosive power, and core strength endurance were evaluated using the 3 min stepping, horizontal jump, and bent-knee sit-up tests, respectively. The interaction between treatment and time demonstrated significant differences in the 3 min step, horizontal jump, and bent-knee sit-up [F(1, 28) = 9.761, 12.189, and 9.098, $p < 0.05$, $\eta p^2 = 0.259$, 0.303, and 0.245, respectively]. The 3 min step ($p = 0.002$, $d = 0.98$), horizontal jump ($p = 0.003$, $d = 0.91$), and bent-knee sit-up ($p = 0.005$, $d = 0.86$) showed significant improvement within the experimental group, and regular fitness training could only

TABLE 5 Effects of Bajiquan martial arts training on body composition and physical fitness.

Items	Experimental group			Control group			p value		
	Pre-test	Post-test	△	Pre-test	Post-test	△	Treatment	Time	Interaction
Body weight (kg)	72.7 ± 11	70.5 ± 9.8	−2.2 ± 2.2#	74.1 ± 11	73.8 ± 10	−0.27 ± 1.4	0.542	0.001	0.008
BMI (kg/m^2)	25.0 ± 2.9	24.2 ± 2.7*	−0.7 ± 0.01#	23.4 ± 2.2	23.4 ± 2.1	−0.04 ± 0.4	0.219	0.001	0.003
Body fat percentage (%)	24.5 ± 6.5	22.4 ± 5.8*	−2.1 ± 2.1#	20.0 ± 7.0	20.0 ± 7.1	0 ± 1.54	0.160	0.004	0.004
Muscular mass (kg)	30.5 ± 4.3	30.3 ± 4.1	−0. 2 ± 0.53	33.5 ± 6.1	33.4 ± 6.1	−0. 1 ± 0.68	0.116	0.277	0.573
Visceral fat (%)	6.9 ± 2.9	6.3 ± 2.3*	−0. 7 ± 0.97	5.7 ± 2.6	5.6 ± 2.7	−0. 1 ± 0.92	0.332	0.028	0.134
3 min stepping	70.8 ± 9.5	80.7 ± 11.5*	9.9 ± 9.1#	78.3 ± 14.9	75.2 ± 15.6	−3.0 ± 13	0.822	0.109	0.004
Horizontal jump (cm)	187.5 ± 30.1	206.1 ± 20.9*	18.5 ± 20#	190.5 ± 29.0	190.3 ± 29.7	−0. 2 ± 3.9	0.514	0.002	0.002
Bent-knee sit-up (times)	37.3 ± 9.3	46.4 ± 6.3*,#	9.1 ± 11#	37.7 ± 6.7	38.5 ± 6.8*	0. 8 ± 1.3	0.118	0.001	0.005

△Change (gain scores) within groups. *Significant differences within group. #Significant differences between groups. BMI, body mass index.

significantly elevate core strength endurance ($p = 0.028$, $d = 0.66$) within the control group. In addition, a significant difference in core strength endurance was observed between the two groups ($p = 0.003$, $d = 1.21$) in the post-test. A difference-in-differences analysis, based on gain scores in 3 min stepping ($p = 0.004$, $d = 1.14$), horizontal jump ($p = 0.003$, $d = 1.27$), and bent-knee sit-up ($p = 0.009$, $d = 1.10$), revealed that participants in the Bajiquan martial arts training group experienced significantly greater improvements than those in the control group (Table 5).

4 Discussion

Martial arts, which originate from diverse cultures and historical backgrounds, are rooted in various forms of physical activity and fitness. Traditionally considered a method of self-defense and military training, martial arts encompass a broader purpose that includes continuous mental, physical, emotional, and spiritual self-improvement. In recent years, martial arts training has emphasized whole-body movement patterns, philosophical teaching, interpersonal interactions, and functional self-defense. Thus, martial arts have been proposed as a form of exercise therapy suitable for individuals of all ages with the potential to promote health (2. Sun, 2024). However, previous research on martial arts, particularly Bajiquan, remains limited, and further empirical investigation is required to evaluate its potential benefits on functional fitness, as well as its physiological and psychological effects. In the present study, the 8-week Bajiquan Martial Arts Training Program resulted in significant improvements in body composition and physical fitness. Additionally, the martial arts exercise perceived benefit questionnaire effectively assessed improvements in personal and social relationships.

Improvements in physical fitness with various martial arts interventions have been well documented. Tai Chi, one of the most well-known soft martial arts exercises, is an effective neuromotor exercise that emphasizes movement control and sustained stretching across multiple muscle groups. A systematic review has demonstrated that Tai Chi significantly enhances balance, BMI, BFP, vital capacity, and flexibility (as measured by the sit-and-reach test) in adults, which is supported by high-quality evidence. However, its effects on blood pressure regulation and sympathetic activity were insignificant (19). Additionally, Tai Chi significantly improves handgrip strength, 6 min walking distance, standing time in a single-leg stance with open eyes, and thoracolumbar spine flexibility, although further validation is needed for younger, healthy populations (20). Hard martial arts, such as Karate and Taekwondo, are characterized by their emphasis on forceful and direct techniques, relying on strength and aggression. These disciplines often prioritize physical conditioning, powerful strikes, and linear movements. A systematic review of Taekwondo training has revealed significant improvements in cardiopulmonary and muscular endurance among Korean elementary students (21). Additionally, the implementation of Taekwondo has been associated with statistically significant improvements in weight, BMI, waist circumference, waist-to-hip ratio, body fat mass, BFP, lean mass, and muscle mass (14). Consequently, improvements in specific physical fitness and body composition may vary between soft and hard martial arts. Nonetheless, Bajiquan interventions have also demonstrated significant improvements in body weight, BMI, BFP, and aerobic endurance, showing greater effectiveness than other forms of martial arts.

Martial arts training is effective in enhancing physical fitness; however, the extent of these improvements can vary depending on the specific type of martial arts practiced. A previous study comparing the effects of Taekwondo and Wushu on male adolescents has reported that the Wushu group demonstrated significantly higher explosive leg power and superior Wingate anaerobic capacity parameters including mean power, anaerobic capacity, and anaerobic power than the Taekwondo group (22). By contrast, Bajiquan requires a distinct set of physical fitness attributes, with a greater emphasis on explosiveness, kinetic chain strength, and footwork, commonly referred to as Fa Jin (the expression of explosive power), and the study also showed the significant elevation in explosiveness with Bajiquan training. Core training is a novel approach for strength training. Strong core muscles act as the central hub of the kinetic chain, providing a pivotal point for generating limb strength and facilitating the connection and transfer of power between the upper and lower limbs. Core training enhances the transfer of movement and force to distal parts of the body and improves the overall control of physical activities (23). Core training plays an important role in enhancing the functional performance in martial arts. The significance of core strength is often overlooked in martial arts training. However, previous studies have indicated that core training improves functional movement performance in martial arts, particularly in Greco-Roman wrestling, as demonstrated by exercises, such as overhead medicine ball throws, suplexes, bridges, and medicine ball chest throw (24). The significance of core strength training in the martial art Muay Thai could enhance both velocity and force in distal limbs (25). The core strength and explosive power of Bajiquan martial arts training can also significantly improve the speed and power of punches and kicks, demonstrating the effectiveness of enhanced core activation. Improved core strength and explosiveness were significantly observed with Bajiquan martial implementation in the current study. In addition to traditional training methods, further research is required to determine whether practicing various martial arts disciplines can complement and enhance functional fitness and athletic performance.

Previous studies have indicated that the intensity and mode of swimming exercises lead to different adaptations in physical fitness. High-intensity interval swimming has been shown to enhance cardiovascular endurance, while aquatic resistance training improves muscular strength and endurance (26). Additionally, in a comparative study between high-intensity functional training and running, high-intensity functional training demonstrated significant benefits in muscular fitness, particularly in horizontal jump performance and sit-ups (27). Similarly, another comparative study between high-intensity interval resistance training and running found that high-intensity interval resistance training resulted in superior cardiovascular and muscular fitness (sit-ups) (28), highlighting the influence of exercise intensity and training modality on physical fitness adaptations. A meta-analysis on the effects of yoga practice reported moderate positive effects on muscle strength, balance, flexibility, and lower-body mobility. However, no significant effects were observed on cardiorespiratory endurance or upper-body flexibility (29). In the present study, the control group was not given specific instructions regarding exercise intensity or type, which may have influenced the observed physical fitness outcomes.

The Bajiquan program in this experiment focused on fundamental principles and coordinated movements under the guidance of a coach. In addition to improvements in functional fitness, the program also showed beneficial effects on body composition including reductions in body weight, BMI, and BFP. From the perspective of exercise therapy and physical activity, martial arts can be applied to individuals of all ages for promoting health (2). Physical activity plays a vital role in maintaining physical and mental health. Lack of physical activity not only increases the risk of noncommunicable diseases (NCDs) but also significantly elevates morbidity and mortality rates among individuals affected by these diseases. Engaging in physical activity dose-dependently can reduce the risk of NCDs, such as cardiovascular diseases, type 2 diabetes, and cancer (30). Martial arts remain a niche activity compared to other exercise categories. In a prior survey conducted among Polish participants, the primary motivation for engaging in martial arts was “pleasure”, followed by “maintaining health and physical fitness” and “overall health”, which, in the present study, may be categorized as “personal benefits”. In addition to educational promotion, the availability of facilities and promotional platforms also plays a significant role in participation in martial arts activities (31). This study also conducted a dimensional analysis of health behaviors related to martial arts physical activities, which can be applied in the future to identify facilitating and inhibiting factors across various populations, age groups, educational levels, and cultural backgrounds, thereby highlighting the significance of behavioral engagement.

Moreover, this study showed the benefits of physical activity, highlighting significant improvements in personal fitness, such as physical ability and explosive strength. Martial arts research has revealed the social and psychological benefits and barriers associated with these practices. For instance, judo-related studies have indicated that adult participation in intervention programs can yield psychosocial benefits (e.g., enhanced self-confidence) and physiological improvements (e.g., increased physical fitness) (32). Similarly, Taekwondo interventions have demonstrated notable personal development and self-acceptance among adolescents including increased confidence, happiness, mental satisfaction, improved cognitive abilities, and enhanced focus. Social benefits include fostering positive social relationships, respect for others, kindness, discipline, and patience (33, 34). For the elderly population, Tai Chi interventions provide positive psychological effects, such as increased confidence, self-esteem, and well-being, while alleviating stress and depressive symptoms and improving emotional states (35). Social benefits for this demographic group included expanded social networks and reduced feelings of loneliness (36). Additionally, existing studies have highlighted the role of psychological factors as moderators influencing behavioral changes during activity interventions. Negative attitudes may act as barriers to behavior, whereas factors such as insufficient social support, ineffective teaching methods, and the complexity of movements during interventions can also hinder behavioral engagement (37, 38). In a previous systematic review concerning adherence to lifestyle behaviors including diet and physical activity, three levels of facilitators and barriers were identified as follows: individual (encompassing attitudes, health concerns, and physical changes), environmental (including social support, social accountability, and community factors), and intervention. Lifestyle interventions that promote self-regulatory skills, provide opportunities for social engagement, and allow for the personalization of goals may enhance adherence to desired behaviors (37). However, a systematic review indicated that the multifaceted nature of martial arts may lead to diverse, and sometimes even conflicting, effects on mental health. This highlights martial arts research requires extensive theoretical and practical advancements to better understand its impact on mental health (39).

5 Limitation

Regarding the study’s experimental limitations, variations in caloric expenditure due to exercise intervention may have affected body composition and physical activity levels. Furthermore, as Bajiquan remains a niche martial art unfamiliar to the public, participants' engagement and training emphasis could have influenced its effects on physical fitness. Given the limited empirical research on Bajiquan, this study aimed to establish a structured training program under the guidance of martial arts instructors and explore its potential health benefits. Future research should include a larger sample size to further investigate its effects following the broader promotion of Bajiquan. Additionally, heart rate monitoring and comparisons with other martial arts could provide deeper insights into the exercise intensity and health benefits associated with Bajiquan practice.

6 Conclusion

The Bajiquan training program may serve as a viable alternative physical activity for enhancing physical fitness and supporting weight management as part of health promotion efforts. Additionally, martial arts could influence practitioners' physical fitness, social interactions, psychological barriers, and overall attitude toward exercise. Through the established Martial Arts Exercise Perceived Benefits Questionnaire, this study also provides valuable insights into the unique personal and psychological benefits associated with this martial art.

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 This study was reviewed and approved by the Fu Jen Catholic University Institutional Review Board (New Taipei City, Taiwan; C111137). 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.

Author contributions

CT: Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft. CW: Data curation, Methodology, Validation, Visualization, Writing – original draft. WH: Conceptualization, Funding acquisition, Methodology, Project administration, 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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Acute physiological responses and performance determinants in Hyrox© – a new running-focused high intensity functional fitness trend

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Aims: Hyrox© is a fitness modality combining 8 functional exercises with running in a comprehensive competition format. Within this first scientific study on Hyrox©, acute physiological responses, relative perceived exertion (RPE), and possible performance determinants were assessed during a simulated Hyrox© competition to derive training recommendations and potential practical applications.

Methods: Eleven recreational Hyrox© athletes [27% women, Hyrox© experience median (interquartile range): 18 (19) months] participated. In a pre-test, height, body composition, hand grip strength (HGS), maximum oxygen consumption (VO_2max), and volume of resistance and endurance training were assessed. After 48 h rest, a simulated Hyrox© was conducted according to the competition-standards of the “Individual Open Division”. Heart rate (HR) was tracked throughout the Hyrox©. Blood lactate (BL) and RPE were recorded at the beginning and after each run and exercise station. Differences between runs and exercise stations for HR, BL, and RPE were analyzed via Wilcoxon signed rank test. Spearman’s rank correlation test was conducted to identify associations between completion times (Hyrox©, runs, exercise stations) and participant characteristics. Values are given as median (interquartile range).

Results: Completion time of the Hyrox© was 86.5 (14.5) minutes, whereby runs (51.2 (14.1) minutes) were significantly longer than the exercise stations [32.8 (6.1) minutes] ($p = 0.003$). Most of the Hyrox© was performed at very hard and hard intensities [79.5 (21)% and 19.6 (20.7)% of maximum HR]. Maximum BL was higher during the exercise stations [8.5 (5.4) mmol/L] compared to the runs (7.7 (4.6) mmol/L) ($p = 0.006$). Similar results were found for maximum RPE [exercise stations: 18 (2), runs: 16 (2), $p = 0.003$]. The highest values for HR, BL, and RPE occurred during the last exercise (wall balls). The exercise stations with the heaviest loads were completed the fastest [sled push: 128 (34) seconds, sled pull: 155 (38) seconds]. Faster Hyrox© completion correlated significantly with higher VO_2max ($p = 0.01$), greater endurance training volume ($p = 0.04$), and lower body fat percentage ($p = 0.03$).

Conclusion: Hyrox© is a HIFT modality with an emphasis on endurance capacity and moderate to low requirements in terms of maximum strength, coordination, and mobility when compared to other forms HIFT. Hyrox© may be suitable for health promotion and tactical population training.

KEYWORDS

fitness racing, HIFT, concurrent training, high intensity interval training, heart rate, maximum oxygen consumption, lactate, relative perceived exertion

1 Introduction

High-intensity interval training (HIIT), strength training with free weights, bodyweight training, and functional fitness training (FFT) have been ongoing trends for years and were among the top 10 trends in the fitness industry in 2023 (Thompson, 2023). Fitness racing such as Hyrox© (Upsolut Sports GmbH, Hamburg, Germany) is a new fitness domain combining elements of these training modalities in a comprehensive competition format (Bergmann, 2024). Similar to CrossFit© (CF) (CrossFit, Inc., Washington, DC, United States) – one of the most popular FFT concepts – Hyrox© also incorporates elements of gymnastics, weightlifting, and endurance sports (Glassman, 2020). In contrast to CF, a Hyrox© competition always consists of the same 8 exercises (ski ergometer, sled push, sled pull, burpee broad jump, rowing ergometer, farmers carry, sandbag lunges, and wall balls) and 8 runs [each 1,000 meters (m)]. Runs and exercises are completed alternately one after the other, whereby the competition always starts with a run. Weights and distances of the exercises are adjusted based on gender, division, and mode (e.g., Individual Open, Individual Pro, Double, Relay), allowing athletes of varying fitness levels to participate. The first Hyrox© competition took place in 2017. Considering that in the 2022/2023 season already 90,000 Hyrox© athletes worldwide competed despite the corona pandemic, a further increase in popularity could be expected (Bergmann, 2024). Nevertheless, Hyrox© is not represented in the scientific literature up to date. Accordingly, little is known about acute physiological responses and performance determinants. However, this information is essential for developing effective training programs and exploring potential application areas of Hyrox© beyond competitive sport. Indeed, previous research on other sports respectively training concepts that appear to be closely related to Hyrox© such as CF, concurrent training (CT), and running may provide some insight in this regard.

Looking at CF, there is a considerable amount of research providing information for coaches, athletes, and health professionals in terms of physiological and psychological demands, performance predictors, injury rates, health benefits, and motivational aspects (Claudino et al., 2018; Dexheimer et al., 2019; Ángel Rodríguez et al., 2022; Brandt et al., 2024; Dominski et al., 2021). Regarding health and fitness, previous research showed that CF improves cardiovascular fitness, body composition, mobility, strength, and back health, while being associated with a low injury risk (1.9 – 3.2 injuries per 1000 hours [h]) (Gianzina and Kassotaki, 2019; Brandt et al., 2024; Hak et al., 2013). In terms of performance, it was demonstrated that a lower body fat percentage, higher total body strength, and maximum oxygen consumption (VO_2max) correlated with better CF performance (Meier et al., 2023a). However, the investigated CF workouts (e.g., Fran, Cindy, Isabel, Murph) were considerably shorter than a Hyrox© competition (Ahmad et al., 2018; Rios et al., 2024a; Rios et al., 2024b; Carreker and Grosicki, 2020). The single study on physiological demands covering longer bouts of CF was conducted over the course of regular 60-minute [min] CF training sessions (Meier et al., 2023b). This limits the extent to which conclusions could be derived about the physiological demands of Hyrox©. Unlike CF, which emphasizes constantly varied functional movements, Hyrox© places a greater focus on running, with a total of 8 kilometers [km] per competition and less exercise variety (Bergmann, 2024; Glassman, 2020).

On endurance exercise such as running, extensive research has been carried out in a large number of different populations with regard to physiological demands, health benefits, or injury patterns. Performance in Olympic endurance events is typically achieved at intensities exceeding 85% of the VO_2max. Joyner and Coyle concluded that endurance athletes need to be relatively fatigue resistant at intensities that stimulate significant anaerobic metabolism (Joyner and Coyle, 2008). The most important factors especially for running performance therefore include maximal oxygen uptake (VO_2max), lactate threshold, and running economy (Joyner, 1991). Regarding health benefits, a meta-analysis with a pooled sample of N = 232,149 participants showed that running is associated with a 27%, 30%, and 23% reduced risk of all-cause, cardiovascular, and cancer mortality (Pedisic et al., 2020). Lee et al. stated that, from a public health perspective, running could be the most cost-effective lifestyle medicine, exceeding the importance of risk factors like smoking, obesity, hypertension, or diabetes (Lee et al., 2017). Nevertheless, running is associated with an injury risk of 6.8–59 injuries per 1,000 h whereby history of previous injuries, mileage but also training volume and frequency need to be considered to prevent injury (Saragiotto et al., 2014; Fields et al., 2010). While research on endurance exercise – and in particular running – provides indications regarding the demands and effects of Hyrox©, the specific characteristics of Hyrox© (e.g., integration of functional exercises) might lead to divergent findings.

Besides running, Hyrox© includes exercises such as sled pushes (men: 202 kilograms [kg], women: 152 kg) and sled pulls (men: 153 kg, women: 103 kg) where heavy external weights need to be moved (Bergmann, 2024). This suggests that Hyrox© training regimes should also include resistance training to some extent. Notably, resistance training may not only improve competition performance but health (e.g., reducing cardiovascular disease, hypertension, all-cause-mortality, and the offset of age-related declines in strength, power, and muscle mass) (Fyfe et al., 2022). Nevertheless, implementation of additional strength training needs to be done with caution because volume and frequency are critical risk factors for injury (Saragiotto et al., 2014; Fields et al., 2010). Furthermore, previous research in the field of CT showed that combining resistance and endurance training poses a challenge, as the specific adaptations from each type of training may potentially interfere with one another. Therefore, to manage overall fatigue, reduce negative interferences, and avoid injuries, knowing the specific demands of Hyrox© in terms of strength and endurance capacity is essential according to CT research (Methenitis, 2018; Wilson et al., 2012).

However, no scientific studies to date have investigated Hyrox© in this respect, making it difficult to develop evidence-based training programs or identify potential benefits and practical applications beyond competitive sports. Therefore, this study analyzed the acute physiological responses as well as potential performance predictors in Hyrox© athletes during a simulated Hyrox© competition.

2 Materials and methods

2.1 Trial overview

This study was conducted at the University of the Bundeswehr Munich (UniBw M). Participants attended 2 separate test sessions – a pre-test and a simulated Hyrox© competition. The simulated Hyrox© was performed 2–14 days after the pre-test. The Institutional Ethics Committee of the UniBw M approved the study protocol, ensuring that it conformed to the ethical guidelines of the 1975 Declaration of Helsinki. Informed consent was obtained from all subjects involved in the study (08.02.2024; EK UniBw M 24-05). An overview of the trial is displayed in Figure 1.

2.2 Participants

The study involved recreational Hyrox© athletes (N = 11, 27% women, Hyrox© experience: 18 (19) months) who were at least 18 years old and had participated in at least one official Hyrox© competition prior to the study. Exclusion criteria were health issues that would preclude participation in the applied tests (e.g., cardiovascular diseases, respiratory disorders, severe injuries to the musculoskeletal system, osteoporosis, intervertebral disc damage, joint replacements, hypertension). No adverse events occurred during the test sessions. Participant characteristics are displayed in Table 1.

2.3 Procedure

2.3.1 Pre-test

The aim of the pre-test was to collect measures of body composition, strength, cardiorespiratory fitness, and training status. Participants were instructed to avoid any intensive physical activity 48 h, alcohol consumption 24 h, and food intake 3 h prior the test. Moreover, they should not drink more than 500 mL of water 30 min before the measurement and empty their bladder. The pre-test comprised a questionnaire, bioelectrical impedance analysis (BIA), hand grip strength (HGS) test, and cardiopulmonary exercise test on a treadmill (CPET).

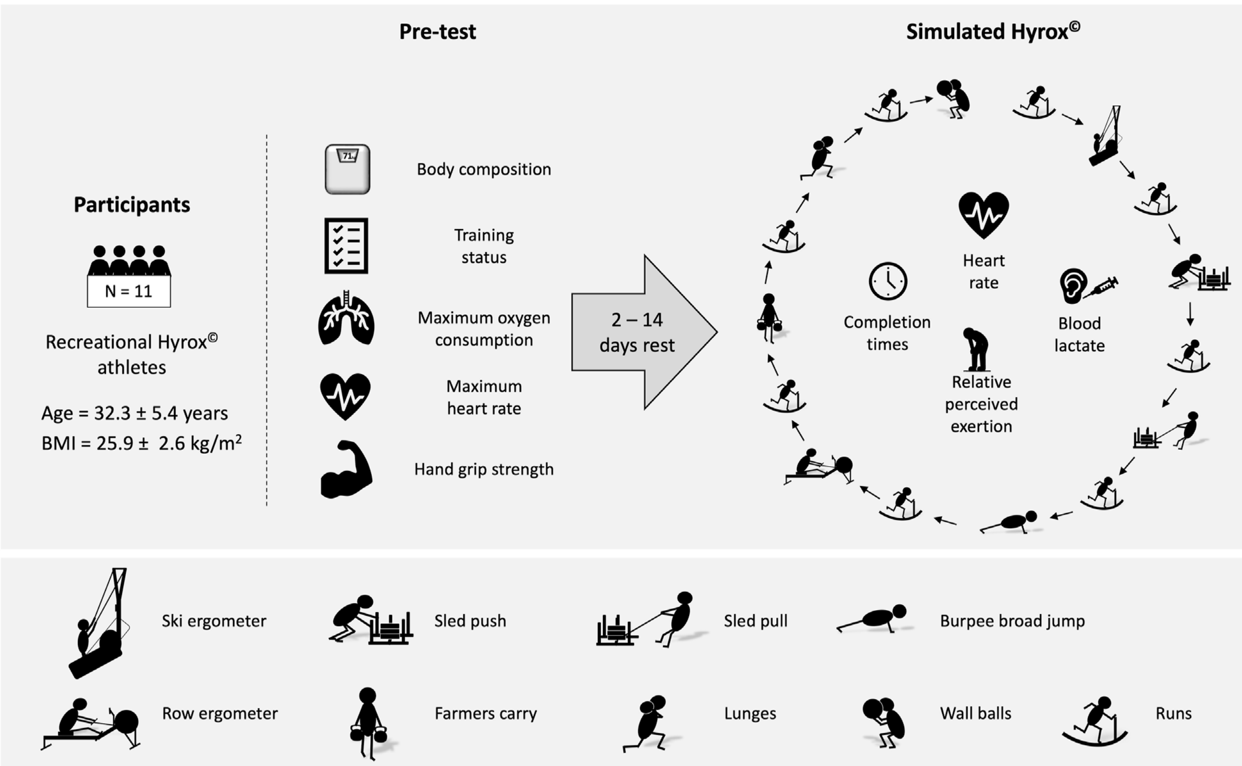

FIGURE 1
Trial overview.

TABLE 1 Characteristics of participants.

Parameter	Median	IQR	Min	Max
N	11			
Male (N) Female (N) Diverse	72.7% (8) 27.3% (3) 0%			
Age [years]	33	9	23	43
Body mass [kg]	71.6	20.5	62.4	108.5
BMI [kg/m^2]	24.2	4.6	23.3	30.6
Body fat [%]	21.3	7.3	10.7	25
Muscle mass [%]	37.7	4.6	34.5	40.8
Hand grip strength [kg]	51.1	10.7	35.1	73.3
VO_2max [mL/min/kg]	51	10.8	46.6	72
HR_{max} [bpm]	186	24	166	201
Hyrox© experience [months]	18	19	2	48
Endurance training [hours/week]	3	2.5	2	7
Resistance training [hours/week]	4	3	1	7

Abbreviations: BMI, body mass index; bpm, beats per minute; HR_{max}, maximum heart rate; kg, kilograms; m, meter; mL, milliliter; min, minute; IQR, interquartile range; VO_2max, maximum rate of oxygen consumption.

2.3.1.1 Questionnaire

Participants were asked for their gender and age [years], hours of resistance as well as endurance training per week [h/wk], and Hyrox© experience in months.

2.3.1.2 Body composition and height

Height [cm], weight [kg], and body composition (body fat percentage [%] and muscle mass percentage [%]) were measured in underwear. Height was assessed with a SECA® 213 (seca GmbH and Co. KG, Hamburg, Germany) and body composition with a SECA® mBCA 515 scale (seca GmbH and Co. KG, Hamburg, Germany). According to Bosy-Westphal et al., the SECA® mBCA 515 is a valid and precise tool to estimate body composition (Bosy-Westphal et al., 2017; Bosy-Westphal et al., 2013).

2.3.1.3 Hand grip strength test

HGS was measured with the Baseline® Smedley Digital hand-held dynamometer (Fabrication Enterprises, New York, United States) and given in kg. For the measurement, participants sat upright on a chair with their feet on the ground and a 90° angle in their knee joint. The elbow was flexed at 90° with the fingertips pointed ventrally and the palm facing medially. Starting with the dominant hand, participants were instructed to squeeze the dynamometer as hard as they could for 5 seconds [sec]. Each hand was measured thrice with 30 s of rest between trials, whereby the highest of all 6 measures was used for the analysis. HGS strongly correlates with strength in other muscle groups and can be used as a predictor for total muscle strength (Wind et al., 2010). Furthermore, since Hyrox© is a fitness racing modality including exercises that require athletes to hold and pull external loads during sled pulls and farmers carry, HGS could influence performance.

2.3.1.4 Cardiopulmonary exercise test

The participants performed an incremental exercise test on a h/p/cosmos pulsar® 3p treadmill (h/p/cosmos, Traunstein, Germany). Women started at 6 km/h and men at 7 km/h, both at an incline of 1%. The speed was increased by 1 km/h every 3 min until participants were unable to maintain running pace. As proposed by Rosenerger and Schommer, exhaustion criteria comprised a respiratory exchange ratio >1.1, plateauing of VO_2 consumption, and a HR reaching or exceeding 100% ± 10% of the age-predicted HR_{max} (Scharhag-Rosenberger and Schommer, 2013). Heart rate (HR) was continuously tracked with a smartLAB hrm W sensor worn at the chest (HMM Diagnostics GmbH, Heddesheim, Germany). To assess cardiopulmonary indices the COSMED Quark CPET (COSMED, Rome, Italy) was used. VO_2max [mL/min/kg] was determined by averaging the oxygen uptake over the last 30 s at the participant's peak performance.

2.3.2 Simulated Hyrox© competition

In the simulated Hyrox© competition test, physiological responses were assessed in order to estimate the demands of a

FIGURE 2
Test setup for the simulated Hyrox© competition.

Hyrox© competition. Participants were instructed to avoid any intensive physical activity 48 h prior the test. All participants completed the Hyrox© according to the standards of the "Individual Open Division". The exercise execution followed the guidelines outlined for Hyrox© competitions (Bergmann, 2024). Each participant completed the test alone in a gym. The 8 runs and exercise stations were performed in alternating order, always starting with a 1 km run on a Woodway Curve treadmill (WOODWAY, Weil am Rhein, Germany). The exercise stations were (1) ski ergometer (1000 m; Concept2, Morrisville, USA), (2) sled push (4 × 12.5m, women: 102 kg, men: 152 kg, including weight of the sled) (3) sled pull (4 × 12.5m, women: 78 kg, men: 103 kg, including weight of the sled), (4) burpee broad jumps (4 × 20 m), (5) rowing ergometer (1000 m; Concept2, Morrisville, USA), (6) farmers carry (8 × 25 m, women: 2 × 16 kg kettle bell, men: 2 × 24 kg kettle bell), (7) sandbag lunges (4 × 25 m, women: 10 kg, men: 20 kg), and (8) wall balls (women: 75 repetitions with 4 kg, men: 100 repetitions with 6 kg). Participants were instructed to complete the Hyrox© as fast as possible. The test setup in the gym is shown in Figure 2.

The completion times were recorded for the full Hyrox©, the accumulated runs, the accumulated exercise stations as well as for each run and exercise station. During the test, the participants wore a smartLAB hrm W sensor at the chest (HMM Diagnostics GmbH, Heddesheim, Germany) to track their HR. The maximum heart rate (HR_{max}) and average HR (HR_{avg}) was determined for the complete Hyrox©, as well as for the accumulated runs, accumulated exercise stations, and each individual run and exercise station. The relative HR [$\%HR_{max}$] was calculated to the second for the entire Hyrox© to estimate the exercise intensity according to the guidelines of the American College of Sports Medicine (very light, light, moderate, hard, very hard, maximum) (Pollock et al., 1998).

Blood lactate concentration (BL) in millimoles per liter [mmol/L] was measured with a Lactate Scout+ (SensLab GmbH, Leipzig, Germany) before the test, after each run, after each exercise station, and at 3 and 6 min after the completion of the final exercise station. Simultaneously with the lactate measurements, relative perceived exertion (RPE) was assessed using the Borg scale (scale from 6–20 with 6 being the lowest and 20 the highest possible perceived exertion). The scale was presented and explained to the participants beforehand, following the standards for its use in sports medicine as recommended by Löllgen (Borg, 1998; Löllgen, 2004). The maximum BL (BL_{max}), maximum RPE (RPE_{max}), average BL (BL_{avg}), and average RPE (RPE_{avg}) was determined for the complete Hyrox©, as well as for the accumulated runs, and accumulated exercise stations.

2.4 Statistical analysis

The statistical analysis was conducted with Microsoft Excel (Microsoft, Redmond, United States) and SPSS 29® (IBM SPSS, Armonk, NY, United States). Normal distribution was analyzed via Kolmogorov-Smirnov test and Q-Q-plots. Values are given as median (interquartile range). Differences between the runs and workout stations in terms of physiological responses and RPE were analyzed via Wilcoxon signed rank test. The effect size r was calculated based on the z-value and the sample size. Spearman's rank correlation test was performed to identify associations between the completion times (complete Hyrox©, runs, exercise stations) and participant characteristics (e.g., measures of body composition, strength, and endurance). Spearman's rho was reported as the correlation coefficient. Statistical significance was set at $p \leq 0.05$.

3 Results

Participants completed the Hyrox© in 86.5 (14.5) min, whereby the time spent running [51.2 (14.1) min] was significantly longer than the time to complete the exercise stations [32.8 (6.1) min] ($p = 0.003$, $r = 0.88$). The percentage share of the specific exercise stations and runs in the total time to completion is displayed in Figure 3. The shortest median times to completion occurred for sled push [2.1 (0.6) min], sled pull [2.6 (0.6) min], and farmers carry [2.7 (0.7 min]. Run 5 [7.4 (1.6) min], Run 8 [6.8 (1.3) min], and Run 6 [6.8 (1.9) min] took participants the longest.

During the Hyrox, participants achieved a HR_{max} of 185 (26) bpm, with significantly higher values for the exercise stations [185 (26) bpm] compared to the runs [180 (26) bpm] ($p = 0.04$, $r = 62$). Similarly, the HR_{avg} in the full Hyrox© reached 170.9 (21.2) bpm while participants completed the exercise stations at a higher HR_{avg} (173.7 (19.5) bpm) compared to the runs [168.9 (21.9) bpm] ($p = 0.03$, $r = 64$). Most of the time, participants performed at very hard [79.5 (21) %] and hard [19.6 (20.7) %] intensities. The distribution of the intensity ranges is shown in Figure 4.

Physiologically, the hard to very hard intensity was also reflected in the values for BL_{max} [8.5 (5.4) mmol/L] during the Hyrox©. Again, BL_{max} was significantly higher after the exercise stations [8.5 (5.4) mmol/L] compared to the runs [7.7 (4.6) mmol/L] ($p = 0.006$, $r = 83$). Looking at BL_{avg} during the Hyrox© [6.3 (3.8) mmol/L], the values after the workouts [6.6 (3.7) mmol/L] were higher in comparison to the runs [6.2 (3.9) mmol/L] ($p = 0.003$, $r = 0.88$).

The RPE_{max} score during the Hyrox© reached 18 (2), whereby the participants rated the exercise stations [18 (2)] as significantly more strenuous than the runs [16 (2)] ($p = 0.003$, $r = 0.91$). Likewise, participants had a RPE_{avg} of 14.1 (1.5) in the Hyrox©, with significantly higher values during the exercise stations [14.4 (1.9)] compared to the runs [13.4 (1.3)] ($p = 0.003$, $r = 0.89$). Values for physiological responses and RPE are given in Table 2.

The highest values for HR_{max} [183 (21) bpm], BL [8.5 (4.9)], and RPE [18 (1)] were seen in the last exercise station, the wall balls. The course of the HR as well as BL and RPE values are displayed for the Hyrox© in Figure 5.

Correlation analyses showed multiple associations between the participant characteristics and performance in the Hyrox©. The strongest correlation was found for VO_2max (ρ = - 0.71, $p = 0.01$), followed by endurance training volume (ρ = - 0.68, $p = 0.04$), and body fat percentage ($\rho = 0.67$, $p = 0.03$). Independent analyses of performance during runs and workouts with participants characteristics revealed correlations only for the runs, but not the exercise stations. Strong correlations were seen for VO_2max (ρ = - 0.73, $p = 0.01$) and body fat percentage ($\rho = 0.68$, $p = 0.02$). Results of the correlations analyses are shown in Table 3.

All participants had the technical proficiency and mobility to perform the exercises according to the Hyrox© movement standards. They further had sufficient strength to execute all exercise station with the competition-standard loads.

4 Discussion

4.1 Classification and physiological demands of Hyrox©

The observed physiological responses and RPE clearly illustrated the high-intensity nature of Hyrox© (Pollock et al., 1998). Given that Hyrox© comprises multi-joint, compound movements performed at high intensities, with loads reaching up to 152 kg for women and 202 kg for men, Hyrox© can be classified as a HIFT modality (Feito et al., 2018). Since more than 60% of the total completion time was spent running, Hyrox© should be further specified as a running-focused form of HIFT.

Based on the overall duration [86.5 (14.5) min] in conjunction with HR and BL values, it is to assume that participants had to rely on both aerobic as well as anaerobic metabolic pathways to complete the Hyrox©. Compared to the runs, the exercise stations were significantly more intense indicating higher energy demands per time. In this regard, it is to note that the exercise stations with the heaviest external loads (sled push and sled pull) were completed the fastest. Median completion times of these movements still ranged between 2–3 min indicating that Hyrox© requires athletes to exert a considerable amount of force over prolonged periods of time with anaerobic glycolysis being a key contributor to energy production during these phases. The importance of anaerobic energy production was also confirmed for other HIFT domains such as CF. However, Fernandez et al. and Forte et al. reported considerably higher BL values for CF workouts (mean ± standard deviation: up to 15.8 ± 4.9 mmol/L) (Fernández et al., 2015; Forte et al., 2022). This is in line with recent findings of Sousa Neto et al. who investigated physiological responses after the CF benchmark workout "Karen" (150 repetitions of wall balls with a 9 kg ball as fast as possible) and found significant increases of BL reaching even higher values 17.5 ± 3 mmol/L) (Sousa Neto et al., 2022). Nevertheless, most of the investigated CrossFit© workouts were shorter than 20 min (Fernández et al., 2015; Forte et al., 2022; Sousa Neto et al., 2022). One exception might be the CF workout Murph, in which physiological responses similar to Hyrox© were observed (HR_{max} = 185.6 ± 7.6 bpm, HR_{avg} = 168.8 ± 6.4 bpm, and BL = 10 ± 3 mmol/L). However, Murph was completed substantially faster (43.4 ± 4.6 min) and classified by shorter running distance (2 miles) and time (17.6 ± 2 min) leading to divergent demands for the athletes (Carreker and Grosicki, 2020).

On the other hand, unlike HIFT modalities such as CF where athletes are prepared for "the unknown and unknowable," exercises but also the loads being moved in Hyrox© competitions are fixed (Bergmann, 2024; Glassman, 2020). This suggests that once strength and power exceed a certain level, benefits of further improvements in these parameters might diminish. Contrastingly, the importance of muscular endurance (e.g., utilizing, tolerating, and clearing lactate) could become more prominent in order

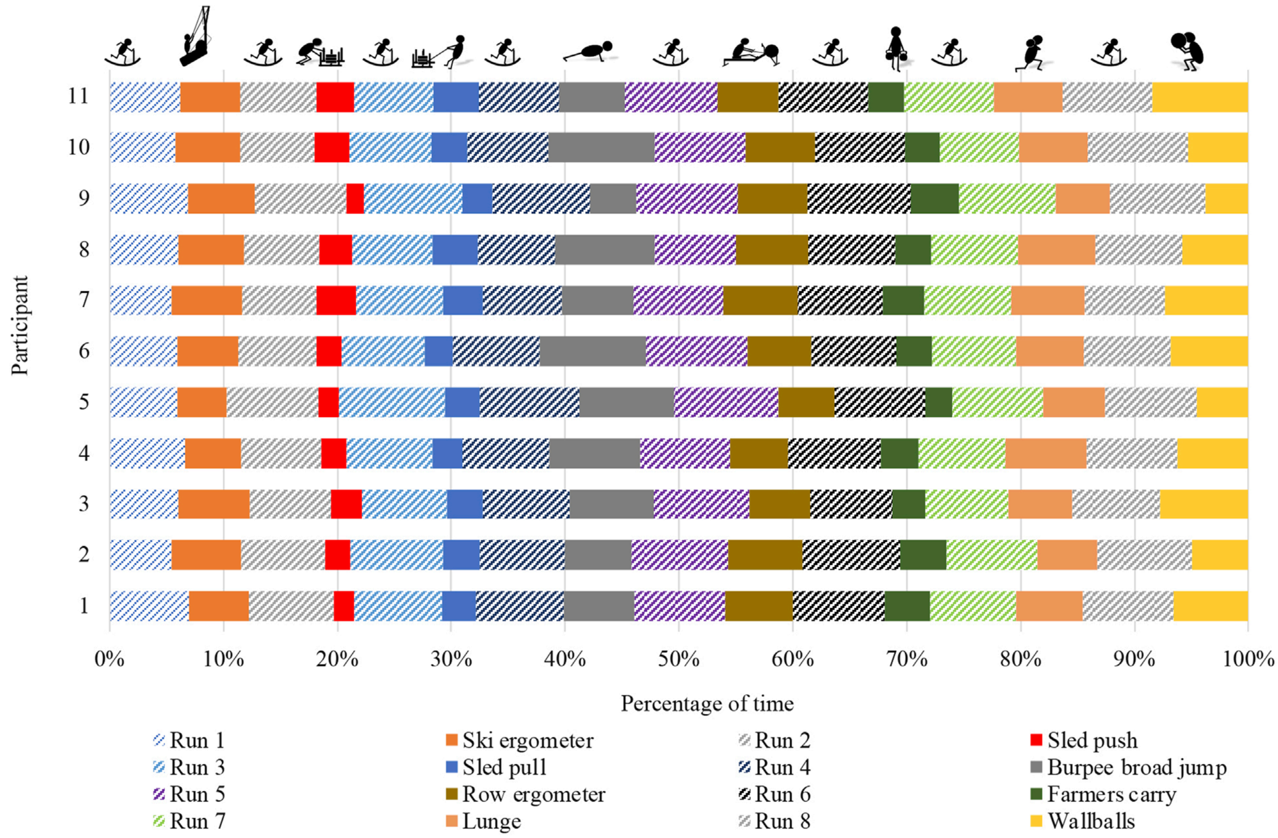

FIGURE 3
Distribution of the time spent completing the exercise stations and runs during the simulated Hyrox© competition.

to sustain the repeated high-intensity efforts. In this context, it is worth mentioning that the various movements performed in Hyrox© involve the upper as well as lower body musculature (Bergmann, 2024). It is therefore to assume, that both the transition between fatiguing upper-body-dominant as well as lower-body-dominant movements and running inhibits running performance and requires specific adaptions (e.g., redistribution of blood to the legs after movements involving large amounts of upper body musculature; running after high lactate accumulation in the legs due to lower-body-dominant movements). Running under such circumstances could have negatively affected running technique respectively economy which is highly relevant to achieve high running speeds. This could explain the relatively low running pace during the Hyrox© compared to that observed in recreational half-marathon runners (Ogueta-Alday et al., 2018). Therefore, economizing the transition between different metabolic demands as well as maintaining efficient technical execution under fatigue seem to be important aspects for Hyrox© athletes. This is in line with the findings of Peeling et al., who showed that swimming at too high an intensity has detrimental effects on subsequent cycling performance as well as overall performance in triathletes (Peeling et al., 2005). Similarly, Ribiero et al. reported lower overall performance in the CF workout "Fight Gone Bad" when participants completed it in all-out pacing compared to a controlled-split pacing strategy (Ribeiro et al., 2024).

In comparison to endurance sports (e.g., running, cycling, rowing, swimming), Hyrox© athletes need to excel in a greater variety of movement patterns and components of physical fitness (Bergmann, 2024). However, compared to CF, the degree of variation in terms of movements, distances, and loads, the technical demands appear to be relatively low (Bergmann, 2024; Glassman, 2020). This was also displayed by the fact that all participants were able to perform the movements according to Hyrox© competition standards without any scaling. It can therefore be assumed that as performance level and technical proficiency increase, the optimization of metabolic adaptations and proper pacing becomes increasingly important for Hyrox© athletes.

4.2 Performance determinants

The correlation analyses were in line with the assumptions drawn from the observed physiological responses and RPE. Strong correlations with VO_2max suggested that aerobic capacity could be an important performance determinant for Hyrox© athletes. This was also evident in previous research investigating half-marathon runners as well as CF athletes (Meier et al., 2023a; Nikolaidis and Knechtle, 2023). The proximity to CF and running disciplines was further reflected in the strong correlations between the completion times of the Hyrox© and runs with body fat

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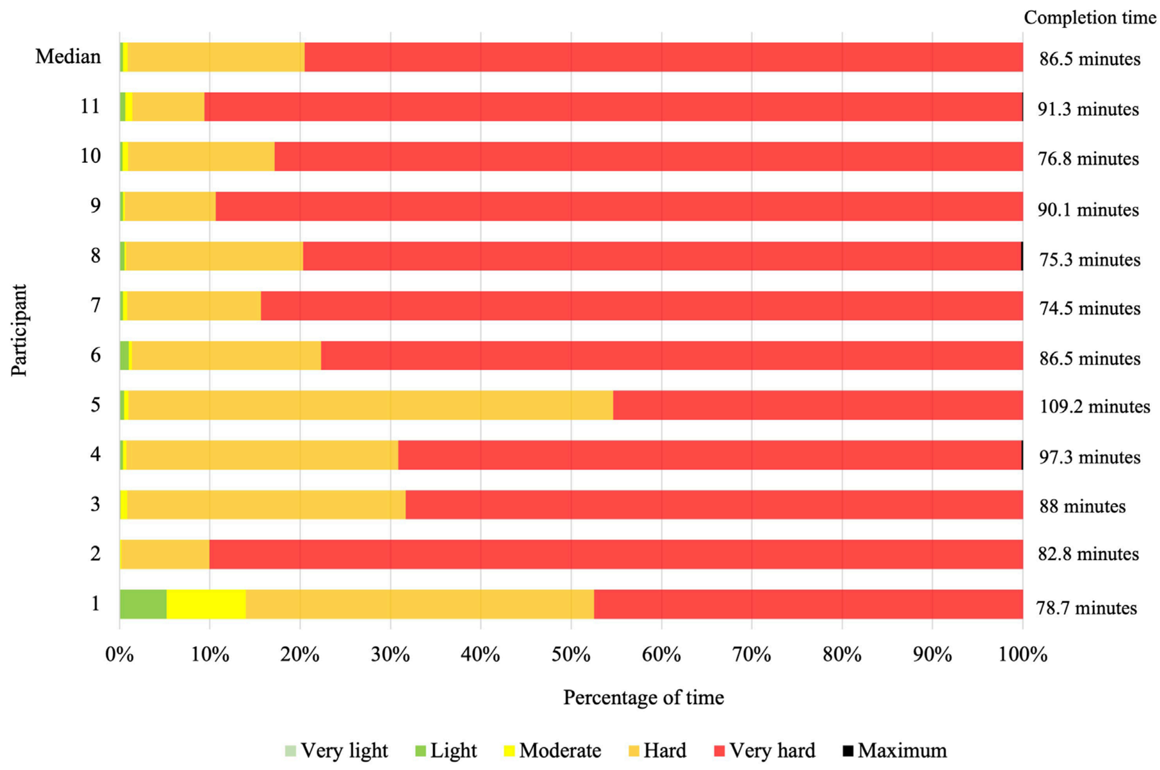

FIGURE 4
Percentage of time spent in different intensity ranges during the simulated Hyrox© competition. Note: Intensity ranges were determined based on the percentage of participants' maximum heart rate (very light: <35%, light: 35%–55%, moderate: 55%–70%, hard: 70%–90%, very hard: 90%–100%, maximum = 100%).

TABLE 2 Physiological responses and relative perceived exertion during the simulated Hyrox© competition.

	Full Hyrox©	Runs	Exercise stations	r	p
Completion time [min]	86.5 (14.5)	51.2 (14.1)	32.8 (6.1)	0.88	**0.003**
HR_{max} [bpm]	185 (26)	180 (25)	185 (26)	0.62	**0.04**
HR_{avg} [bpm]	170.9 (21.2)	168.9 (21.9)	173.7 (19.5)	0.64	**0.03**
BL_{max} [mmol/L]	8.5 (5.4)	7.7 (4.6)	8.5 (5.4)	0.83	**0.006**
BL_{avg} [mmol/L]	6.3 (3.8)	6.2 (3.9)	6.6 (3.7)	0.88	**0.003**
RPE_{max} score	18 (2)	16 (2)	18 (2)	0.91	**0.003**
RPE_{avg} score	14.1 (1.5)	13.4 (1.3)	14.4 (1.9)	0.89	**0.003**

Note: Values are expressed as median (interquartile range). Effect sizes and significance levels were calculated for differences between runs and Exercise stations. The significance level was set at $p < .05$. The effect size is given as Pearson´s r. Significant results are displayed in bold.
Abbreviations: BL_{avg}, average blood lactate; BLmax, maximum blood lactate HR_{avg}, average heart rate; HR_{max}, maximum heart rate, bpm = beats per minute, max = maximum, min = minimum, RPE_{avg}, average relative perceived exertion; RPE_{max}, maximum relative perceived exertion.

percentage (Meier et al., 2023a; Nikolaidis and Knechtle, 2023). However, in contrast to CF, where measures of muscular strength were found to be important performance determinants, neither HGS nor muscle mass percentage correlated with performance in the present study (Meier et al., 2023a). This was also reflected in the lack of correlation between resistance training and completion times. On the other hand, endurance training volume was strongly associated with completion times of the Hyrox© as well as the runs. However, more information regarding training parameters (e.g., volume, intensity, exercise selection, training history) would be required to better estimate the relevance of resistance and endurance training. Furthermore, only maximum HGS but no direct assessment of lower body strength or strength endurance was conducted.

FIGURE 5
Heart rate, blood lactate, and relative perceived exertion for each exercise station and run during the simulated Hyrox©competition. Abbreviations: BL, blood lactate; bpm, beats per minute; HR, maximum heart rate; RPE, relative perceived exertion, mmol/L, millimoles per liter.

4.3 Training recommendations

When training for a Hyrox©, a broad training strategy needs to be applied. According to the observations in the present study, endurance training should to be emphasized to perform a Hyrox© at hard to very hard intensities. Hyrox© training programs should therefore include endurance activities at moderate intensities as well as forms of HIIT to improve aerobic as well as anaerobic capacity. Since athletes spent the majority of time running, a substantial amount of training volume has to be dedicated to running-based training sessions. However, excessive running mileage has been shown to increase the injury risk and should be treated with caution (Fields et al., 2010). A strategy to avoid running-related overuse or injury would be to replace or combine running with other Hyrox© specific endurance activities such as rowing or skiing (Bergmann, 2024). Infact, combining running with other Hyrox© movements should be an integral part of Hyrox© training to improve running economy in a pre-fatigued state and the ability to transition between different metabolic demands.

Although strength appeared to be less important, athletes still need to be able to move external weights according to the competition standards. Previous research on CT indicated that endurance and resistance training may interfere with each other, affecting overall adaptations. To minimize interference, Methenitis recommended separating resistance and endurance training into distinct sessions. When endurance and resistance training have to be done in the same session, the most important aspect should be trained first. In case of athletes that substantially lack maximum strength, power, or muscular endurance to handle competition-standard loads, a training cycle focusing on resistance training could be utilized. For optimal resistance training adaptations, a ratio of 2:1 or 3:1 (resistance: endurance training) in terms of training frequency is recommended. On the other hand, optimal endurance training adaptions should be achieved with a ratio of 1:1 or 1:2 (resistance: endurance training) (Methenitis, 2018). Due to the high-intensity nature of Hyrox©, an efficient training method for Hyrox© athletes should be HIIT as it effectively improves measures of endurance such as VO_2max and leads to less interference effects compared with high-volume, moderate-intensity endurance training (Methenitis, 2018; Mallol et al., 2019). Furthermore, by incorporating Hyrox© exercises and running within a HIIT-style endurance protocol, multiple training objectives could be achieved within a single session and thus minimize overall fatigue. Such training protocols would closely mirror the demands of a Hyrox© competition, possibly enabling athletes to refine transitions between exercises, enhance movement efficiency, and adapt to the specific metabolic demands of Hyrox©. While findings of this study allowed

TABLE 3 Correlations between Hyrox© performance and participant characteristics.

	Full Hyrox		Runs		Exercise stations	
	Spearman's ρ	p	Spearman's ρ	p	Spearman's ρ	p
VO_2max	−0.71	**0.01**	0.73	**0.01**	−0.11	0.74
Body mass	0.02	0.96	−0.11	0.75	0.48	0.14
BMI	−0.07	0.83	−0.16	0.65	0.28	0.4
Body fat percentage	0.67	**0.03**	0.68	**0.02**	0.12	0.72
Muscle mass percentage	−0.03	0.94	−0.07	0.83	0.21	0.53
Hand grip strength	0.09	0.79	−0.03	0.94	0.53	0.09
Endurance training volume	−0.68	**0.04**	−0.63	0.07	−0.43	0.25
Resistance training volume	0.34	0.31	0.29	0.39	0.35	0.3

Note: The time to completion for the complete Hyrox©, the accumulated runs, and the accumulated exercise stations were tested for correlations with participant characteristics. The significance level was set at $p < 0.05$. The correlation coefficient is given as Spearman´s ρ. Significant results are displayed in bold.
Abbreviations: BMI, body mass index; VO_2max, maximum rate of oxygen consumption.

for several general training recommendations, assessing individual capabilities and circumstances remains detrimental to design an effective, customized training program.

4.4 Perspectives for practice and research

4.4.1 Health promotion

As a form of HIFT, Hyrox© shows a significant overlap with the top recent fitness trends such as HIIT, FFT, and bodyweight training (Thompson, 2023). It is therefore to assume that its popularity will further increase. Besides the competitive execution of Hyrox©, it could also be attractive for health-oriented individuals. As outlined above, Hyrox© training should include endurance training at moderate and high intensities as well as resistance training including all major muscle groups. Hyrox© training therefore appears as an efficient way to meet the guidelines of the World Health Organization (WHO) (Bull et al., 2020). The effectiveness of HIFT in terms of fitness and health (e.g., body composition, musculoskeletal, and cardiorespiratory fitness) has already been shown in previous studies (Claudino et al., 2018; Brandt et al., 2024; Bycura et al., 2017). Additionally, physical activity interventions based on Hyrox©, could benefit from positive motivational aspects that were found in other forms of HIFT such as CF indicating great potential for behavioral change and maintenance (Brandt et al., 2024; Bycura et al., 2017). The lower number and complexity of exercises compared to CF could further reduce barriers for participation in diverse populations with reduced physical capabilities (e.g., overweight and obese individuals, older adults, and those with physical impairments) (Winter and Gutman, 2022). Nevertheless, Hyrox© still provides considerably more variation than other endurance activities (e.g., running, cycling, swimming) which has been reported to facilitate exercise participation among fitness practitioners (Winter and Gutman, 2022). Due to its similarity to CF, it is to assume that Hyrox© participants also benefit from intrinsic motives such as enjoyment, challenge, and affiliation that support long-term adherence (Fisher et al., 2017). Furthermore, Hyrox© offers different divisions with scaled competition standards, allowing participants of varying fitness levels and age groups to compete with each other (Bergmann, 2024). This does not only increase the accessibility of Hyrox© for different populations, but might additionally results in levels of interest and enjoyment typically seen in sports (Frederick and Ryan, 1993).

4.4.2 Tactical populations

Another potential application area could be the training of tactical populations including soldiers, firefighters, and law enforcement personnel. These groups have to be prepared for a high variety of physical tasks such as dismounted patrols, casualty carry, or intensive combat situations while carrying heavy equipment. Hyrox© could address the need for versatile fitness adaptions (e.g., strength, power, aerobic, and anaerobic capacity) in tactical populations and additionally teach movement patterns such as lifting, pulling, pushing, carrying, and throwing external loads that are common in mission tasks (Bergmann, 2024). Previous studies have already demonstrated the potential of HIFT for tactical populations. Haddock et al. concluded that HIFT modalities (e.g., CF, SEALFIT, US Marine Corps' High Intensity Tactical Training) provide several benefits such as improved conditioning and strength, general physical preparedness for unpredictable physical demands, less injury potential, low equipment costs, high scalability, and 25%–80% lower training volume compared to conventional military fitness training (Haddock et al., 2016).

4.4.3 Implications for future research

While the present study provided a valuable foundation regarding the characteristics of Hyrox©, further research that builds on these results and addresses the limitations identified in this study is needed to gain a comprehensive understanding of this novel HIFT modality. Firstly, it is important to note that all but one participant in the present study demonstrated very good to excellent cardiorespiratory fitness levels based on their VO_2max values (exception was one male participant showing good cardiorespiratory fitness) (Heyward, 2006). In terms of strength, again 8 participants showed above-average HGS for their age-group whereby only 3 male participants ranged slightly below-average (93.2%–99.6% of reference values) (Ewald and Kohler, 1991). This needs to be considered since physiological differences between athletes differing in experience or fitness level could affect performance and physiological responses (Mangine et al., 2020; Lorenz et al., 2013). Consequently, together with the small sample size, the generalizability of the present findings remains limited. To establish a more nuanced understanding of the characteristics of Hyrox© across different fitness levels, future studies could include a larger, more heterogenous sample. An alternative approach might be to continue working with small sample sizes but homogeneous groups (e.g., only elite men or women), allowing for more distinct conclusions regarding the specific cohort, as was done by Martínez-Gómez et al. and Sauvé et al. for elite CF athletes (Sauvé et al., 2024; Martínez-Gómez et al., 2020). Furthermore, investigations should be extended to other Hyrox© divisions besides the “Individual Open” (e.g., Individual Pro, Doubles, Relay).

Further limiting factors of the present study were that each participant performed the Hyrox© alone (no competitors or spectators), runs did not take place on a track, and the sled used differed from the official competition sled. Especially running on a competition-standard track could lead to different results. For instance, Peserico and Machado found lower running velocity and HR_{avg} but higher HR_{max} when participants ran 60 min on a treadmill compared to a track. Additionally, the authors reported differences in pacing strategies between the track and treadmill condition (Peserico and Machado, 2014). Similar results were confirmed in previous studies investigating shorter distances (Nummela et al., 2007; Morin and Sève, 2011). In future studies, efforts should be made to replicate competition conditions more accurately or measure athletes during official competitions. To enhance the understanding of potential performance determinants, it is also recommended to expand the test battery with additional measurements. An effective method could be the determination of a total athleticism score, as recently proposed by Tibana et al. in the context of CF. The authors calculated the score based on body fat percentage, VO_2max, muscle power, and muscle endurance providing a holistic measure for overall athleticism (Tibana et al., 2024). A similar tool could be developed and applied in Hyrox©, incorporating Hyrox-specific movements and accessible tests (e.g., the critical speed test). Lastly, the potential effectiveness of Hyrox© in terms of health-promotion and tactical training has not been confirmed yet and must be investigated in future studies. In this context, future research should focus not only on fitness and health adaptions but also on motivational aspects, the potential for behavioral change and maintenance, training time and volume, costs, equipment requirements, injury prevalence as well as the applicability across various settings (e.g., commercial gyms, workplace health promotion, military bases, and during deployments abroad).

5 Conclusion

Hyrox© is an endurance-focused form of HIFT that combines running with 8 different functional movements. Performing a Hyrox© required athletes to engage both aerobic as well as anaerobic metabolic pathways and to transition between varying metabolic demands depending on the executed movement. Participants spent the majority of the Hyrox© running whereas the intensity according to HR, BL, and RPE values was higher during the exercise stations. Although endurance capacity respectively training appeared to be of greater importance for performance than measures of strength, individual weaknesses should be considered to design effective and sustainable training programs. In this regard, it is suggested to apply CT training recommendations (Methenitis, 2018). Despite the limitations of this first Hyrox© study and the need for further investigations, Hyrox© has emerged as a form of HIFT likely to gain further popularity and offering practical applications beyond its competitive nature, including health promotion and tactical population training.

Data availability statement

The datasets presented in this article are not readily available because The data that support the findings of this study are available from the corresponding author upon reasonable request. Requests to access the datasets should be directed to tom.brandt@unibw.de.

Ethics statement

The studies involving humans were approved by the Ethics Committee of the University of the Bundeswehr Munich, Germany. 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.

Author contributions

TB: Conceptualization, Data curation, Formal Analysis, Methodology, Supervision, Visualization, Writing–original draft, Writing–review and editing. CE: Data curation, Formal Analysis, Investigation, Visualization, Writing–original draft. CL: Data curation, Formal Analysis, Investigation, Visualization, Writing–original draft. AS: Conceptualization, Methodology, Supervision, Writing–review and editing.

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Conflict of interest

The Results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. Professional relationships with companies or manufacturers who will benefit from the results of the present study do not exist.

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Impact of exercise video-guided bodyweight interval training on psychophysiological outcomes in inactive adults with obesity

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Purpose: Determine the impact of a 6-week YouTube-instructed bodyweight interval training (BW-IT) program on cardiometabolic health, muscular strength, and factors related to exercise adherence in adults with obesity.

Methods: Fourteen adults (30.7 ± 10.3 yrs, BMI 35.5 ± 5.4 kg/m^2) participated in this study. The BW-IT program progressed bi-weekly from a 1:3 to 1:1 work-to-rest ratio, using maximum effort intervals of high knees, squat jumps, scissor jacks, jumping lunges, and burpees. Pre- and post-intervention measures included peak oxygen consumption ($\dot{V}O_{2peak}$), relative quadriceps isometric muscular strength, waist circumference (WC), body composition via bioelectrical impedance, and cardiometabolic blood markers (blood glucose, insulin, lipid panel, and C-reactive protein). Self-efficacy (task and scheduling) and physical activity enjoyment (PACES) were also assessed.

Results: Relative isometric muscular strength increased by 12.5% (p = 0.02, dz 0.4) and absolute $\dot{V}O_{2peak}$ by 4.2% (p = 0.03, dz = 0.2). WC reduced by 2.1% (p < 0.001, dz = 0.2). Task self-efficacy was similar pre- to post-intervention (p = 0.53, dz = 0.2), while scheduling self-efficacy was reduced (p < 0.004, dz = 1.1). PACES scores were 9.6% higher week one compared to week six of BW-IT (p = 0.003, dz = 0.6). No changes occurred in body composition or cardiometabolic blood markers.

Conclusion: In previously inactive adults with obesity, 18 sessions of YouTube-instructed bodyweight interval training elicited small to moderate effects on lower extremity muscular strength, cardiorespiratory fitness, and waist circumference. Future studies may benefit from longer interventions and adding a greater variety of calisthenics to determine interventions that improve physiological health and maintain or enhance factors associated with exercise adherence.

KEYWORDS

bodyweight exercise, interval training, obesity, cardiorespiratory fitness, muscular strength, enjoyment, self-efficacy

Introduction

Obesity is defined as having a body mass index (BMI) value of ≥30 kg/m^2 (World Health Organization, 2021). Currently, approximately 42% of adults in the United States are considered to have obesity (Centers for Disease Control and Prevention, 2022), and it is predicted to increase to 49% by 2030 (Ward et al., 2019). Obesity is associated with premature mortality and exacerbates the risk of several chronic diseases, including hypertension, type 2 diabetes, and cardiovascular disease (Jastreboff et al., 2019). Thus, prevention and treatment strategies for obesity present one of the biggest medical challenges of the 21st century.

Exercise is a key intervention for mitigating cardiometabolic risks in obesity; however, some forms of exercise may be more efficacious than others. A systematic review and meta-analysis by Batrakoulis and colleagues concluded that for adults with overweight/obesity, multimodal combined training (CT) (i.e., continuous aerobic exercise plus resistance exercise) is superior to single modality training for improving cardiometabolic and physical health parameters (lipid profile, homeostatic model of insulin resistance (HOMA-IR), blood pressure, body composition, cardiorespiratory fitness (CRF), and muscular strength) (Batrakoulis et al., 2022). The second most effective mode noted was hybrid training (HT), a multi-component exercise in which the cardiovascular and musculoskeletal systems are engaged simultaneously (e.g., functional high-intensity interval training), with less time requirement than CT (Batrakoulis et al., 2022). A caveat of both CT and HT protocols is that they often require exercise equipment (e.g., agility ropes, ergometers, barbell rigs, etc.) and lack of time, access to exercise facilities/equipment, poor body image, and fears of embarrassment and stigma are common reported barriers to exercise among adults with obesity (Collins et al., 2022; Hamer et al., 2021; Korkiakangas et al., 2009). Thus, CT and HT may not be feasible or attractive for some individuals facing such barriers.

Bodyweight interval training (BW-IT) may serve as a practical and appealing option for adults with obesity to participate in cardiovascular and muscle strengthening exercise. This style of training is like HT in that it requires full-body movements using one's body weight as resistance against gravity (Batrakoulis et al., 2021). However, unlike HT, BW-IT does not require the use of adjunct equipment, such as those mentioned above (Batrakoulis et al., 2021). Additionally, the intervals of BW-IT are often prescribed for as many repetitions as possible followed by recovery periods (Machado et al., 2019), a structure similar to well-studied styles of high-intensity interval training (HIIT) performed on cycle ergometers or treadmills (MacInnis and Gibala, 2017). Due to these characteristics, BW-IT may elicit similar cardiometabolic benefits to HIIT and HT in adults with obesity (Al-Mhanna et al., 2024; Batrakoulis et al., 2021; Batrakoulis and Fatouros, 2022). Moreover, it holds promise for promoting exercise adherence since bodyweight training, and on-demand exercise classes are currently ranked among the top global health and fitness trends (Newsome et al., 2024).

The purpose of the present study was to evaluate the effects of a 6-week, YouTube-instructed BW-IT program in physically inactive adults with obesity. The primary variables of interest included peak oxygen uptake ($\dot{V}O_{2peak}$), isometric muscular strength, and cardiometabolic biomarkers. In addition, we aimed to understand psychological factors related to our BW-IT protocol, including enjoyment, task self-efficacy and scheduling self-efficacy.

Methods

Study design

Participants visited the Exercise Physiology laboratory at the University of New Mexico on two separate visits (baseline and post-intervention). Prior to each visit, participants were instructed to arrive in a hydrated and fasted state (no food or caffeine for ≥8 h) and abstain from alcohol and vigorous exercise for 24 h. During the baseline visit, written consent was obtained, and baseline data were collected (anthropometrics, body composition, CRF, maximal isometric strength, and cardiometabolic markers). In addition, participants were familiarized with the study protocol and given a wrist-based wearable technology device (Fitbit Inspire™) to measure heart rate (HR) during remote training sessions. After all fasted measurements were taken, a light snack (1–2 granola bars) was provided. Following the 6-week intervention, participants reported back to the lab for the post-intervention data collection visit comprised of the same variables collected at the baseline visit.

Participants

The inclusion criteria were: 1) adults between 18 and 55 years; 2) classified with obesity (BMI ≥30 kg/m^2); 3) physically inactive (<150 min of moderate to vigorous PA per week); and 4) non-smokers. Participants completed health history and physical activity readiness (PAR-Q+) (Warburton et al., 2021) questionnaires. If a participant indicated signs or symptoms of cardiovascular, metabolic, or renal disease, medical clearance was required prior to participation (Riebe et al., 2015). Participants who reported taking glucose or lipid-lowering medications were excluded from the study. To exclude individuals with unknown/potential prediabetes or Type II diabetes, a fasting (≥8hrs.) blood capillary glucose sample was collected from the finger using a lancet and analyzed by a portable glucose meter TRUE METRIX™ Blood Glucose Monitor (Trividia Health, Inc., United States). Individuals with blood glucose values

TABLE 1 Participant characteristics pre- and post-BW-IT ($n = 14$).

Variable	PRE	Post	*p*	*dz*
Sex (M/F)	2/12	—	—	—
Age (years)	30.7 ± 10.3	—	—	—
Height (cm)	167.6 ± 8.6	—	—	—
Weight (kg)	99.8 ± 16.6	100.5 ± 17.1	0.21	0.04
BMI (kg/m²)	35.5 ± 5.4	35.8 ± 5.5	0.22	0.06
WC (cm)	99.9 ± 10.7	97.8 ± 10.2	<0.001	0.20
HC (cm)	121.9 ± 9.1	121.4 ± 9.4	0.60	0.05
BF (%)	43.9 ± 5.3	44.2 ± 4.9	0.42	0.06
SMM (kg)	31.3 ± 6.3	31.3 ± 5.0	0.76	0.01
LLM (kg)	16.8 ± 3.1	16.6 ± 3.2	0.17	0.05

Note. Data are presented as mean ± SD. M, male; F, female; BMI, body mass index; WC, waist circumference; HC, hip circumference; cm, centimeters; kg, kilograms; kg/m^2, kilograms per meters squared; BF, body fat; %, percent; SMM, skeletal muscle mass; LLM, leg lean mass; *dz*, Cohen's *d*.

within ±15% of 100 mg/dL were included due to the accuracy range reported by the manufacturer. Blood glucose levels were confirmed prior to proceeding with the study by sending blood samples to a local commercial lab (Quest Direct™, Albuquerque, NM, United States) for fasting blood glucose and hemoglobin A1c (HgbA1c).

G*Power Sample 3.1 software (G*power, Dusseldorf, Germany) was used to calculate the required sample size based on an *a priori* analysis for a paired samples t-test. The power analysis was conducted using the following parameters: test family difference between two dependent means (matched pairs), with power set to 0.80 and alpha at 0.05. A minimum sample (n = 14) was determined to achieve statistical power (1-β) of 0.80, using $\dot{V}O_2$ (mL/kg/min) as the primary dependent variable of interest. This was based on a previous assessment of $\dot{V}O_2$ (mL/kg/min) after 4-weeks of a home-based bodyweight exercise program in physically inactive adults with obesity (Scott et al., 2019). Participant demographics are summarized in Table 1.

Baseline and post-testing measurements

Anthropometrics and body composition

Height was measured to the nearest centimeter (cm) using a stadiometer (Holtain Limited, Crymych, Dyfed, Great Britain), and weight to the nearest 0.1 kg (kg) using a digital weight scale (MedWeight MS-3900, Itin Scale Company, Brooklyn, NY, United States). Body mass index was calculated using body mass (kg) divided by the square of the height (meters). Waist circumference (WC) and hip circumference (HC) measurements were obtained according to WHO standard techniques (World Health Organization, 2011). Body composition [body weight (kg), skeletal muscle mass (SSM) (kg), BF%, and lean leg mass (LLM) (kg)] was assessed using a tetrapolar bioelectrical impedance (BIA) device (InBody 570, Biospace, INC., United States) according to manufacturer guidelines. This method was chosen to prioritize participant comfort, and previous research supports the use of BIA to provide accurate estimates of body composition in adults with obesity (Bosy-Westphal et al., 2008; Pietiläinen et al., 2013). Prior to measurement of body composition, hydration status was checked using urine specific gravity (USG) and participants with >1.02 were considered dehydrated (Armstrong, 2005) and rescheduled to reassess body composition.

$\dot{V}O_2$ peak and ventilatory threshold

Participants performed an individualized maximal incremental treadmill test (C966i, Precor Inc., Woodinville, WA, United States). The protocol used a fixed incline of 1% with speed increasing by 0.5 mph until the eighth minute. Starting speed was determined during warm-up by asking participants to briefly and gradually increase the treadmill speed to a speed that they believed they could maintain for 1 minute (perceived max speed, Vmax). After reaching the maximal speed with the eighth minute, the treadmill grade was increased by 1% per minute until volitional fatigue. During the test, heart rate was continuously recorded using a HR monitor (Polar V800, Polar Electro, Kempele, Finland). Gas exchange and ventilation (VE) were measured continuously using a metabolic cart (Parvo Medics True One 2,400, Sandy, UT, United States) while participants wore a nose clip and mouthpiece (Hans Rudolph Inc. Kansas City, MO, United States). The metabolic cart was calibrated according to manufacturer guidelines. All tests were completed within eight to 12 minutes (Yoon et al., 2007). Data were extracted using a 15-s breath running average and the highest data point was recorded as absolute (L/min) and relative (mL/kg/min) $\dot{V}O_{2peak}$ (Robergs et al., 2010). Ventilatory threshold (VT) was determined using the V-slope method (i.e., visual inspection of the point at which carbon dioxide ($\dot{V}CO_2$) rose disproportionately to $\dot{V}O_2$ against time) (Beaver et al., 1986). Two experienced exercise physiologists determined VT ($\dot{V}O_2$ at VT) and compiled results. A third research team member verified VT by visually inspecting values and making a final decision if VT varied more than 15s.

Maximal isometric muscular strength

Before testing, participants warmed up on a cycle ergometer at a self-selected pace for approximately 5 minutes. Maximal voluntary isometric knee extensor strength was measured using an isokinetic dynamometer on the participants' dominant leg (Model 850–230, Universal Pro Single Chair Assembly, Biodex Medical Systems, Inc., Shirley, New York, United States). Each participant was seated on the dynamometer chair with the ankle firmly strapped to the distal pad of the lever arm. The measurements included three five-second maximal isometric contractions, with the knee joint angle fixed at 90°. Each maximal isometric contraction was interspersed with 10-s of rest. Participants performed a minimum of one submaximal practice set of the protocol with a 2-min rest period before testing, respectively. A complete knee extension corresponded to a joint angle of 0°. Peak torque (Nm) values were used for data analysis and expressed relative to body mass (kg).

Fasting blood samples

Fasting blood samples of approximately 15 mL were collected from an antecubital or dorsal hand vein. Samples were collected in serum separator tubes to allow the blood to clot by leaving it undisturbed at room temperature. Serum was obtained by centrifuging the tubes for 15 min (1,000 g, 22°C) (Allegra X-14R Centrifuge, Beckman Coulter, Brea, CA) and stored at −80°C for subsequent analysis. Serum concentrations of insulin, glucose, low-density lipoprotein (LDL), high-density lipoprotein (HDL), triglycerides (TG), total cholesterol (TC), C-reactive protein (CRP) were sent to a commercial laboratory (Quest Direct™, Albuquerque, NM, United States). Additionally, whole blood samples were collected in EDTA tubes for HgbA1c and sent to the same commercial laboratory. Insulin resistance was calculated using HOMA-IR (fasting insulin (uIU/mL) x fasting glucose (mg/dL)/405) (Gastaldelli, 2022).

Self-efficacy and physical activity enjoyment

Task self-efficacy and scheduling self-efficacy were assessed at the pre- and post-intervention time points using previously established recommendations (Bandura, 1997). The first 12 items were designed to determine participants' confidence in repeating BW-IT task self-efficacy (both intervals and complete sessions). All items included the same stem, "Over the next 6 weeks, how confident are you in your physical capabilities to…" and the items were: "perform (4, 6, 8, 10, and 12, 30s BW-IT intervals on your own) and (1, 2, 3, 4, 5, 6, and 7 or more, sessions of BW-IT on your own)". The subsequent seven items used the same stems and were designed to determine participants' confidence in scheduling self-efficacy. Responses for task self-efficacy and scheduling self-efficacy were scored as a percentage from 0%, "not at all confident," to 100%, "extremely confident", in 10% increments. The averages for the 12 task self-efficacy and seven scheduling self-efficacy items were computed. Physical activity enjoyment of the BW-IT protocol was assessed using the original seven-point Likert, 18-item PACES questionnaire (Kendzierski and DeCarlo, 1991). Negatively worded items were reverse scored to calculate a total score from 7 to 126, with higher scores representing more positive enjoyment of BW-IT.

BW-IT familiarization procedures

Participants were familiarized with the BW-IT exercises upon completion of baseline testing procedures. A certified exercise physiologist/personal trainer demonstrated the technique of each bodyweight exercise along with cues and explanations of proper movement mechanics. In addition, participants watched a pre-recorded BW-IT familiarization video (see Supplemental Material). Participants also received an electronic step-by-step guide with links to the YouTube workouts, the program's general instructions, and the study timeline.

YouTube-based BW-IT program

Participants were encouraged to perform BW-IT on three nonconsecutive days per week across the 6-week intervention; however, they were informed that they could exercise on days that suited their schedule (even if on consecutive days). Each BW-IT video consisted of a 2-minute warm-up (30s of four calisthenics: jogging in place, side-stepping heel to glute kicks, ski jumps, and high knees or marching in place with high knees). The BW-IT protocol workouts consisted of two sets of five bodyweight exercises performed in the following order for as many repetitions as possible (AMRAP): high knees, squat jumps, scissor jacks, jumping lunges, and modified burpees (without push-ups). Each AMRAP interval was interspersed with active recovery intervals consisting of side-to-side stepping in place. The video displayed advanced and modified versions of each bodyweight exercise for participants to choose from based on their ability. A 2-min rest period was provided after the first five intervals. The protocol progressed every 2 weeks by increasing the duration of the work interval and decreasing the duration of the recovery interval (week 1–2: 30s work x 90s recovery, week 3–4: 40s work x 80s recovery, week 5–6: 60s work x 60s recovery). Shortly after each AMRAP interval (~10–15s), participants were instructed to record their HR displayed on the Fitbit in an exercise journal. Each video was approximately 28 min; however, the protocol itself was 20 min (excluding the warm-up and 2-min rest between sets one and two).

Participants completed an exercise intensity survey using a link via Qualtrics™ after each BW-IT session. The survey required participants to log the date, week, and day the BW-IT workouts were completed. Next, they were asked to rank their overall level of exertion during BW-IT using the omnibus rating of perceived exertion scale (OMNI), with zero representing 'extremely easy' to ten 'extremely difficult'. The OMNI scores were averaged for weeks one through six. In addition, participants were asked to enter the 10 HR values recorded in their exercise journal for their session that day. The HR values for each session were averaged for weeks one through six. Additionally, participants ranked their overall level of muscle soreness using a sliding scale from zero (no soreness) to one hundred (extreme soreness). Muscle soreness values were averaged for weeks 1–6. The exercise intensity survey was also used by the research team as a guide to determine if participants were staying on track with the program by completing their exercise sessions for the week.

Statistical analyses

All statistical analyses were performed using IBM SPSS (IBM Corp., Version 23.0 Armonk, NY, United States), except for Cohen's *dz* which was calculated using G*Power (G*power, Dusseldorf, Germany). All data visualization was performed using GraphPad Prism v8.4 (GraphPad Software, Inc., United States). Student's paired t-test was used to compare outcome variables measured pre- and post-BW-IT. Cohen's *dz* was used to determine the magnitudes of effects from pre- to post-intervention and interpreted as trivial (<0.2), small (≥0.2 and ≤0.49), moderate (≥0.5 and ≤0.79), and large (≥0.8) (Cohen, 1992; Lakens, 2013). A repeated measures one-way analysis of variance (RM-ANOVA) was used to compare means of OMNI, HR, and muscle soreness for weeks one through six of BW-IT. A Greenhouse-Geisser correction was applied if a violation of sphericity was detected. Partial eta squared (η2) effect sizes were calculated and categorized as small (≤0.01), medium (0.06), and large (0.14) effects, respectively (Cohen, 1992; Lakens, 2013). All data are reported as mean ± standard deviation unless otherwise specified, and statistical significance was set at $p \leq 0.05$.

Ethical considerations

This single-group study, where all participants received the same intervention, was approved, by the University of New Mexico

(UNM) Institutional Review Board (IRB) [reference # 21319] and adhered with the Declaration of Helsinki. Prior to participation, all subjects were informed of study objectives, procedures, potential risks, and benefits. Written and informed consent was obtained by all study participants.

Results

Adherence

Six individuals completed the program within 42 days (6 weeks) while seven completed the program late (within seven to 8 weeks). The individuals who completed the program later than expected reported difficulty with work/schedule conflicts and illness as reasons for falling behind. Thirteen participants completed the intervention with 100% compliance (18 total BW-IT sessions), while one completed it with 78% (14 total BW-IT sessions). No injuries from the BW-IT program were reported by participants.

Anthropometrics and body composition

Anthropometric and body composition data are summarized in Table 1. A significant reduction in WC (t (13) = 12.1, $p < 0.001$, $dz = 0.21$) was observed pre- to post-BW-IT. No differences in hip circumference (HC), body weight, BMI, skeletal muscle mass, leg lean mass, or BF% were observed from pre- to post-BW-IT.

Blood biomarkers

No differences in blood-based markers of cardiometabolic health were observed pre- to post-BW-IT (i.e., glucose, insulin, HOMA-IR, HgbA1c, total cholesterol, HDL, triglycerides, LDL, and CRP) (Table 2).

TABLE 2 Blood-based markers of cardiometabolic health pre- and post-BW-IT (n = 14).

Variable	PRE	POST	*p*	*dz*
Glucose (mg/dL)	87.1 ± 7.5	89.4 ± 8.8	0.37	0.27
Insulin (uIU/mL)	11.2 ± 7.5	12.1 ± 7.0	0.29	0.12
HOMA-IR	2.5 ± 1.7	2.8 ± 1.7	0.15	0.17
HgbA1c (%)	5.2 ± 0.4	5.1 ± 0.7	0.39	0.29
TC (mg/dL)	169.4 ± 34.9	165.7 ± 32.0	0.34	0.11
HDL (mg/dL)	48.4 ± 11.0	47.9 ± 11.9	0.78	0.04
TG (mg/dL)	99.5 ± 50.4	103.1 ± 38.7	0.61	0.08
LDL (mg/dL)	102.4 ± 30.5	98.0 ± 25.6	0.20	0.15
CRP (mg/dL)	6.0 ± 3.3	5.0 ± 3.1	0.12	0.31

Note. Data are presented as mean ± SD.; mg/dL, milligrams per deciliter; uIU/mL, mili-international units per liter; HOMA-IR, homeostatic model of insulin resistance; HgbA1c, hemoglobin A1c; TC, total cholesterol; HDL, high density lipoprotein; TG, triglycerides; LDL, low density lipoprotein; CRP, C-reactive protein.

Cardiorespiratory fitness

Absolute $\dot{V}O_{2peak}$ significantly increased pre- to post-BW-IT (2.4 ± 0.5 vs. 2.5 ± 0.6 L/min, t (13) = 2.4, $p = 0.03$, $dz = 0.2$) (Figure 1). No difference in relative $\dot{V}O_{2peak}$ occurred (24.4 ± 4.1 vs. 25.5 ± 4.5 mL/kg/min, t (13) = 2.1, $p = 0.05$, dz 0.2). No change in VT occurred pre- to post BW-IT (1.6 ± 0.4 vs. 1.7 ± 0.4 L/min, t (13) = 1.7, $p = 0.11$, $dz = 0.30$), (15.8 ± 3.3 vs. 16.7 ± 3.3 mL/kg/min, t (13) = 1.5, $p = 0.07$, $dz = 0.29$).

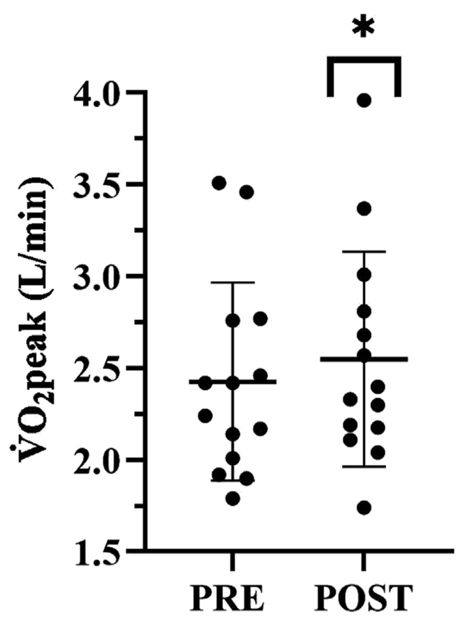

FIGURE 1
Peak oxygen consumption $\dot{V}O_{2peak}$ (L/min) pre- to post BW-IT. Data represented as mean and standard deviation,* = p < 0.05 post BW-IT.

Isometric muscular strength

Peak torque relative to body weight significantly increased pre- to post-BW-IT (1.6 ± 0.4 vs. 1.8 ± 0.5 Nm/kg, t (13) = 2.4, $p = 0.02$, $dz = 0.4$) (Figure 2). The average coefficient of variation (CV) for isometric muscular strength was 6.0% ± 4.7% at baseline and 4.1% ± 2.2% post-testing.

Self-efficacy and physical activity enjoyment

Task self-efficacy (i.e., confidence to perform BW-IT) did not change pre- to post-intervention (86.7% ± 12.2% vs. 83.6% ± 15.1%, t (13) = 0.7, $p = 0.53$, $dz = 0.2$). Scheduling self-efficacy (i.e., confidence to allocate time to schedule BW-IT) was significantly reduced pre- to post-intervention (94.7% ± 7.2% vs. 82.7% ± 13.5%,

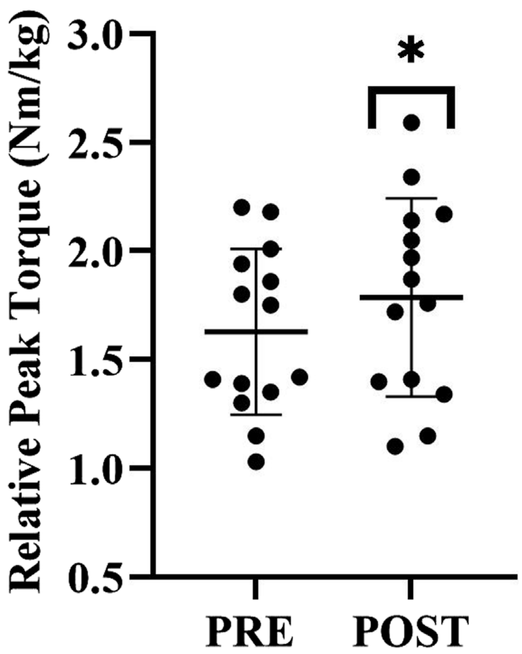

FIGURE 2
Peak torque (Nm) per body weight (kg) pre- to post BW-IT. Data represented as mean and standard deviation,*= p < 0.05 post BW-IT.

t (13) = 3.5, $p = 0.004$, $dz = 1.0$). Task self-efficacy and scheduling self-efficacy constructs demonstrated good internal consistency at each administration (Cronbach's $\alpha's \geq 0.91$). PACES scores were higher after week one (102.8 ± 16.5) compared to week 6 (92.9 ± 16.9) of BW-IT, t (13) = 3.7, $p = 0.003$, $dz = 0.59$). The PACES demonstrated good internal consistency at each administration (Cronbach's $\alpha \geq 0.92$).

RPE and muscle soreness

Week-by-week data for RPE, heart rate, and muscle soreness can be found in Table 3. No differences in these measurements occurred for weeks one through six: RPE (F (2.5, 32.8) = 1.2, $p = 0.32$, η2 = 0.08), heart rate (F (2.9, 37.6) = 0.7, $p = 0.54$, η2 = 0.05), muscle soreness (F (3.0, 38.3) = 2.7, $p = 0.06$, η2 = 0.17).

Discussion

Main findings

The main finding of the present study suggests that 18 sessions of bodyweight interval training (BW-IT) elicited significant, small to moderate effects on lower extremity isometric muscular strength, absolute $\dot{V}O_{2peak}$, and waist circumference (WC). Body composition did not improve (skeletal muscle mass, leg lean mass, and BF%) assessed via bioelectrical impedance (BIA). In addition, there were no changes in cardiometabolic biomarkers including fasting insulin, glucose, low-density lipoprotein, high-density lipoprotein, triglycerides, total cholesterol, C-reactive protein, hemoglobin A1c, and insulin resistance determined via the homeostatic model of insulin resistance (HOMA-IR). Our self-efficacy data suggests that participants were confident in their abilities to perform BW-IT but lacked confidence in scheduling it beyond the study duration. Moreover, the physical activity enjoyment (PACES) results suggest that these individuals may have enjoyed the shorter duration work intervals performed during week 1 (30s work x 90s recovery) as opposed to week 6 (60s work x 60s recovery) of BW-IT. It is also possible that participants were initially enthusiastic about beginning a structured exercise program in week one, but by week six, experienced a decline in motivation or engagement.

Cardiorespiratory and muscular fitness

Previous research supports the idea that BW-IT has the potential to offer both aerobic and muscle-strengthening benefits (Archila et al., 2021; Iversen et al., 2021; Mcleod et al., 2019; Scott et al., 2019). In the present study, we used a BW-IT protocol that alternated between rhythmic, aerobic-type exercises (high knees, scissor jacks, and burpees) and muscle-strengthening type exercises, which naturally require longer time under tension (squat jumps and jumping lunges). This protocol was previously characterized in our lab as vigorous-intensity aerobic exercise in a group of healthy active, adults (Bellissimo et al., 2022). In agreement with the current findings, previous research suggests that performing high repetition (in our case, as many repetitions as possible) and low-load (in our case, using only body weight) has been reported to effectively improve CRF (Archila et al., 2021) and muscular strength (Iversen et al., 2021; Mcleod et al., 2019).

The training protocol in the present study elicited ~4% improvement in CRF, which is slightly lower (~3%) than the results of a previous 6-week BW-IT study in physically inactive but otherwise healthy adults (Archila et al., 2021). Furthermore, Scott and colleagues observed an 8% improvement in CRF after 4 weeks of a home-based BW-IT protocol in adults with obesity (Scott et al., 2019). Although direct comparisons between BW-IT studies are challenging due to the versatility of exercise selection, we speculate our results differ because both Archila et al. (2021) and Scott et al. (2019) employed a supervised (in-person and virtual) intervention with higher average $\%HR_{max}$ values reported during exercise. For instance, Archilia et al. reported that all sessions were performed in a supervised lab setting, and mean intensity during training was 82% ± 5% HR_{max}. Further, Scott et al. (2019) supervised exercise virtually and encouraged participants to reach a target heart rate of ≥80% HR_{max} which was achieved in 99% ± 1% of exercise sessions (Scott et al., 2019). In contrast, our cohort performed all workouts independently and were instructed to perform work intervals at a self-selected relative (maximal effort) intensity. Nonetheless, even minimal improvements in CRF hold clinical relevance (Imboden et al., 2019), especially for populations like those observed in the present study who are at increased risk for cardiometabolic disease. In addition, it is important to note that 13 of our 14 participants had 100% compliance using this unsupervised protocol, suggesting that this type of intervention may be practical for use in the real world. Moreover, our task self-efficacy data suggests that participants were confident in their ability to perform BW-IT at the start and upon completion of the study.

TABLE 3 Weekly exercise characteristics (n = 14).

Week	RPE (0–10)	Heart rate (bpm)	Muscle soreness (0–100)
1	7.0 ± 1.0	139.3 ± 11.9	46.6 ± 15.2
2	6.6 ± 1.6	140.5 ± 12.2	43.4 ± 18.2
3	6.9 ± 2.0	141.1 ± 12.3	44.5 ± 19.7
4	6.8 ± 2.0	141.2 ± 10.9	45.6 ± 21.5
5	7.3 ± 1.3	142.9 ± 11.7	55.6 ± 19.3
6	7.3 ± 1.4	140.7 ± 11.3	55.6 ± 20.9

Note. Data is presented as mean ± SD. RPE, rating of perceived exertion; bpm, beat per minute.

In addition to enhanced CRF, dominant leg isometric muscular strength improved by 12.5%. These results align with those of longer duration BW-IT interventions. For example, Batrakoulis et al. (2018) report a significant progressive increase in muscular strength (1 repetition maximum leg press) at a 20-week and 40-week timepoint of BW-IT in sedentary females classified as overweight or obese (Batrakoulis et al., 2018). However, to our knowledge, there is limited evidence on the effectiveness of shorter duration BW-IT interventions on muscular strength in adults with obesity. Our findings suggest that a relatively brief intervention (18 sessions) can yield meaningful improvements in lower extremity strength. This finding is noteworthy, as lower body strength is a key predictor of functional limitations and physical disabilities with aging (Hairi et al., 2010). The importance of our findings is underscored by evidence that suggests muscular strength is an independent predictor of disease risk and all-cause mortality (Kim et al., 2018; Volaklis et al., 2015). These results highlight the potential for shorter duration BW-IT to provide meaningful lower body strength benefits.

Body composition and cardiometabolic health

Findings from the present study indicate that apart from WC, 6-weeks of BW-IT was not sufficient to improve body composition (skeletal muscle mass, leg lean mass, and BF%) assessed via bioelectrical impedance. Therefore, the small effect observed in WC (dz = 0.21) should be interpreted with caution. In addition, no changes in cardiometabolic biomarkers occurred, including fasting insulin, glucose, low-density lipoprotein, high-density lipoprotein, triglycerides, total cholesterol, C-reactive protein, hemoglobin A1c, and HOMA-IR. Our results are in agreement with a meta-analytic evidence that suggests there is no effect of low-volume HIIT (≤500 MET-min/week) on body composition parameters (total body fat mass and BF%) assessed via dual-energy X-ray absorptiometry (DXA), BIA, or air displacement plethysmography (ADP) (Sultana et al., 2019). Similarly, a meta-analysis by Batacan et al. (2017) suggests that short-term HIIT interventions (<12-weeks) may be insufficient for stimulating improvements in insulin, lipid profile and C-reactive protein in adults classified with overweight/obesity (Batacan et al., 2017).

Several factors related to BW-IT make it difficult to determine its potential impact on body composition and cardiometabolic health. For example, challenges in controlling exercise intensity, individual differences in movement mechanics, and variations in exercise selection, all contribute to variability. Timmons et al. (2022) used an 8-week "Tabata-inspired" protocol ("20 s on, 10 s off") where participants performed six different bodyweight exercises, each for 4 minutes (Timmons et al., 2022). Lean body mass increased by 2% pre- to post intervention, determined via DXA (Timmons et al., 2022). The protocol had no effect on fat mass, blood lipids, or glucose in men classified with overweight/obesity (Timmons et al., 2022). In contrast, Scott et al. (2019) found no changes in lean body mass following 8-weeks of a home-based BW-IT program, while visceral fat was reduced by 27% in adults with obesity (Scott et al., 2019). Future research is needed to determine consistencies in BW-IT protocols that elicit improvements in body composition and cardiometabolic risk factors in this population.

Psychological outcomes

No change in task self-efficacy occurred (−3.6%, p = 0.53, dz = 0.2), while scheduling self-efficacy significantly declined (−12.7%, p = 0.004, dz = 1.0). This data suggests that participants were confident in their ability to perform BW-IT but their confidence in allocating time for BW-IT did not improve. Our results are in line with those by Dunston and Taylor (2023) who report no change in self-efficacy in previously sedentary adults after a 6-week, partially supervised, intervention of either moderate intensity continuous training (MICT) or HIIT (Dunston and Taylor, 2023). In contrast, Locke et al. (2018) observed an initial increase in self-efficacy following 2-weeks of supervised MICT or HIIT in individuals at high risk for type II diabetes (Locke et al., 2018). However, after transitioning to a 24-week unsupervised phase, self-efficacy in these participants declined, suggesting that the improvements in self-efficacy may not be maintained in free-living conditions (Locke et al., 2018). These results indicate the potential role of structured support and supervision in improving and/or sustaining self-efficacy, which may, in part, explain the lack of change observed in the present study.

In addition to the self-efficacy findings, we observed that exercise enjoyment was greater after week one (30s work x 90s recovery) compared to week 6 (60s work x 60s recovery). We speculate that the progression of the protocol may have impacted enjoyment, as it is common for adults with overweight or obesity to stop exercise when the program ramps up to higher volumes or intensities (Collins et al., 2022). Similar findings have been reported by Foster et al. (2015) who observed a progressive decline in exercise enjoyment across three 8-week exercise interventions (MICT, moderate-intensity interval training, or HIIT) in previously sedentary adults (Foster et al., 2015). Further, Foster et al. (2015) note that the lowest enjoyment was found in the most intense training protocol. It is important to note that our exercise intensity data on perceived exertion, heart rate, and muscle soreness do not suggest that the program became significantly more difficult from the first to the final sessions. Nonetheless, future BW-IT protocols using smaller incremental increases, and a greater variety of calisthenics may elicit more positive psychological outcomes. We recommend that future BW-IT training interventions incorporate small incremental increases in the duration of work intervals (e.g., 5 seconds) and a wider variety of bodyweight exercises to prevent monotony and boredom. Additionally, we suggest integrating forms of social support for interventions being performed remotely, such as positive reinforcement and virtual group sessions.

Practical applications

Recent data show that only 28% of adults in the United States meet aerobic and muscle strengthening physical activity guidelines (≥150 min of moderate-intensity aerobic activity, ≥75 min of vigorous-intensity activity, or an equivalent combination of the two, along with ≥2 days/week of muscle-strengthening activity) (Abildso et al., 2023). We found that a relatively small volume of BW-IT (20 min/session, 60 min/week), led to improvements in both cardiorespiratory fitness and muscular strength. Notably, this improvement occurred despite participants completing the program independently. Thus, BW-IT may serve as a viable option for participating in aerobic and muscle strengthening physical activity. Our results are especially applicable to populations who report fears of embarrassment and enacted stigma as barriers to physical activity participation (Hamer et al., 2021). This protocol was instructed completely asynchronously and can be performed at locations most convenient and comfortable to the individual.

Limitations

There are several limitations to the present study. The study was not a randomized controlled trial. The outcomes will be used to design a larger-scale study; however, the lack of randomization and a non-exercise control group increases the bias of our results. In addition, while the study was adequately powered to detect improvements in oxygen consumption, the sample size may have been insufficient to detect differences in other outcomes, such as blood biomarkers. Furthermore, although participants were classified with obesity, there was variability in the degree of obesity and the presence of cardiometabolic risk factors among individuals. We asked participants to exercise three non-consecutive days a week and aim to complete the program within 42 days (6 weeks). However, some individuals needed to postpone exercise days due to illness and schedule conflicts. Although these factors are representative of a real-world setting, they may have made an impact on the anticipated physiological and cardiometabolic responses. Participants were requested to maintain their normal diet throughout the study; however, we did not control nutritional habits. Additionally, we did not track participants' physical activity habits throughout the study. Although we attempted to do so, compliance with regularly charging and wearing the provided FitBit devices was inconsistent, except for during exercise. Lastly, it is difficult to standardize the intensity of bodyweight exercise since biomechanics and coordination vary individually. Other BW-IT interventions may have different outcomes.

Conclusion

Eighteen sessions of unsupervised bodyweight interval training (BW-IT) delivered via YouTube produced small to moderate effects on muscular strength, cardiorespiratory fitness, and waist circumference. Confidence allocating time to schedule BW-IT was lower after the program, while physical activity enjoyment was higher at the start. The results of this study may facilitate the use of BW-IT in previously inactive adults with obesity and highlight important variables for designing future protocols. Future BW-IT interventions that can sustain or improve factors related to exercise adherence and enhance physiological health in this population are highly warranted.

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 University of New Mexico Institutional Review Board. 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.

Author contributions

GB: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. AB: Data curation, Writing–original draft, Writing–review and editing. KB: Writing–original draft, Writing–review and editing. CM: Writing–original draft, Writing–review and editing, Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization. AC: Writing–original draft, Writing–review and editing. QB: Data curation, Writing–original draft, Writing–review and editing. JoS: Data curation, Writing–original draft, Writing–review and editing. JeS: Data curation, Writing–original draft, Writing–review and editing. JD: Methodology, Writing–original draft, Writing–review and editing. MS: Writing–original draft, Writing–review and editing. JL: Writing–original draft, Writing–review and editing, Conceptualization, Methodology. LK: Writing–original draft, Writing–review and editing, Conceptualization, Visualization. FC: Writing–original draft, Writing–review and editing, Conceptualization, Visualization. AG: Writing–original draft, Writing–review and editing, Conceptualization, Visualization. FA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, 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.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. Grammarly, Inc. was used for grammar and sentence structure.

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Supplementary material

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The effect of whole-body electromyostimulation on visceral adipose tissue volume in overweight-to-obese adults with knee osteoarthritis: A randomized controlled study

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Introduction: Physical exercise favorably affects visceral adipose tissue (VAT), which is a risk factor for cardiometabolic diseases. However, many people are unable or unwilling to conduct frequent and intensive exercise programs that have favorable effects on VAT. The present study aimed to determine the effect of time-efficient and joint-friendly whole-body electromyostimulation (WB-EMS) technology on VAT volume in overweight-to-obese adults with osteoarthritis of the knee.

Methods: In total, 46 women and 26 men (58.4 ± 7.0 years; BMI: 30.2 ± 4.2 kg/m^2) with femuro-tibial knee osteoarthritis were randomly allocated to WB-EMS (n = 36) with 1.5 × 20 min/week for 29 weeks or a usual care control group (CG: n = 36) with six sessions of physiotherapy. Magnetic resonance imaging (MRI) using a non-contrast enhanced two-point Dixon gradient echo volumetric interpolated breath-hold examination determined the VAT from mid L2 to mid L3.

Results: In summary, VAT volume increased non-significantly in the CG (p = 0.246) and decreased non-significantly in the WB-EMS group (p = 0.143). We failed to determine significant WB-EMS-induced effects, i.e., group differences for absolute changes in the VAT volume (p = 0.090). However, we observed gender differences with significantly higher effects in men than in women (p = 0.032).

Discussion: We conclude that low volume, non-superimposed WB-EMS is not a perfect tool for decreasing VAT, particularly in overweight-to-obese women.

KEYWORDS

electromyostimulation, exercise, intra-abdominal fat, visceral fat, magnetic resonance imaging, obesity, adults

1 Introduction

Visceral adipose tissue (VAT) is a complex and metabolically active tissue that produces different adipokines and hormones (Silveira et al., 2021). Accumulation of VAT is a strong predictor of all-cause, cardiovascular- and cancer-specific mortality (Brown et al., 2016). In addition, many studies have provided evidence that VAT is closely related to an increased risk of insulin resistance (Kim and Kim, 2023; Zhang et al., 2015), atherosclerosis (ohman et al., 2009), dyslipidemia (von Kruchten et al., 2022), hypertension (Hall et al., 2015), hepatic steatosis (Park et al., 2008), coronary heart disease (Chen et al., 2022; Silveira et al., 2021), and different types of cancer (Silveira et al., 2021). There is striking evidence that participating in exercise interventions had favorable effects on accumulated VAT (Chen et al., 2023; Lee and Lee, 2021). In summary, combined aerobic and resistance exercise seems to be particularly effective in reducing abdominal obesity in overweight/obese individuals (Batrakoulis et al., 2022). However, considering the time required for these protocols (≈2–3 × 30–45 min), many people, with or without overweight and obesity, might be unmotivated or unable to join frequent, time-consuming exercise programs. Similar to the popular high-intensity interval training (HIIT) (A'Naja et al., 2024), whole-body electromyostimulation (WB-EMS) has been recognized as a very time-efficient training technology (Kemmler et al., 2020) to address cardiometabolic conditions (Batrakoulis et al., 2021; Guretzki et al., 2024). However, in contrast to HIIT, WB-EMS is much more joint-friendly, which may particularly attract people with joint disorders. Unfortunately, there is limited evidence of the positive effects of WB-EMS on VAT. A recent study provided significant positive evidence for the WB-EMS effects on intraabdominal fat (Park et al., 2021) in obese elderly women; however, the authors applied a rather unusual (Beier et al., 2024), high-volume approach with aerobic dance superimposed by WB-EMS. As this approach differs greatly from the low-volume, non-superimposed concepts primarily applied in research (Beier et al., 2024) and commercial WB-EMS settings (Kemmler et al., 2024), the aim of the present study was to determine the effect of a time-effective, joint-friendly WB-EMS program on VAT in overweight or obese people. Since there is strong evidence that the VAT response to RT exercise is more pronounced in men (Chen et al., 2023), we also considered gender differences in our analyses of VAT changes, and we hypothesized that the low-volume, non-superimposed WB-EMS program significantly decreases VAT compared to the control group.

2 Material and methods

2.1 Study design

The randomized controlled WB-EMS trial (RCT) is part of the "electromyostimulation for the treatment of knee osteoarthritis (OA) (EMSOAT) study." This study applied a balanced parallel group design (WB-EMS versus control group) and evaluated the effects of 7 months of WB-EMS application on outcomes related to knee osteoarthritis in middle-aged and older adults who were overweight and obese. The present study focused on WB-EMS effects on visceral adipose tissue volume. Briefly, the EMSOAT was planned, initiated, and conducted by the Institute of Radiology, University Hospital Nürnberg, Germany. The University Ethics Committee of the FAU approved this trial (No. 352_20 B), which fully complies with the Helsinki Declaration "Ethical Principles for Medical Research Involving Human Subjects"(World_Medical_Association, 2013). After receiving detailed information, all the study participants provided their written informed consent. This project was fully registered under ClinicalTrials.gov (NCT05672264).

2.1.1 Participants

Briefly, between March 2022 and June 2022, local newspapers, social media, and selected physicians disseminated our study calls, which included the core eligibility criteria. A total of 440 women and men responded via email or telephone and were provided with more detailed written study information. Potential participants who confirmed their preliminary eligibility were further checked through detailed standardized phone calls conducted by carefully briefed research assistants. Inclusion criteria were (a) age 40–70 years old; (b) overweight or obese (BMI>25 kg/m^2); (c) fulfilling clinical ACR criteria for knee OA (Altman et al., 1991); and(d) osteoarthritic knee pain on at least 50% of the days during the last 3 months with an average pain intensity of >2.5 on a 0–10 numerical rating scale (Bennell et al., 2020). Exclusion criteria were (a) any WB-EMS application or regular resistance exercise (≥60 min per week) during the last 12 months; (b) glucocorticoid or opioid pain therapy; (c) trauma of the knee joint within the last 12 weeks; (d) intra-articular injections in the knee joint in the last 12 weeks; (e) conditions, diseases, and corresponding therapy with a relevant impact on our study outcomes (e.g., rheumatoid arthritis and fibromyalgia); (f) contraindications for WB-EMS (Kemmler et al., 2019) or MRI application; and (g) ≥4 weeks of absence during the 29-week conditioning and intervention phase. Lastly, the study physician verified the final eligibility. Twelve of the 84 eligible participants refused to participate predominately due to the random allocation to the study groups (WB-EMS or control). Thus, finally 72 participants were eligible and willing to participate in the present study. However, mainly due to time constraints, four participants (all CG) were unable to join the MRI assessments (i.e., baseline and 29-week control); thus, 68 participants (43 women and 25 men) with MRI data were included in the present analysis of the WB-EMS effects on visceral adipose tissue changes (Figure 1; Table 1).

2.1.2 Randomization and blinding

Participants allocated themselves to the WB-EMS or control group by drawing lots. Lots were placed in small opaque capsules ("kinder egg", Ferrero, Italy) and drawn from a bowl. A researcher who was not involved in the present project prepared the lots to ensure allocation concealment. After the randomization procedure, the primary investigator (SK) enrolled participants and instructed them in detail about their study status and corresponding dos and don´ts. Research assistants, testers, and outcome assessors were unaware of the participants' group status (WB-EMS or CG) and were not allowed to ask either.

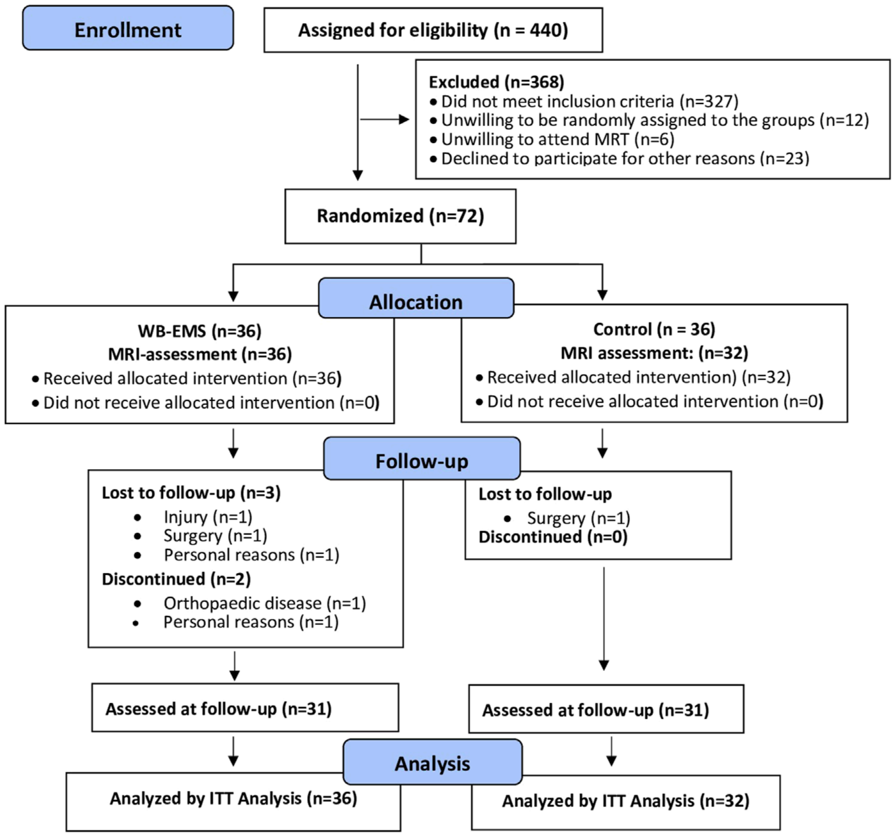

FIGURE 1
Participant flow throughout the study adapted for MRI assessment.

2.2 Study procedures

The WB-EMS training group (WB-EMS) conducted 7 months of WB-EMS application as described below, while the control group (CG) was provided with a "usual care" intervention (physiotherapy – see below). Furthermore, the WB-EMS and CG completed a self-management education program for knee OA. Apart from the intervention described above, participants were instructed to maintain their lifestyle, including physical activity, exercise, and dietary habits during the intervention period. There was a monthly reminder about this requirement during the self-education sessions.

2.2.1 WB-EMS intervention

We conducted a standard WB-EMS session (Beier et al., 2024; Kemmler et al., 2021) 1.5 × 20 min per week (e.g., every Monday and every second Thursday) for 29 weeks, including 4 weeks of familiarization and conditioning with the Miha Bodytec type II device (Gersthofen, Germany). Briefly, the thighs and upper arms, gluteals, abdomen, chest, lower back, latissimus, and upper back were stimulated simultaneously but with dedicated impulse intensity. Using bipolar current, the WB-EMS protocol scheduled an impulse low frequency of 85 Hz, an impulse width of 350 µs, and a direct impulse boost with 6 s of EMS stimulation intermitted by a 4 s impulse break. Based on the close interaction between the licensed trainer and a maximum of two trainees, the impulse intensity as prescribed by the rate of perceived exertion (RPE) was carefully increased to "6-7" (i.e., "hard+ to very hard") on the Borg CR10 Scale (Borg, 2010). During the session, the impulse intensity for all electrodes was carefully adjusted every 3 min to ensure a constant impulse intensity (Kemmler et al., 2023). Video-guided low-intensity exercises (low-amplitude squat with latissimus pulleys, butterfly reverse with angled arms, straight pullovers with trunk flexion, standing trunk flexion, one-legged stand with biceps curl, side step with weight shift, and biceps curl (Weissenfels et al., 2019)) without additional load were conducted during the 6s impulse phase in a standing position. Figure 2 shows an example of a typical exercise/movement conducted during a WB-EMS session.

2.2.2 Control intervention (physiotherapy)

As per the standard care practice in Germany, the control group was provided with six standardized physiotherapy sessions of 20 min each. Physiotherapy treatment was carried out individually in the sense of "standard care" in a diagnosis-oriented manner. The specific content was at the discretion of the treating physiotherapists and included techniques and exercises for reducing pain and detonization of the muscle tissue, increasing mobility of the knee joint, and strengthening leg muscles.

TABLE 1 Baseline characteristics of the study participants.

Variable	CG (n = 32) MV ± SD	WB-EMS (n = 36) MV ± SD	p
Gender (women/men) [n]	21/11	22/14	0.803
Age [years]	59.2 ± 6.0	58.3 ± 7.2	0.602
Body height [cm]	174.3 ± 9.5	173.2 ± 9.9	0.628
Body height, men [cm] Body height, women [cm]	183.5 ± 7.2 169.6 ± 6.6	183.4 ± 6.7 166.7 ± 4.8	0.993 0.107
Body mass [kg]	89.4 ± 15.7	93.2 ± 15.1	0.322
Body mass, men [kg] Body mass, women [kg]	101.3 ± 14.2 83.2 ± 12.8	102.5 ± 13.7 87.2 ± 13.0	0.832 0.315
Lean body mass (LBM) [kg][a]	57.8 ± 12.4	60.2 ± 12.5	0.435
LBM men [kg] LBM women [kg]	71.1 ± 10.5 50.9 ± 6.1	73.9 ± 7.4 51.5 ± 4.5	0.429 0.730
Total body fat [%][a]	35.3 ± 7.4	35.2 ± 9.2	0.946
Total body fat, men [kg] Total body fat, women [kg]	29.6 ± 6.4 38.2 ± 6.2	27.3 ± 5.9 40.1 ± 7.4	0.358 0.373
Waist circumference [cm]	101.3 ± 11.9	102.7 ± 10.9	0.616
WC men [cm] WC women [cm]	108.7 ± 8.2 97.4 ± 11.8	109.5 ± 8.4 98.3 ± 10.0	0.801 0.790
Obesity (BMI ≥30.0 kg/m[b]) [n][b]	17	18	0.814
Physical activity [index][b]	3.6 ± 1.1	3.6 ± 1.3	0.878
No frequent exercise (≥60 min/w) [n][b]	18	18	0.606
Mean arterial pressure [mmHg]	104.8 ± 9.5	103.6 ± 9.4	0.536
Number of diseases [n][b]	1.47 ± 1.11	1.31 ± 0.95	0.515
Number of medications [n][b]	1.25 ± 1.19	1.22 ± 1.27	0.926

[a]As assessed by bioimpedance analysis (BIA).
[b]As assessed by detailed questionnaires.

2.2.3 Self-management

A self-management program for osteoarthritis (Nelson et al., 2014) with six sessions of 60 min each was applied for both groups. Briefly, the program aimed to provide education, information, and counseling to prevent the progression of OA, reduce fear and avoidance attitudes, and improve the quality of life and mobility of the participants.

2.3 Study outcomes

As stated, the EMSOAT study predominately focuses on outcomes related to knee osteoarthritis. The present study addressed abdominal fat changes considered secondary outcomes of the EMSOAT project.

- Visceral adipose tissue (VAT) volume between baseline and 29-week follow-up (FU)

2.3.1 Explanatory outcomes

- Changes in the physical activity and exercise between baseline and 29-week FU
- Changes in the dietary intake between baseline and 29-week FU
- Changes in the medication use between baseline and 29-week FU.

2.4 Assessments

2.4.1 MRI data acquisition and examination

MRI scans were acquired at baseline and after 29 weeks of intervention. All scans were consistently acquired using a 3 T scanner (PRISMA, Siemens Healthineers, Erlangen, Germany). We applied a non-contrast-enhanced two-point Dixon Gradient Echo

FIGURE 2
Example of a typical exercise/movement performed during the WB-EMS session.

Volumetric Interpolated Breath-hold Examination (VIBE) sequence (TE: 1.29 ms; TR: 3.97 ms; matrix size: 320 × 260; voxel size: 1.2 × 1.2 × 3.5 mm^3; and slice gap: 0.7 mm). Twelve slices covered a total length of approximately 5 cm from mid-L2 to mid-L3. Image analysis was performed using the medical image analysis framework (MIAF, Friedrich-Alexander University Erlangen-Nürnberg), as described in detail in a previous publication (Chaudry et al., 2020). The first and last slices were excluded because of intensity inhomogeneity. In the remaining ten slices, the outer contour of the body was determined automatically. The contour of the abdominal cavity was manually segmented by a supervised and trained research assistant. This was performed slice by slice using the Fiji open-source software (Schindelin et al., 2012). Between the measurements of each participant, the position of the scanned volumes was evaluated, and non-overlapping slices were cut off if necessary. In order to separate the VAT inside the abdominal cavity from the inner organs such as the kidneys, intestines, and blood vessels, we used a threshold calculated using the Otsu method (Otsu, 1979) (Figure 3).

2.4.2 Baseline characteristics and confounding factors

Body height was assessed using a Holtain stadiometer (Crymych Dyfed, United Kingdom). Direct-segmental multi-frequency bioimpedance analysis (DSM-BIA, InBody 770, Seoul, Korea) was used to determine the body mass and body composition. Overweight (25.0–29.9 kg/m^2) and (≥30.0 kg/m^2) obesity were classified according to the body mass index (BMI).

At baseline, a detailed standardized questionnaire collected information on (a) demographic parameters; (b) physical limitations, diseases, operations, pharmacologic therapy, dietary supplements; and (c) lifestyle, including physical activity, exercise, and diet. After 29 weeks of intervention, all participants completed the FU questionnaire that aimed to determine changes in

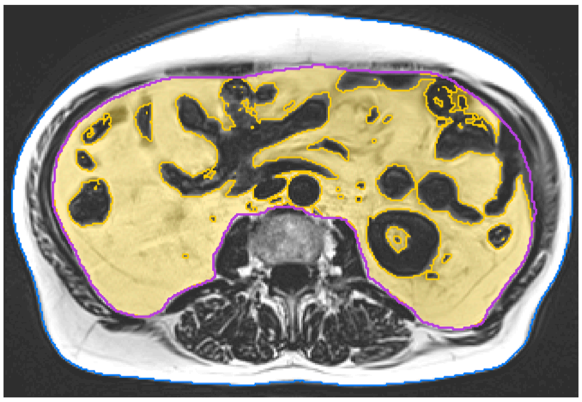

FIGURE 3
Final segmentation result of VAT (yellow overlay) without inner organs and intestines, inner abdominal volume (magenta contour), and outer contour of the body (blue)".

conditions/diseases, pharmacologic and physical therapy, physical activity, exercise, and diet, i.e., factors with a potential impact on the present outcomes. The questionnaires were carefully checked for consistency, completeness, and accuracy by the primary investigator (SK), together with the participants.

2.5 Sample size calculation

The sample size calculation was based on a parameter not addressed in the present study. Briefly, 36 participants per group were needed to determine the effects on the primary outcome, "pain of the knee joint," as determined by the KOOS (Knee Injury and Osteoarthritis Outcome Score; (Roos and Lohmander, 2003)) questionnaire, applying a statistical power of 80%, an α-level of 5%, and a two-tailed t-test approach.

2.6 Statistical analysis

As recommended for RCTs, we applied the intention-to-treat (ITT) principle that included all participants randomly assigned to the study arms (WB-EMS vs CG), regardless of their loss to follow-up. However, as reported, due to the lack of baseline MRI and FU data, four participants in the CG could not be included in the analysis. We used R statistics software (R Development Core Team Vienna, Austria) in combination with Amelia II (Honaker et al., 2011) for multiple imputation (ITT). The full data set was used for multiple imputations, with the imputation repeated 100 times. Normal distribution was checked graphically (gg-plots and residual plots). Within-group changes were analyzed using the t-test. ANCOVA adjusted for baseline differences in VAT volume was applied to determine between-group differences (i.e., "effects") after 29 weeks. A second ANCOVA was adjusted for baseline VAT volume and gender to determine possible gender differences. Differences in the distribution of categorical variables were analyzed using Pearson's chi-square tests (Table 1). The standardized mean

TABLE 2 Baseline data and changes in visceral adipose tissue parameters in the CG and WB-EMS groups. SMD: standardized mean difference;$^{n.s.}$: non-significant intra-group changes.

	CG (n = 32) MV ± SD	WB-EMS (n = 36) MV ± SD	Difference MV (95% CI)	SMD (d`)	p-value
Visceral adipose tissue (VAT) volume [cm^3]					
Baseline	569 ± 396	662 ± 382	------------	------	0.425
Changes	13 ± 66$^{n.s}$	−16 ± 69$^{n.s}$	28 (−5 to 61)	0.43	0.090

difference (SMD) was calculated using Cohen (Cohen's d). All tests were 2-tailed, and significance was set at $p < 0.05$.

3 Results

Table 1 displays the baseline results of 43 women and 15 men (58.7 ± 6.9 years; BMI: 30.2 ± 4.1 kg/m^2) with MRI data. In summary, no significant differences were observed between the WB-EMS and the CG at baseline.

Drop-out and loss to follow-up are displayed in Figure 1. Briefly, four participants (WB-EMS: n = 3 vs CG: n = 1) were unable to attend the 29-week FU assessment. A further two participants of the WB-EMS group quit the study due to reasons not related to the intervention. The attendance rate averaged 88% ± 10% in the WB-EMS group. Predominately due to diseases, four participants (WB-EMS) exercised, on average, less than once a week. Attendance in the physiotherapy sessions (CG) was >90%. Adherence to the WB-EMS or physiotherapy (CG) protocol did not differ significantly between the genders. Furthermore, no adverse effects or injuries were observed during the WB-EMS sessions, and (apart from occasional delayed onset muscular soreness) no participants reported any WB-EMS-related relevant discomfort during or after WB-EMS application.

3.1 Study outcome

Table 2 shows the results for VAT at baseline and the changes after 29 weeks of intervention adjusted for baseline VAT (ANCOVA). In summary, no significant WB-EMS-induced effects (p = 0.090; d' = 0.43), i.e., group differences for absolute changes between WB-EMS and CG, on the visceral adipose tissue volume were observed. In detail, VAT volume increased non-significantly in the CG (p = 0.246) and decreased non-significantly in the WB-EMS groups (p = 0.143).

Applying ANCOVA that adjusted for baseline VAT and gender revealed significant gender differences with significantly higher WB-EMS-induced effects in men than in women (p = 0.032, d' = 0.67). A separate analysis of the WB-EMS effects on VAT in women and men is provided in Table 3.

In summary, although borderline non-significant (p = 0.052), we observed pronounced intra-group (WB-EMS vs CG) differences in men, while the effect of WB-EMS on VAT changes was negligible in women (p = 0.911).

3.2 Confounding factors

After the intervention period, no significant changes within the groups or between-group differences in physical activity (p = 0.124), exercise participation ≥60 min/w (p = 0.607), or exercise volume (p = 0.976) were reported by the participants. Five participants in the CG (three women and two men) and four participants in the WB-EMS (two women and two men) group (p = 0.794) reported changes in dietary habits, consistent with a reduction in carbohydrates/sugar and/or lower energy intake during the study period. Finally, no relevant changes in medication (e.g., glucocorticoids), conditions (e.g., eating disorders), or diseases (e.g., thyroid function) with potential impacts on abdominal adipose tissue parameters were reported.

4 Discussion

In this trial, which compared WB-EMS to a control group of standard care (physiotherapy), we could not find significant effects on VAT after 7 months of 1.5 × 20 min/week WB-EMS in overweight-to-obese adults. Reviewing the mechanisms of WB-EMS effects on body fat changes induced by increments of energy expenditure, largely comparable to conventional RT exercise, at least three effects can be identified. (a) First, acute energy expenditure during WB-EMS (Kemmler et al., 2012) is limited by the low training volume. (b) The post-exercise effect induced by energy restoration, repair, and adaptive processes post-exercise (EPOC) is particularly pronounced after WB-EMS application (Teschler et al., 2018). (c) Changes in the resting metabolic rate due to hypertrophic effects after WB-EMS (Kemmler et al., 2021).

A review of the literature shows that vigorous aerobic exercise/HIIT is particularly effective in reducing VAT in overweight-to-obese individuals (Chang et al., 2021; Chen et al., 2023; Poon et al., 2024). Aerobic exercise with low or moderate intensity, RT, or a combination of aerobic exercise and RT, on the other hand, is considered less favorable (Chang et al., 2021; Chen et al., 2023). Although there are a few exceptions (Chang et al., 2021), most meta-analyses (Chen et al., 2023; Khalafi et al., 2021; Lopez et al., 2022) reported significant (low to moderate) effect sizes for RT studies; single RCTs in the area of isolated RT and VAT rarely revealed significant effects. Thus, our results of positive, albeit non-significant findings of WB-EMS effects on VAT do not come as a surprise.

TABLE 3 Baseline data and changes in visceral adipose tissue parameters in the CG and WB-EMS groups categorized by gender. SMD: standardized mean difference; [n.s.]: non-significant intra-group changes

Visceral adipose tissue (VAT) volume [cm^3]					
Women	CG (n = 21) MV ± SD	WB-EMS (n = 22) MV ± SD	Difference MV (95% CI)	SMD (d`)	p-value
Baseline	493 ± 349	567 ± 300	------------	------	0.460
Changes	5 ± 45[n.s]	2 ± 47[n.s]	3 (−26 to 28)	0.07	0.911
Men	CG (n = 11)	WB-EMS (n = 14)			
Baseline	712 ± 396	813 ± 452	------------	------	0.581
Changes	29 ± 88[n.s]	−47 ± 92[n.s]	76 (−1 to 152)	0.83	0.052

Nevertheless, a gender-specific sub-analysis of our data revealed differences with significantly more favorable, albeit still non-significant, VAT effects (WB-EMS vs CG) for the male subgroup (Tab. 3). This finding was supported by a recent network meta-analysis (Chen et al., 2023), which observed a much more pronounced VAT response to RT in men than in women. The same network meta-analysis (Chen et al., 2023) reported that in contrast to people with low body fat, RT was ineffective in reducing VAT in people with body fat rates ≥40%[1]. However, while only one man in the CG suffered from severe obesity, ten of the 22 women in the WB-EMS group had body fat rates ≥40%. In contrast to our finding of negligible WB-EMS effects on VAT in women, the pilot study by Park et al. (2021) reported significant positive effects on intra-abdominal fat after 8 weeks of 3 × 40 min/week of WB-EMS superimposed on aerobic dance in 30 older women with a similar body fat rate (39% ± 3%) compared to our female subgroup. Thus, there is some evidence that women need a higher training volume or/and superimposed WB-EMS to significantly affect the VAT. In contrast, a lower training volume seems to be sufficient for men for generating relevant VAT effects. This latter speculation was confirmed by a recent low-volume (2 × 40 min/week) RT trial with 43 older, predominantly overweight-to-obese men that determined similarly pronounced and (presumably due to the higher statistical power) significant net effects on VAT compared to the present male cohort (Knauer et al., 2023). In summary, adding significantly higher training frequency and strenuous voluntary exercises would not be a reasonable option, considering that the unique selling point of present WB-EMS concepts is their time-effective and joint-friendly characteristics.

Apart from cohort and exercise characteristics, one may argue that changes in dietary intake may have confounded the VAT results. Although participants were frequently instructed to maintain their dietary habits, nine of the 68 participants listed changes during the 29-week study period. As a similar number of people in the WB-EMS and CG groups reported changes in dietary habits, we feel that this aspect does not relevantly impact our findings. Undoubtedly, however, a more detailed monitoring of dietary records would have provided deeper insight into this issue.

Other limitations and peculiarities of the present trial of VAT should be addressed. (a) First, the primary outcome of this project, which included overweight and obese knee OA patients, was "pain of the knee joint", while VAT was considered a secondary study outcome. One may argue that the alignment of the intervention was thus not customized to (optimally) address the VAT. However, the most effective WB-EMS protocol to achieve this outcome remains clear. Considering further that time efficiency is a key characteristic of WB-EMS, we applied the 20-min WB-EMS standard protocol (Beier et al., 2024; Le et al., 2024), which is known to trigger significant positive effects on a large variety of different outcomes (Kemmler et al., 2024). Another limitation of this satellite study of a larger project was the sample size analysis that did not address VAT. (b) Similarly, we did not focus on one gender but included women and men. Although the sample size of at least 32 participants/group included in the primary ITT analysis exceeds the statistical power of most RT studies with significant positive effects on VAT (Chen et al., 2023; Khalafi et al., 2021), in particular the low statistical power among the male subgroup (WB-EMS: n = 14 vs CG: n = 11) might have contributed to the borderline non-significant WB-EMS effect on VAT in men. (c) The study included adults with moderate-to-advanced knee osteoarthritis who were overweight and obese. Overweight/obesity is a strong predictor of knee OA (King et al., 2013), not only due to the higher mechanical load but also to the pro-inflammatory effects, particularly triggered by the VAT fraction (Kawai et al., 2021). Although the low-frequency, non-superimposed WB-EMS concepts might not be the most promising exercise for VAT reduction, the rationale for WB-EMS application in this cohort with OA was the opportunity for a joint-friendly protocol with low-amplitude, low-intensity movements/exercises. (d) Finally, another methodological weakness could be the lack of participant blinding. Optionally, the CG could have received the same intervention but with a pulse intensity below the motor threshold. We decided against this alternative since (a) even low stimulus intensity (e.g., low-intensity TENS) might trigger favorable effects on (knee) pain intensity (as the primary study outcome),

1 However, the author had not adjusted on gender differences. Overweight and obesity thresholds vary considerably between the genders (with lower values for men) when applying body fat rate (Tomlinson et al., 2019). Thus, gender differences might have confounded the effect of body fat rate (and *vice versa*) on VAT changes

and (b) we considered it more appropriate to provide a real-world comparison with an established therapy approach for knee OA.

In summary, we failed to determine significant positive effects of low-volume, non-superimposed WB-EMS on VAT, whether in women or (borderline) in men. Nevertheless, we are still convinced that individuals with OA will benefit from WB-EMS by improving their musculoskeletal outcomes. Although some participant characteristics might have contributed to our results, we conclude that, largely due to the low application volume, the present WB-EMS protocols applied most in scientific and commercial settings might not be the perfect tool for decreasing VAT, particularly in overweight-to-obese women.

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 University Ethics Committee of the Friedrich-Alexander University of Erlangen-Nürnberg (FAU), Erlangen, Germany (No. 352_20 B). 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.

Author contributions

BB: conceptualization, data curation, software, visualization, writing – original draft, and writing – review and editing. OC: data curation, investigation, software, visualization, writing – original draft, and writing – review and editing. SK: data curation, investigation, project administration, resources, supervision, writing – original draft, and writing – review and editing. SV: conceptualization, funding acquisition, investigation, methodology, project administration, writing – original draft, and writing – review and editing. MK: conceptualization, formal analysis, methodology, visualization, writing – original draft, and writing – review and editing. FR: conceptualization, investigation, methodology, project administration, resources, writing – original draft, and writing – review and editing. KE: conceptualization, methodology, software, validation, visualization, writing – original draft, and writing – review and editing. MU: conceptualization, funding acquisition, methodology, resources, writing – original draft, and writing – review and editing. WK: conceptualization, data curation, funding acquisition, investigation, methodology, project administration, resources, validation, writing – original draft, and 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.

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

The reviewer HK declared a past co-authorship with the authors WK and MK to the handling editor.

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Acute changes in urinary metabolites: vinyasa yoga compared to cycle ergometer exercise

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Introduction: Increased interest in unconventional exercise such as vinyasa yoga has outpaced our understanding of the physiological response to yoga exercise. The objective of the current study was to evaluate changes in urinary metabolites (i.e., alanine, phenylalanine, glycine, choline, taurine, creatinine, creatine, dimethylamine, citrate, pyruvate, acetate, and beta-hydroxybutyrate) elicited by vinyasa yoga compared to moderate intensity aerobic exercise in young healthy adults.
Methods: Twelve participants, six women and six men, completed a vinyasa yoga exercise session (VY) and a moderate intensity cycle ergometer exercise session (ME) in a sequential fashion. The intensity of the ME was matched to heart rate and rating of perceived exertion elicited during the initial VY. Urine samples were collected at baseline and following the completion of each of VY and ME. Metabolite concentrations after each exercise were normalized to their baseline levels to obtain a relative exercise-induced change in concentration. We hypothesized that activation of large muscle groups in the lower extremities would foster greater ME-induced alterations in metabolites.
Results: Exercise-induced changes in urinary concentrations of phenylalanine, creatinine, creatine, glycine, choline, taurine, dimethylamine, citrate, pyruvate, alanine, and beta-hydroxybutyrate were greater in ME compared to VY ($P < 0.05$). There was no difference between the exercise-induced changes in lactate between groups ($P < 0.05$).
Discussion: The results of this study demonstrate that ME promotes more robust changes in urinary metabolites compared to VY. These differences may be due to a greater localized workload on the large muscle groups of the lower extremities during ME, and potentially highlight the distributed metabolic demand of VY.

KEYWORDS
urine, metabolism, exercise modality, nuclear magnetic resonance, unconventional exercise

1 Introduction

Vinyasa yoga exercise (VY) has become increasingly popular in westernized societies (1). Individuals who participate in yoga exercise gain improvements in flexibility, strength, endurance, and overall health (2). Whereas conventional aerobic exercise is typically performed using rhythmic sequences of light to moderate physical activity, VY is a relatively vigorous subtype of yoga that meets the criteria for moderate intensity aerobic activity using a distributed combination of strength and stamina postures (3). VY training programs utilize a combination of powerful movements, and muscular endurance that decreases chronic stress, improves heart rate variability and enhances quality of life (3). Intensity criteria for VY include 40%–59% of heart rate reserve, 64%–76% of heart $rate_{max}$, 46%–63% of VO_{2max}, and a rating of perceived exertion (RPE) of 12–13 or light to somewhat hard (4). Yoga exercise that meets these criteria promotes beneficial changes in oxygenated blood flow, autonomic balance, blood pressure, respiratory function, and orthostatic tolerance (5). Reports have also suggested that yoga may be one of the most effective means of metabolic disease prevention (6), but the protective mechanisms responsible are not well understood.

An overwhelming amount of research in the field of exercise physiology has well characterized the physiological adaptations for a wide range of exercise modalities (7). When the human genome was sequenced almost 25 years ago, the development of high-throughput omics techniques such as epigenomics, transcriptomics, proteomics, metabolomics and lipidomics provided scientists with new opportunities to evaluate metabolites that may have otherwise gone unnoticed or underappreciated (8, 9). Coupled with robust research designs and precision instrumentation, metabolomics technology can improve our understanding of physiological regulation and contribute to the development of new hypothesis driven investigations (8).

We know that lactate, pyruvate, and citrate are inextricably linked to exercise-induced changes in glycolysis and/or the tricarboxylic acid (TCA) cycle (10). Elevations in urinary alanine are linked by interrelated pathways and may reflect conversion from pyruvate to alanine via transamination (11). Exercise-induced alterations in urinary amino acids may also be elevated due to protein degradation (8). Alterations in creatine and creatinine seem variable, whereas dimethylamine implicated in the regulation of blood flow is modestly affected (12). Changes in beta-hydroxybutyrate reflect the augmentation of fatty acid metabolism (13). Moderate intensity exercise performed on a stationary cycle ergometer is a commonly used exercise modality in the scientific literature. Whereas vinyasa yoga exercise activates multiple muscle groups in a distributed fashion, moderate intensity exercise on a cycle ergometer relies more exclusively on skeletal muscle located in the lower extremities.

To our knowledge, there are no peer-reviewed studies in the literature that compare acute changes in metabolites during conventional exercise to VY, despite a growing interest in yoga in general. Therefore, there is a clear gap in knowledge in this regard. Based on studies that demonstrated greater acute changes in urinary metabolites during vigorous cycle exercise compared moderate cycle exercise (ME) (14), we hypothesized that the sustained engagement of large localized muscle groups would yield greater ME-induced alterations in metabolites that reflect greater local muscle metabolism in ME. The purpose of this study is to compare exercise-induced changes in urinary metabolites reflective of variations in metabolism, kidney function and/or blood flow during VY and ME.

2 Materials and methods

2.1 Study design and participants

The protocol, informed consent, medical history questionnaire, and a research personnel list were drafted and submitted to the University of Alaska Fairbanks (UAF) Institutional Review Board for review. Once approved, twelve research participants, including six males and six females were enrolled from the UAF campus and provided informed consent (Table 1). All participants completed a study questionnaire that included questions about their sex, age, dietary restrictions, exercise history (both present and past), tobacco and alcohol usage, medication usage, caffeine usage, and a comprehensive medical history questionnaire. Exclusion criteria included an existing history of substance abuse, cardiovascular, metabolic and/or cancer diseases, seizures, and any other conditions that might be exacerbated by fasting and/or exercise. All females were below the age of menopause, and no efforts were made to control the menstrual cycle.

Research participants were scheduled to attend two exercise sessions, the first session of which was 1 h of VY. The first session

TABLE 1 Clinical characteristics

Clinical characteristics	Yoga	Cycle	Yoga	Cycle	Yoga	Cycle
	Combined	Combined	Males	Males	Females	Females
Gender (M/F)	6/6	6/6	6	6	6	6
Age (years)	23.1 ± 7.1	23.2 ± 7.1	27.5 ± 4.5	27.5 ± 4.5	22.5 ± 2.4	22.5 ± 2.4
Body height (meters)	1.6 ± 0.4	1.6 ± 0.4	1.8 ± 0.1*	1.8 ± 0.1*	1.6 ± 0.1	1.6 ± 0.1
Body mass (kg)	63.2 ± 18.2	63.4 ± 18.1	71.9 ± 8.2*	72.0 ± 7.8*	62.5 ± 16.0	62.9 ± 16.0
Body fat mass (kg)	13.6 ± 8.3	13.6 ± 8.0	9.6 ± 2.1	9.9 ± 2.1	17.4 ± 11.1**	17.3 ± 10.7**
Body fat free mass (kg)	49.6 ± 15.8	49.8 ± 15.5	62.3 ± 6.4*	62.1 ± 6.0*	45.1 ± 5.2	45.6 ± 5.6
Total body water (kg)	36.3 ± 11.5	36.5 ± 11.4	45.6 ± 4.7*	45.4 ± 4.4*	33.0 ± 3.8	33.4 ± 4.1
Body mass index (kg/m^2)	21.1 ± 5.6	21.2 ± 5.7	21.5 ± 1.4	21.6 ± 1.4	23.0 ± 4.9**	23.2 ± 4.9**
Body fat (%)	19.1 ± 8.9	19.1 ± 8.6	13.2 ± 1.9	13.6 ± 2.0	25.6 ± 9.1**	25.4 ± 8.5**
Basal metabolic rate (calories)	1,502 ± 429	1,504 ± 429	1,782 ± 153*	1,784 ± 146*	1,452 ± 166	1,456 ± 165

Males were significantly older than females in both trials ($P < 0.05$). Data are presented as Mean ± SD.
*Body height, body mass, body fat free mass, total body water, and basal metabolic rate was higher in males compared to females ($P < 0.05$).
**Body fat mass, body mass index and percent body fat were higher in females compared to males ($P < 0.05$).

of VY established the steady state heart rate (i.e., ~70% of heart $rate_{max}$ and a RPE of 12–13) that would be replicated during the second session, which was 1 h of ME. This sequential approach standardized the relative intensity of the exercise based on heart rate and RPE. VY exercise pairs breath to movement; pairing moving the body into one yoga pose with the inhale, and then onto the next pose with the exhale. The common yoga poses include the following; down dog, updog, forward fold, halfway lift, warrior 1 & 2, extended side angle, child's pose, triangle, crescent lunge, runners lunge, pigeon pose. These poses were repeated 3x on each side of the body during the course of the VY session.

Participants were instructed to fast for 12 h and to drink at least 0.7 L of water 30 min prior to the exercise sessions to standardize their post-absorptive status and hydration levels, respectively. The fasting and water intake protocols were validated consistent with studies evaluating urinary metabolites (15).

Upon arrival for the VY and ME sessions, the height and weight of the participants was measured, and body composition was determined using a Tanita 300 bioelectrical impedance analyzer (Arlington Heights, IL). Participants were issued Soleus Flash heart rate monitors (Cedar Park, TX) and led through the VY session. RYT-200 (registered yoga instructor of a 200-hour certification course) which are accredited through yoga alliance led the VY session. Heart rate was documented at ten equally spaced intervals to ensure homogeneity during the VY session. One week following the VY session, the same participants returned for the ME session. Under direct supervision, participants were then instructed to complete the ME seesion at an intensity that matched their original recorded heart rate from the VY session. Using this approach, we standardized the exercise intensity of the VY session to the ME session. Participants were asked to consume their normal diet with limited variation between the two exercise sessions.

2.2 Sample analysis

Urine samples were collected prior to and immediately following cessation of the exercise sessions, placed in ice, and then frozen at −80°C until analysis. The risk of bacterial contamination was mitigated by using mid-stream urine collections (20). Once all data collection had been completed, urine samples were thawed and agitated in case any separation had occurred and then prepared according to previously published protocol (16). For NMR analysis, 400 µl of urine with 200 µl of pH 7.4 phosphate buffer were transferred into 5-mm NMR tubes (Wilmad Lab Glass, Buena, NJ). ^{1}H–NMR spectra were acquired with a 600-MHz Bruker Avance-III system running TopSpin 3.2 software (Bruker Biospin, Fremont, CA) using a dual resonance high resolution SmartProbe with single axis Z-gradient. The water signal was suppressed using the SPR-w5-watergate sequence (17) with 64 scans, collecting 64k data points, with a 1 ms recycle delay. A standard, trimethylsilyl propionic-2,2,3,3-tetradeuteropropionic acid (TMSP in D_2O) contained in a sealed tube and placed in the NMR tube was used for metabolite quantification of fully relaxed ^{1}H–NMR spectra and as a ^{1}H chemical shift reference (0.0 ppm). The ^{1}H–NMR peaks for single metabolites were identified and referred to published chemical shift or a metabolite chemical shift library. All spectra were process according to previous methods (16). The NMR system is shimmed for every sample to ensure field homogeneity for improved spectral resolution, and pulse parameters are calibrated routinely to maintain proper flip angle in the experiments.

2.3 Data analysis

MetaboAnalyst 2.0 was used to analyze the data. Using the previous work of Pechlivanis et al., where the same research subjects completed two exercise bouts with either 10 or 60 s of rest, our calculation of statistical power using lactate as a variable was 1.00 with an alpha of significance of 0.001 (16). We normalized the metabolites concentrations after each exercise session relative to the pre-exercise levels. Shapiro–Wilk and Kolmogorov–Smirnov normality tests were used to test whether our dataset followed a normal (Gaussian) distribution. Since both tests rejected the null hypothesis (data follows a normal distribution), we used a non-parametric test, i.e., Wilcoxon Signed Ranks test. Mean differences were considered significant at ($P < 0.05$). This test is particularly useful for comparing potential differences between two related samples. The study was underpowered to evaluate sex-specific responses in metabolites in response to VY or ME.

3 Results

We recruited 12 participants for these studies (Table 1). Body height, body mass, body fat-free mass, total body water and basal metabolic rate was greater in males compared to females ($P < 0.05$). Body fat mass, body mass index and percent body fat was higher in females compared to males ($P < 0.05$) (Table 1). The average heart rate was 123 ± 19 beats/min during the VY, which was matched during the ME.

We identified 14 metabolites in our samples. These included phenylalanine, creatinine, creatine, creatinine, creatine, glycine, choline, taurine, dimethylamine, citrate, pyruvate, alanine, lactate, and beta-hydroxybutyrate. Except for lactate, exercise-induced changes in urinary concentrations of phenylalanine, creatinine, creatine, glycine, choline, taurine, dimethylamine, citrate, pyruvate, alanine, and beta-hydroxybutyrate were greater in ME compared to VY ($P < 0.05$) (Table 2).

4 Discussion

The purpose of this study was to examine changes in urinary metabolites in response to VY and ME matched for exercise intensity by heart rate. To our knowledge, this is the first study to describe intensity-matched, exercise-induced changes in urinary phenylalanine, creatinine, creatine, glycine, choline, taurine, dimethylamine, citrate, pyruvate, alanine, and beta-hydroxybutyrate that were greater with ME compared to VY. These changes were greater even though we matched the intensity of the exercise bouts

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TABLE 2 Urinary metabolites measured pre- and post-moderate exercise (ME) and pre- and post-vinyasa yoga (VY).

Metabolites	Phenylalanine (PPM)	Creatinine (PPM)	Creatine (PPM)	Choline (PPM)	Glycine (PPM)	Choline (PPM)	Taurine (PPM)	Dimethylamine (PPM)	Citrate (PPM)	Pyruvate (PPM)	Alanine (PPM)	Lactate (PPM)	BHB (PPM)
Pre-ME	55 ± 57	1,081 ± 1,177	204 ± 213	100 ± 115	57 ± 79	2,045 ± 2,163	93 ± 99	21 ± 24	106 ± 103	29 ± 30	16 ± 16	22 ± 24	25 ± 26
Post-ME	66 ± 79*	1,267 ± 1,509*	183 ± 175*	89 ± 95*	72 ± 86*	2,496 ± 2,906*	128 ± 140*	19 ± 19*	104 ± 94*	41 ± 47*	21 ± 24*	34 ± 41	26 ± 24*
Pre-VY	34 ± 26	652 ± 385	174 ± 125	56 ± 32	43 ± 37	1,292 ± 737	92 ± 66	13 ± 11	77 ± 53	20 ± 15	10 ± 6	14 ± 7	18 ± 10
Post-VY	33 ± 44	624 ± 884	132 ± 146	41 ± 44	44 ± 62	1,257 ± 1,730	113 ± 189	10 ± 14	68 ± 69	17 ± 21	11 ± 12	19 ± 21	17 ± 27

*Denotes significant exercise-induced difference between ME and VY.

based on heart rate. Fold changes in metabolites are directly linked to the work intensity and size of contracting skeletal muscles. The relative work rates of contracting large skeletal muscle groups in the lower extremities may be higher with ME than the work rates of more evenly distributed work rates of skeletal muscles during VY. As a result, these modality dependent work rates may have influenced more robust changes in metabolites associated with carbohydrate, fat, and protein metabolism in ME. The possiblity of sex-specifc responses to ME and VY were beyond the scope of this study, but could be affected by menstrual status or hormone fluctuations.

VY requires a greater overall distribution of mechanical movement compared to ME, utilizing more complex muscle activation, but potentially reducing the absolute metabolic demand on individual skeletal muscles. Pechlivanis et al., detailed the influence of rest intervals (10 vs. 60 s of rest) during sprint training on post-exercise urinary metabolites (16). These studies demonstrated that shorter rest intervals between sprinting bouts led to higher post-exercise urinary metabolites such as phenylalanine, glycine, alanine, dimethylamine, and beta-hydroxybutyrate. These authors posited that the shorter rest intervals reduced the time available for energy substrates to be replenished, therefore causing a greater metabolic disturbance (18). While both VY and ME were performed at a submaximal, steady state intensity, the interactive influence of localized bioenergetic demands and complex systemic pathways may have influenced the appearance of metabolites in the urine (19). In other words, ME demanded constant supply of energy substrate to a more localized muscle group as opposed to variable localized energy demands with VY, potentially elevating urinary metabolites derived from ME.

Given these results, one might question the use of urine as a biofluid for the evaluation of exercise-induced changes in metabolites between these two exercise modalities. Urine as a biological sample is a non-invasive strategy for clinical studies. However, the concentration of urine can be affected by hydration, diet and/or medications. Urinary lactate may not be as sensitive as blood lactate to acute changes in energy metabolism (20). By comparision, blood sampling provides more precise data but requires sterile instruments, the medical supplies to sterilize the blood draw site, a clinical environment in which to draw blood, and a medical professional that is credentialed to perform blood collection procedures. In addition, blood sampling presents a barrier to involvement for some research participants and there is a small risk of infection or inflammation at the site of blood sampling. While blood may show a more precise snapshot of metabolite levels, using it as a biofluid is more complicated.

An ancillary goal of this study was to combine least invasive approaches with H^1–NMR based analytical approaches that could utilize urine as a bio-fluid. Metabolomics represents a mainstream analytical approach to obtain a greater understanding of metabolic processes. The use of a H^1–NMR based metabolomics approach is a reasonable strategy to measure metabolites in human bio fluids that may be linked to metabolism, kidney function and/or blood flow (19), and can be applied to a wide range of health and exercise related studies in a culturally appropriate manner. Notably, all females were pre-menopausal and our study was not powered to examine sex-specific differences in urinary metabolites during VY and ME. This represents a signficiant limitation when interpreting these data. Future studies examining acute changes in plasma metabolities using H^1-NMR may further detail changes in localized metabolism in the skeletal muscle across a continum of exercise modalities and intensities.

5 Conclusion

Significant differences in the exercise-induced changes in phenylalanine, creatinine, creatine, glycine, choline, taurine, dimethylamine, citrate, pyruvate, alanine, and beta-hydroxybutyrate between VY and ME in all metabolites but lactate were noted. These results suggest that localized metabolic rates may influence urinary metabolites and highlights the distributed metabolic demand on skeletal muscle bioenergetics during VY.

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.

Ethics statement

The studies involving humans were approved by University of Alaska Fairbanks Institutional Review Board. 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.

Author contributions

CC: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Data curation. CM: Writing – original draft, Writing – review & editing, Formal analysis. ZB: Formal analysis, Writing – original draft, Writing – review & editing, Methodology. RC: Methodology, Writing – original draft, Writing – review & editing, Conceptualization, Funding acquisition, Project administration, Resources, Supervision.

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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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Effects of asymmetric load bench press offset training on muscle activation levels and exercise-induced fatigue in collegiate bodybuilders

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Objective: This study systematically investigated the effects of graded asymmetric load bench press offset training on muscle activation patterns, exercise-induced fatigue, and movement performance in bodybuilders.

Methods: Ten male athletes (age: 24.20 ± 1.91 years; 1 R M bench press: 120.00 ± 14.66 kg) underwent randomized crossover trials with 0% (symmetrical), 2%, 4%, and 6% asymmetric load interventions (70% 1 R M total load). Surface electromyography (sEMG) quantified activation levels of pectoralis major (PM), anterior deltoid (AD), triceps brachii (TB), and external oblique (EO), while barbell kinematics, blood lactate, and heart rate were analyzed to assess fatigue.

Result: Key findings revealed significant interlimb asymmetry under symmetrical loading, with dominant-side PM (51 ± 6.82 vs 35 ± 5.32 MVIC%, $p = 0.009$) and AD (48.2 ± 5.05 vs 32.6 ± 9.21 MVIC%, $p = 0.038$) exhibiting higher activation than the non-dominant side. Asymmetric loading effectively mitigated this imbalance: 6% intervention increased non-dominant PM (54.4% ± 8.46% vs 0%: 35 ± 5.32 MVIC%, $p = 0.035$) and AD activation (52.3% ± 12.7% vs 0%: 32.6 ± 9.21 MVIC%, $p = 0.022$), but triggered compensatory EO recruitment (31.1% ± 12.3% vs 0%: 12.8 ± 3.34 MVIC%, $p < 0.001$). Performance metrics declined progressively with higher asymmetry: 6% loading reduced barbell velocity (MV: 0.28% ± 0.03% vs 0%: 0.38 ± 0.04 m/s, $p < 0.001$), repetitions (6.63% ± 2.40% vs 0%: 13.90 ± 2.52, $p < 0.001$), and power (MP: 357% ± 43% vs 0%: 437 ± 53.70 W, $p = 0.009$). Physiological fatigue markers intensified at 6% asymmetry, evidenced by elevated post-exercise blood lactate (7.42% ± 1.59% vs 0%: 9.88 ± 0.75 mmol/L, $p = 0.003$) and prolonged heart rate recovery.

Conclusion: The study identifies 2%–4% asymmetric loading as optimal for enhancing non-dominant muscle activation while minimizing fatigue, whereas 6% interventions induce core compensation and performance deterioration. These findings establish evidence-based thresholds for precision training protocols, addressing interlimb asymmetry while balancing neuromuscular efficacy and physiological strain. Methodological innovations include multidimensional analysis of biomechanical, electromyographic, and physiological responses, advancing the understanding of neuromuscular coordination in asymmetric resistance training.

KEYWORDS

interlimb asymmetry, electromyography, resistance training, neuromuscular adaptation, fatigue threshold, core compensation

1 Introduction

The bench press (BP), a comprehensive exercise involving multiple joints and muscle groups, is the preferred training method for athletes, bodybuilders, and weightlifters aiming to enhance upper limb strength and explosiveness (Elliott et al., 1989). Research has demonstrated inherent interlimb asymmetries and biases in the human body, leading to a typically unstable performance of the bench press (Anderson and Behm, 2004; Maloney, 2019). Consequently, strategies to synergize core muscles, responsible for trunk stability, with upper limb muscles, which provide bench press strength, have become a focal point of recent investigations (Shinkle et al., 2012). Scholars have proposed various intervention techniques tailored to the "instability" characteristic of bench press movements. These include alterations in the supporting surface (Saeterbakken and Fimland, 2013), selection of different bench press bars (Costello, 2022), incorporation of swinging loads (either front or side swinging) (Saeterbakken et al., 2020a), and variations in supine trunk position, such as feet-on-ground or active hip and knee flexion (Muyor et al., 2019). The primary objective of these methods is to examine muscle activation patterns during the exercise, aiming to bolster the coordination between the upper limb and core muscle groups, thereby mitigating sports injuries and enhancing bench press proficiency (Costello, 2022; Saeterbakken et al., 2020b; Jarosz et al., 2020; Golas et al., 2018; Lawrence et al., 2021; Ostrowski et al., 2017). Notably, many extant studies predominantly focus on the dominant limb side, overlooking muscle activation changes on the non-dominant side. Golas et al. (2018) observed distinct muscle activation disparities between the dominant and non-dominant upper limbs post-bench press in elite athletes, with the dominant side exhibiting significantly higher activation. Thus, relying solely on data from the dominant side to assess neuromuscular patterns and muscle activation during the bench press may be inconclusive. The observed disparities in muscle activation between the dominant and non-dominant sides can be attributed to interlimb asymmetry effects. Inter-Limb Asymmetries (ILA) quantify the variances in physical attributes such as strength, explosiveness, flexibility, and balance between the left and right sides of the human body. Such asymmetry may stem from inherent factors, like limb dominance, or acquired factors, such as specialized sports training or disparate recovery rates following an injury. These asymmetries can profoundly influence athletic performance and predispose individuals to injuries (Maloney, 2019; Bishop et al., 2023). To mitigate these effects, one can employ targeted strength training, functional training, and biomechanical corrections to harmonize limb capabilities, thereby enhancing overall athletic performance and diminishing injury risks. Recent studies have highlighted the neural control mechanisms underlying these asymmetries, particularly in the upper limbs. Lecce et al. (2025) demonstrated that dominant muscles exhibit greater maximal voluntary force (MVF) and higher motor unit discharge rates, attributed to increased neural drive from greater shared synaptic inputs. This neural drive is not solely due to intrinsic motoneuron properties but is modulated by the distribution of synaptic inputs. Furthermore, cross-education phenomena, where unilateral training affects the contralateral limb, have been shown to enhance muscle activation through neural adaptations at both spinal and supraspinal levels (Lecce et al., 2024). Consequently, investigating the most effective training interventions for rectifying limb asymmetry holds considerable significance.

Offset Training, a novel training method, capitalizes on the disparity in muscle activation levels between the dominant and non-dominant sides of the body. It enhances balance and stability requirements by intentionally creating an asymmetrical distribution of external loads during bilateral resistance training. This significantly increases the activation level of the muscles on the loaded side. Offset Training is effective in rectifying muscle strength imbalances, diminishing injury risk, and enhancing overall athletic performance (Jarosz et al., 2020). The method can be applied to various forms of bilateral resistance training such as flat bench presses, squats, and deadlifts. Several scholars have employed asymmetrical load interventions during bench press exercises (Saeterbakken et al., 2020b; Jarosz et al., 2020), investigating fluctuations in muscle activation levels on the dominant and non-dominant sides. The aim is to identify sports interventions that augment the stability of the bench press. Jarosz et al. (2020) pioneered an analysis of electromyographic test results during the bench press under asymmetric load interventions. They designed comparative experiments with asymmetric load interventions of 2.5%, 5%, and 7.5% on both sides. Their findings revealed that regardless of the side (dominant or non-dominant) where the load was applied, the muscle activation level on the loaded side escalated to varying degrees. However, Saeterbakken et al. (2020b) found in subsequent research that larger asymmetric load interventions (unloading 5% and 10% on the non-dominant side) may challenge subjects to maintain the stability of the bench press movement, potentially causing barbell rod movement. Furthermore, interventions involving asymmetric loads of 5% and 10% resulted in an increase in muscle activity in the core muscle groups on the loaded side by 280% and 320%, respectively. Consequently, there were minimal alterations in the activation levels of the primary muscles in both the dominant and non-dominant upper limbs, such as the triceps brachii (TB), anterior deltoid (AD), and pectoralis major (PM). In a recent study (Sharp et al., 2022), Matthew Sharp discovered that 4 weeks of bench press offset training with an asymmetric load of 5% can enhance both muscle thickness and bench press strength more effectively than traditional symmetrical load training. This underscores the superiority of offset training for muscle hypertrophy and strength gains. It is important to note that none of the aforementioned

TABLE 1 List of basic physiological information of subjects (n = 10).

Years (age)	Height (cm)	Weight (kg)	Years of training	Bench press1RM(kg)
24.20 ± 1.91	174.10 ± 2.93	76.90 ± 6.19	4.55 ± 0.80	120.00 ± 14.66

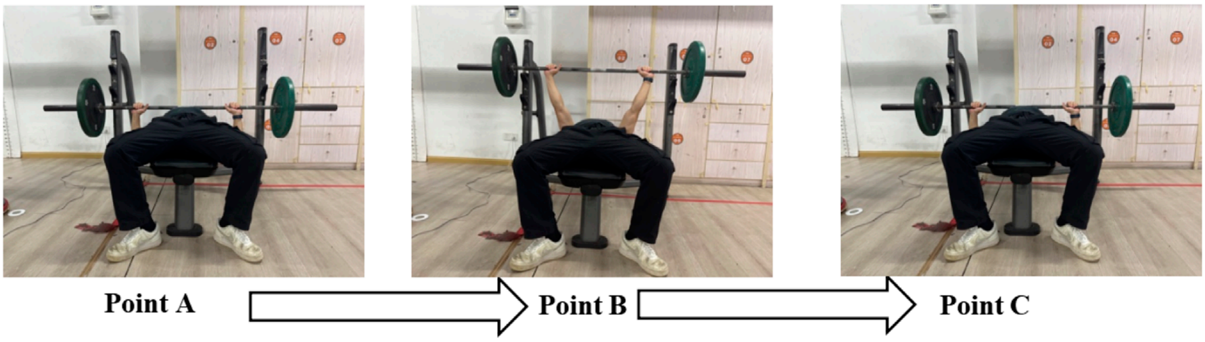

FIGURE 1
Eccentric, concentric phase of bench press.

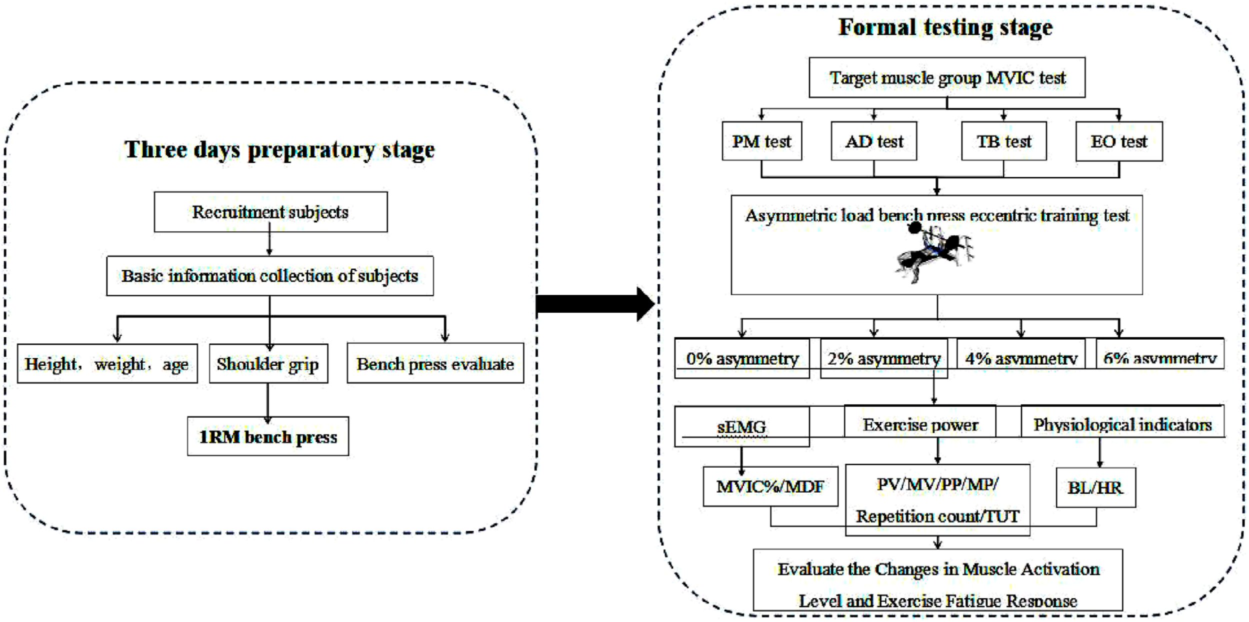

FIGURE 2
Experimental flowchart.

studies addressed the issue of exercise-induced fatigue. Given the significant difference in muscle recruitment patterns between asymmetric load offset training and traditional training, excessive exercise-induced fatigue could negatively impact neuromuscular recruitment. Therefore, it is crucial to investigate the incidence of exercise-induced fatigue during asymmetric load offset training. In conclusion, this study aims to mitigate the increased instability during the bench press caused by significant asymmetrical load interventions (Saeterbakken et al., 2020b). This study builds upon the experimental design of Jarosz et al. (2020), which utilized 2.5%, 5%, and 7.5% asymmetrical load interventions, to further refine the minimum threshold at which asymmetrical load interventions significantly impact muscle activation levels. The goal is to enhance the effectiveness and cost-efficiency of these interventions. Consequently, interventions of 0% (symmetrical load), 2%, 4%, and 6% asymmetrical loads were selected. In analyzing the changes in muscle activation levels of the target upper limb muscles, the study also included the activation changes of the core muscle group's

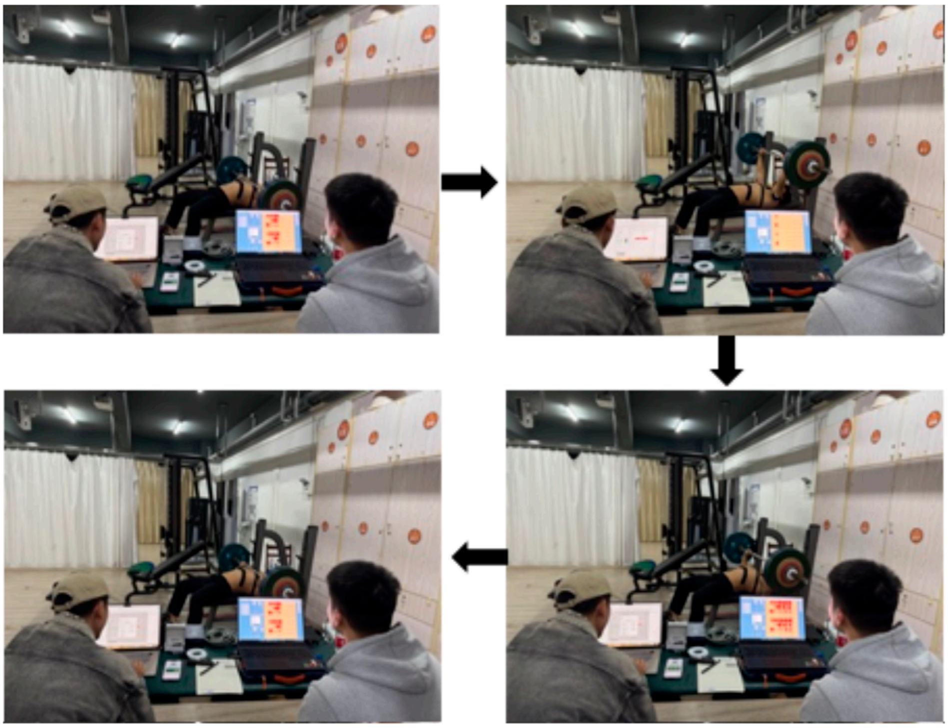

FIGURE 3
Subjects performing the bench press 1 R M test.

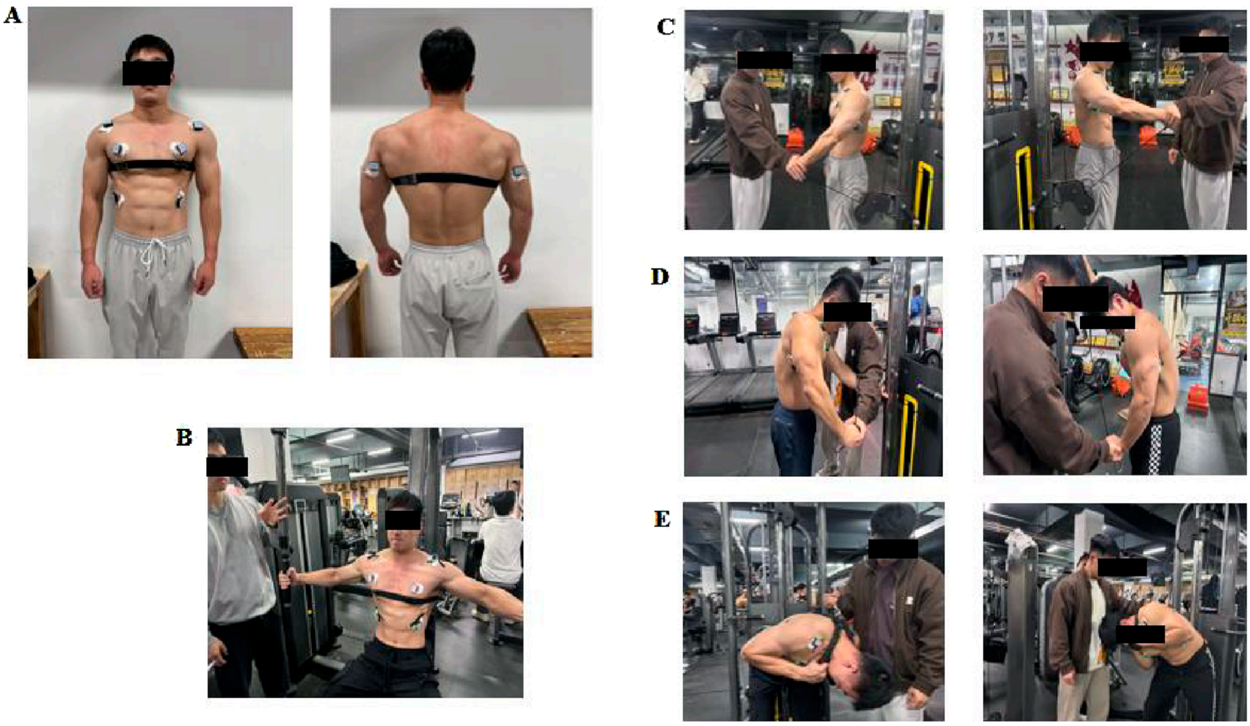

FIGURE 4
Target Muscle Surface EMG Acquisition Process **(A)** Target muscle surface EMG electrode attachment point **(B)** MVIC test of the dominant and non-dominant sides of the pectoralis major muscle **(C)** MVIC test of the dominant and non-dominant sides of the anterior deltoid muscle **(D)** MVIC test of the dominant and non-dominant sides of the triceps brachii muscle **(E)** MVIC test of the dominant and non-dominant sides of the external oblique muscle.

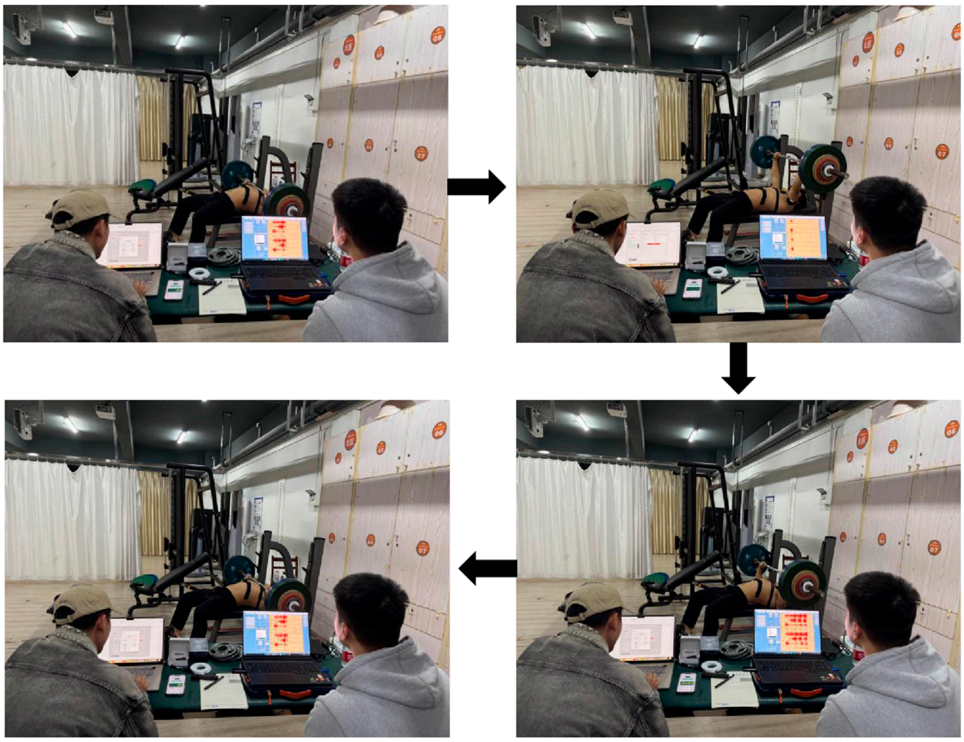

FIGURE 5
Surface EMG and motor power acquisition process during offset training with asymmetric load bench press.

External Oblique (EO). This comprehensive approach allows for a deeper evaluation of the muscle force characteristics of the upper limb and core muscle groups during asymmetrical load bench press offset training. By examining the changes in athletic fatigue under varying asymmetrical load offset trainings, this study aims to precisely understand the beneficial effects of different degrees of asymmetrical load interventions on the stability of the bench press movement. Based on these findings, we hypothesize that graded asymmetric load bench press training will enhance non-dominant muscle activation by increasing neural drive to these muscles. We also expect that this enhanced activation will lead to improved force generation and reduced interlimb asymmetry. Additionally, we anticipate that higher asymmetry levels may induce greater physiological fatigue.

2 Objective and methods

2.1 Objective

The study was conducted from October to November 2024 in a physical training room, employing a research design that combines randomized crossover control with self-control methods. The sample size for this study was determined using G*Power software (version 3.1). The parameters used in the analysis were as follows: an F-test for ANOVA (repeated measures, within factors), a desired power level of 0.8, and an expected effect size $f = 0.56$, which was based on prior studies (Saeterbakken et al., 2020c)· Considering a potential 20% sample loss, the initial calculated sample size was seven subjects. Ultimately, a total of 10 participants were enrolled in the study. Through strict inclusion criteria, a final group of 10 qualified subjects was formed for the study, with their basic information detailed in Table 1. To minimize the risk of subjective bias, the subjects were not informed of the true and comprehensive purpose of the experiment. Before the experiment, they were only given a general overview: that the research was related to the effects of asymmetric load bench press offset training on muscle activation levels and exercise - induced fatigue responses of the target muscle groups on the dominant and non - dominant sides. This general description was provided to ensure that the subjects could understand the basic nature of the experiment and cooperate with the procedures, while keeping them unaware of the in - depth research goals, such as precisely evaluating the optimal asymmetric load thresholds for enhancing non - dominant muscle activation and minimizing compensatory fatigue, and comprehensively understanding the long - term impacts of asymmetrical load training on muscle force characteristics and movement stability. This way, the potential influence of subjects' subjective expectations on the experimental results was reduced. The selection of male subjects was made to control for potential influences of gender-related hormone level fluctuations and physiological cycle changes on muscle activation degrees and training effects, ensuring comparability and reliability of electromyographic signals, force output, and other physiological parameter measurements during the experiment. Previous research has shown that menstrual cycle phases can influence muscle activation patterns and

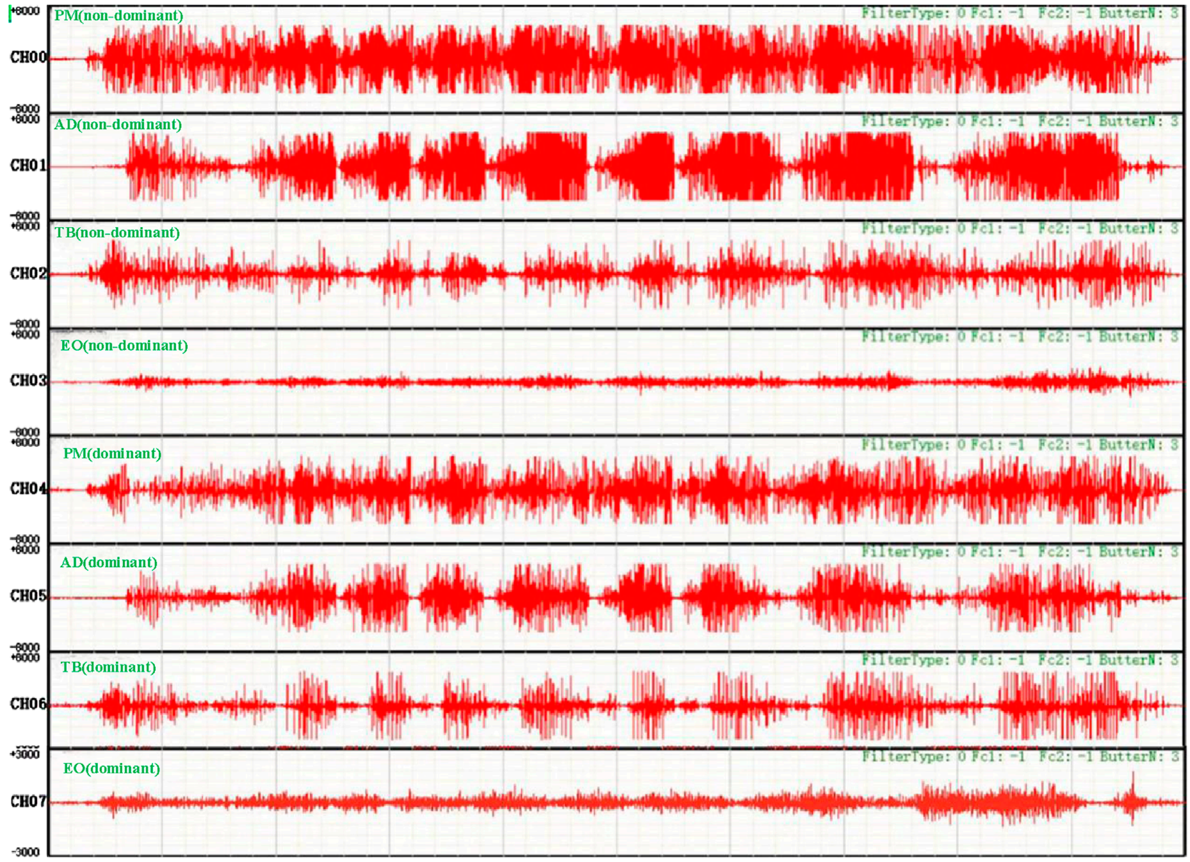

FIGURE 6
Original EMG of a target muscle during an asymmetric load bench press offset training of a subject.

neuromuscular performance due to hormonal fluctuations (Piasecki et al., 2023).

Eligibility criteria included: (1) healthy men aged 19–24 with no chronic diseases or acute injuries; (2) a minimum of 3 years of consistent resistance training experience, with a current regular training regimen; (3) a 1 R M bench press capability of at least 120% of body mass, ensuring a robust foundation in upper extremity strength; (4) proficiency in the standard bench press technique, demonstrating precision in both eccentric and concentric phases as per the experimental protocol; and (5) no significant sports injuries within the past year and no conditions or surgical histories impacting upper limb or core muscle group functionality. The exclusion criteria were as follows: (1) Participation in high-intensity resistance training or aerobic exercise within 72 h prior to the experiment, as this could potentially influence the accuracy of the results. (2) The use of any substances or equipment that could impact muscle performance, such as stimulants, steroids, caffeine, and weightlifting belts, wrist wraps, elbow sleeves, *etc.* (3) Presence of musculoskeletal issues that could hinder bench press performance, including chronic pain in the shoulder, elbow, or back, arthritis, or other similar injuries. (4) Psychological conditions that could potentially affect performance during the experiment, such as anxiety, depression, or other psychiatric disorders.

2.2 Methods

2.2.1 Experimental design and process

Throughout the entire experiment, participants were required to perform four sets of bench press training with different asymmetric loads. Sessions with varying degrees of asymmetric load bench press training were separated by 48-hour intervals to eliminate interference effects between sessions. The asymmetric loads in this experiment were divided into four levels: 0% asymmetry, 2% asymmetry, 4% asymmetry, and 6% asymmetry. The order of these asymmetric load conditions was randomized through participant drawing of lots to ensure randomization, parallelism, and avoidance of cumulative training effects. In all asymmetric load conditions, the total load was maintained at 70% 1 R M (accurate to 0.25 kg). However, the load distribution between the dominant and non-dominant sides differed across conditions. The dominant side was defined as the arm participants preferentially used for throwing (Saeterbakken et al., 2020b). A 1% 1 R M load served as the base value for the load difference between sides, with the dominant side unloaded and the non-dominant side loaded asymmetrically. Specific load designs were as follows:

0% asymmetry: Equal load on both dominant and non-dominant sides.2% asymmetry: Dominant side unloaded by 1% 1 R M, non-dominant side loaded by 1% 1 R M; 4% asymmetry:

TABLE 2 Summary of changes in MVIC% values of target muscle groups during bench press offset training with different asymmetric loads (n = 10).

Muscle group	Asymmetric intervention	Non-dominant side	Dominant side	F	η^2
Pectoralis major (PM)	0% asymmetric	35 ± 5.32	51 ± 6.82**	0.195	0.005
	2% asymmetric	48.4 ± 11.8	47.4 ± 9.71		
	4% asymmetric	50.7 ± 13.3	47 ± 11.4		
	6% asymmetric	54.4 ± 8.46$^{\triangle}$	46 ± 9.17		
Anterior deltoid (AD)	0% asymmetric	32.6 ± 9.21	48.2 ± 5.05*	0.169	0.005
	2% asymmetric	37.6 ± 5.88	47 ± 7.33		
	4% asymmetric	47.5 ± 10.9	43.1 ± 6.48		
	6% asymmetric	52.3 ± 12.7$^{\triangle}$	34.8 ± 11.9		
Triceps brachii (TB)	0% asymmetric	30.2 ± 8.63	42.7 ± 10.3	2.84	0.073
	2% asymmetric	37.4 ± 8.19	39.5 ± 8.66		
	4% asymmetric	38.7 ± 5.84	41 ± 10.5		
	6% asymmetric	43.5 ± 9.20	39.6 ± 10.6		
External oblique (EO)	0% asymmetric	12.8 ± 3.34	15.4 ± 4.06	3.19	0.081
	2% asymmetric	15.1 ± 4.47	19.6 ± 8.06		
	4% asymmetric	18.4 ± 5.29	15.2 ± 5.17		
	6% asymmetric	31.1 ± 12.3$^{\triangle\triangle\S\S}$	17.4 ± 11.5**		

Note: *indicates a significant difference in muscle MVIC% value changes between the non-dominant and dominant sides of the same muscle group within the experimental group (*.p < 0.05;**.p < 0.01); under the same muscle group, △ indicates a significant difference in muscle group MVIC% value changes compared to 0% asymmetry intervention (△.p < 0.05; △△.p < 0.01), § indicates a significant difference in muscle group MVIC% value changes compared to 2% asymmetry intervention (§.p < 0.05; §§.p < 0.01), and # indicates a significant difference in muscle group MVIC% value changes compared to 4% asymmetry intervention (#.p < 0.05; ##.p < 0.01).

Dominant side unloaded by 2% 1 R M, non-dominant side loaded by 2% 1 R M; 6% asymmetry: Dominant side unloaded by 3% 1 R M, non-dominant side loaded by 3% 1 R M.The asymmetric load design was adapted from previous studies (Saeterbakken et al., 2020b; Jarosz et al., 2020) with modifications to refine the minimum threshold of asymmetric load intervention required to significantly affect muscle activation levels. This study strictly adheres to the Helsinki Declaration and has been approved by the Ethics Committee of Henan Sport University.

Three days prior to the formal asymmetric load intervention bench press experiment, baseline information of subjects shall be collected and 1 R M bench press testing shall be conducted. On the experimental day, maximal voluntary isometric contraction (MVIC) measurements should first be performed on eight target muscles: the pectoralis major, triceps brachii, anterior deltoid, and external oblique muscles of both dominant and non-dominant body sides. Subsequently, subjects will perform asymmetric load bench press offset training with controlled movement rhythm and trajectory (using a metronome to maintain 2s duration for eccentric phase (Point A→B) and 1s for concentric phase (Point B→C), ensuring temporal consistency of movement execution). Throughout the exercise, subjects must maintain continuous contact of head, shoulders, and hips with the bench. The barbell must touch the chest during descent and achieve full elbow extension at the top position to ensure standardized movement execution as illustrated in Figure 1.

Each set of asymmetric load bench press training requires subjects to perform repetitions until failure. The criteria for failure determination follow previous research (Krzysztofik et al., 2021): when subjects cannot complete another concentric movement through the full range of motion during bench press, accompanied by movement deviations (e.g., barbell path deviation, shoulder/hip lift-off from the bench), inability to maintain movement rhythm, or decreased core stability, failure is confirmed, and the test is immediately terminated. Throughout the asymmetric load bench press offset training, surface electromyography (sEMG) changes of target muscles, barbell velocity/power output, as well as pre- and post-training heart rate and blood lactate levels are recorded to evaluate muscle activation patterns and exercise-induced fatigue responses under varying degrees of asymmetric loading. The detailed experimental flowchart is presented in Figure 2.

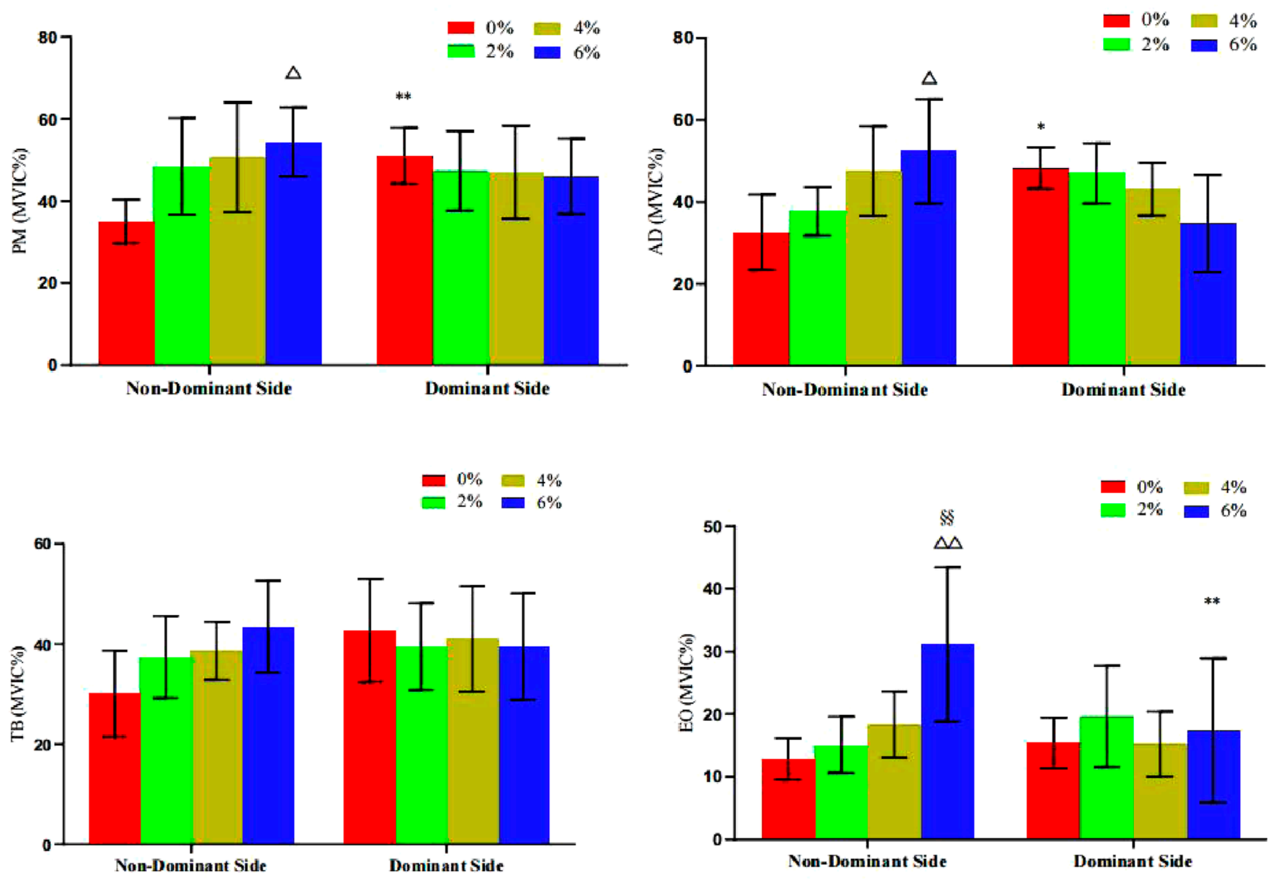

FIGURE 7
The change of MVIC% value of target muscle group during bench press offset training with different asymmetric load.

2.2.2 Main test and observation indicators

(1) Bench Press 1 R M Test: All participants were evaluated for their bench press 1 R M 48 h prior to the commencement of the experimental phase. This assessment determined their maximal strength levels and provided normalized loading parameters for subsequent experiments. Prior to the test, participants underwent a 10-minute standardized warm-up, which included a whole-body warm-up using a power cycle (resistance set at 100 W and cadence maintained at 70–80 rpm). This was designed to elevate heart rate and promote overall blood circulation in preparation for the high-intensity tests that followed. Subsequently, participants performed specific warm-up sets of 15, 10, and five repetitions with loads of 20%, 40%, and 60% of their verbally reported estimated 1 R M, respectively. This progression was intended to activate relevant muscle groups incrementally and familiarize participants with the bench press movement pattern. For the formal test, subjects commenced with an 80% load of 1 R M, performing three to five repetitions. Subsequent attempts increased by 4–9 kg. A 3-min rest interval was enforced between sets to replenish energy levels. The weight was then incrementally increased by 4–9 kg with two to three repetitions. Upon achieving a successful 1 R M, the weight continued to escalate by 4–9 kg. If unsuccessful, the weight decreased by 2–4 kg. The 1 R M was ascertained from three to five attempts and the protocol was repeated until the subject could no longer complete the lift. To ensure both the efficiency of the testing and the subject's safety, all subjects' 1 R M were determined within five attempts. Throughout the test, subjects were mandated to adhere strictly to the standardized technical bench press requirements. This included allowing the barbell to descend to the chest, pushing it upwards until the elbows were fully extended, and maintaining contact of the head, shoulders, and buttocks with the bench during the entire movement. This discipline was essential for the accuracy and reliability of the test results. The detailed procedure is illustrated in Figure 3.

(2) MVIC test of the target muscle group: Prior to the formal test, muscle electromyographic values were recorded under maximal voluntary isometric contractions 5 minutes earlier. This was done to normalize the surface integral electromyographic values in line with SENIAM procedures (Hermens et al., 2000). Electrodes were placed on four muscles bilaterally: the trapezius descendens (TB), anterior deltoid (AD), triceps brachii (PM), and external oblique (EO). The skin covering the muscle belly was shaved and cleaned with alcohol to prepare for the placement of gel-coated, self-adhesive electrodes. For the pectoralis major, electrodes were

TABLE 3 Summary of changes in MDF values of target muscle groups during bench press offset training with different asymmetric loads (n = 10).

Muscle group	Asymmetric intervention	Non-dominant side	Dominant side	F	η^2
Pectoralis major (PM)	0% asymmetric	3.99 ± 0.45	3.25 ± 0.27**	0.365	0.010
	2% asymmetric	3.56 ± 0.38	3.35 ± 0.28		
	4% asymmetric	3.21 ± 0.30△	3.46 ± 0.35		
	6% asymmetric	3.14 ± 0.26△△	3.67 ± 0.29		
Anterior deltoid (AD)	0% asymmetric	4.84 ± 0.27	3.94 ± 0.26**	9.27	0.205
	2% asymmetric	4.47 ± 0.42	3.69 ± 0.33*		
	4% asymmetric	3.61 ± 0.28△△§§	3.72 ± 0.41		
	6% asymmetric	3.66 ± 0.29△△§§	4.23 ± 0.51		
Triceps brachii (TB)	0% asymmetric	4.63 ± 0.81	4.23 ± 0.35	0.476	0.013
	2% asymmetric	4.23 ± 0.59	4.16 ± 0.44		
	4% asymmetric	4.18 ± 0.50	4.21 ± 0.70		
	6% asymmetric	4.12 ± 0.45	4.24 ± 0.59		
External oblique (EO)	0% asymmetric	3.93 ± 0.41	3.58 ± 0.37	1.23	0.033
	2% asymmetric	3.64 ± 0.41	3.5 ± 0.37		
	4% asymmetric	3.53 ± 0.35	3.28 ± 0.20		
	6% asymmetric	2.94 ± 0.28△△	4.16 ± 0.83**		

Note:*indicates a significant difference in muscle MDF, values between the non-dominant and dominant sides of the same muscle group within the experimental group (*.p < 0.05;**.p < 0.01); under the same muscle group, △ indicates a significant difference in muscle MDF, values compared to 0% asymmetric intervention (△.p < 0.05; △△.p < 0.01), § indicates a significant difference in muscle MDF, values compared to 2% asymmetric intervention (§.p < 0.05; §§.p < 0.01), and # indicates a significant difference in muscle MDF, values compared to 4% asymmetric intervention (#.p < 0.05; ##.p < 0.01).

positioned 4 cm medially from the axilla on the costal fibers; for the anterior deltoid, 1.5 cm anteriorly from the acromion process; for the triceps brachii, medial and inferior to the long head belly; and for the external oblique, on the abdominal external oblique muscle belly. Figure 4A illustrates the subjects' target muscle electromyography motor attachment points. During each MVIC trial, participants were instructed to gradually increase force production, achieving their perceived maximum force within 3 s, and then sustain maximal effort for a duration of 3–5 s. Following this, they were to slowly release the muscle tension over a 3-s period, subsequently transitioning gradually back to a resting state. Each muscle was subjected to two trials, separated by a 1-min rest period. The precise testing procedures for each target muscle's MVIC are delineated below.

① Method of measuring pectoralis major MVIC: The subject sits upright on a butterfly chest press machine, with their chest lifted and abdomen tightened, arms slightly bent, and performs a maximum effort chest press at an elbow angle of 170° under maximum load, holding for 3–5 s. The electromyographic data of the pectoralis major muscle is collected at this time.

② The measurement method of the anterior deltoid muscle MVIC: The subject stands sideways in front of the gantry, holding a steel wire to perform a front raise, maintaining a 120° angle between the upper arm and forearm. Then, the subject exerts full effort to raise it upwards, while the tester applies downward resistance, persisting for 3–5 s, capturing the electromyographic data of the anterior deltoid muscle at this moment.

③ Method of measuring the MVIC of the triceps brachii muscle (long head): The subject performs the dragon-gate steel wire arm flexion and extension movement in a forward-leaning position, maintaining a 120° angle between the upper arm and the forearm. The upper arm is clamped to the body and does not move, then the subject exerts full force to extend the forearm while the tester applies a counterforce from the side rear. This position is held for 3–5 s, and the electromyographic data of the triceps brachii muscle is collected at this time.

④ Measurement method for external oblique abdominal muscle MVIC: The subject stands under the gantry, holding a steel wire to perform forward and side bending, rotating the upper body about 45° while generating the maximum force, with the tester applying a counterforce from the side rear, holding

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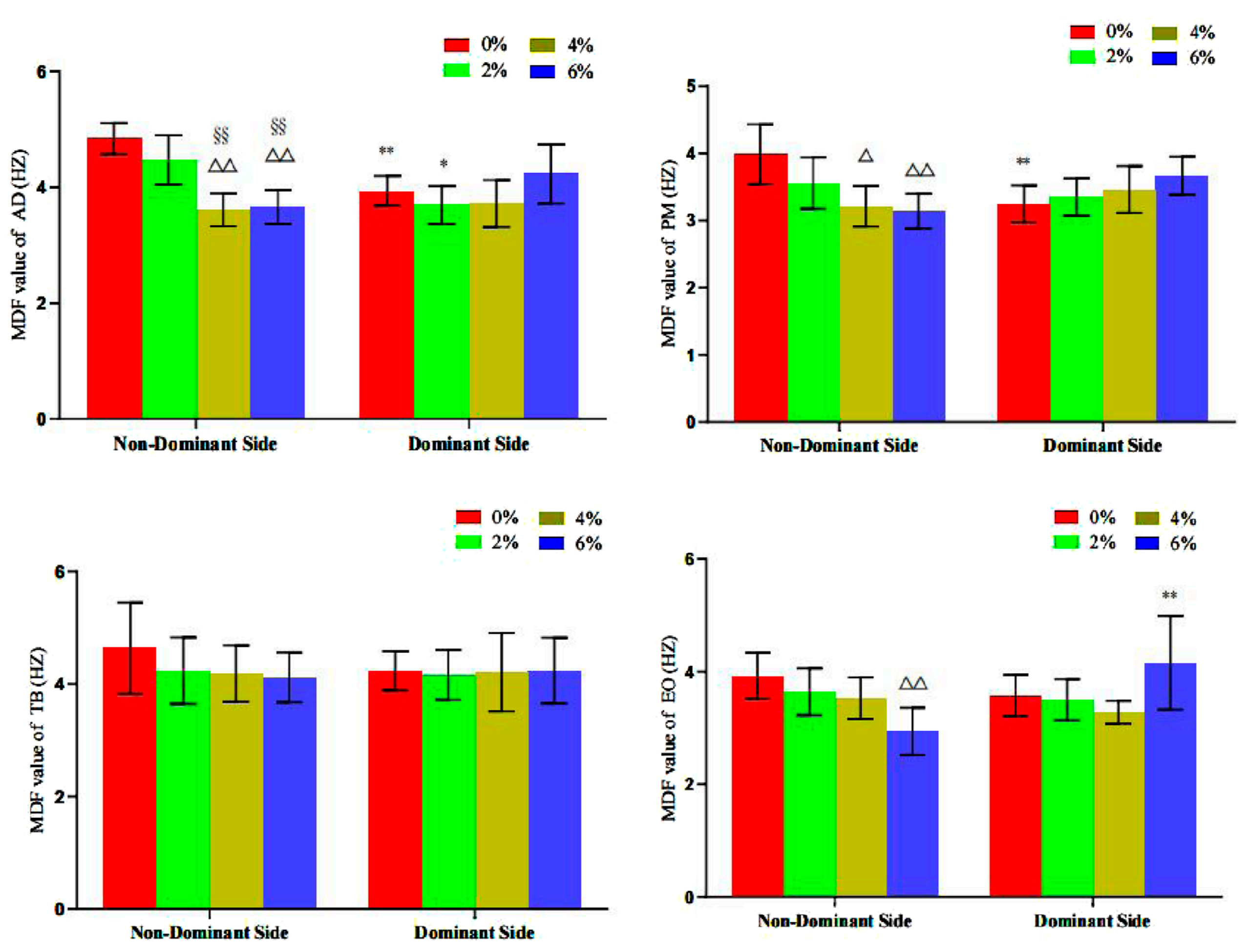

FIGURE 8
The change of MDF value of target muscle group during bench press offset training with different asymmetric load.

TABLE 4 Summary of changes in barbell movement speed indexes in bench press offset training with different asymmetric loads (n = 10).

	0% asym	2% asym	4% asym	6% asym	F
MV	0.38 ± 0.04	0.35 ± 0.02	0.30 ± 0.04**§	0.28 ± 0.03**§§	15.56
PV	0.51 ± 0.05	0.49 ± 0.04	0.44 ± 0.05**	0.42 ± 0.05*	8.00

Note:*indicates a significant difference in the change of index values compared to the 0% asymmetric intervention group (*.p < 0.05;**.p < 0.01), and § indicates a significant difference in the change of index values compared to the 2% asymmetric intervention group (§.p < 0.05; §§.p < 0.01).

for 3–5 s, collecting electromyographic data of the external oblique abdominal muscle (Saeterbakken et al., 2019).

(3) Asymmetrical load bench press test: Subjects in the asymmetric load bench press test adhered to the standard bench press movement, executing bench press offset training under four distinct asymmetric load interventions: 0%, 2%, 4%, and 6%. Warm-up routines preceding the bench press training and movement standards during the training session were consistent with prior descriptions. The 8-channel Noraxon wireless surface electromyographic signal acquisition device was employed to measure and analyze the bioelectric potential of muscles throughout each asymmetric bench press offset training session. Concurrently, the Enode pro sports performance strength and power collection device was utilized to record the movement speed and power of the barbell rod. The entire test procedure was video-synchronized, capturing the surface electromyographic signals and bench press performance of various muscles during different degrees of asymmetric load bench press offset training. Additionally, blood lactate and heart rate indicators of the subjects were collected both before and after the training (Figure 5). The EmgServer3.0 analysis software was employed to analyze the mean peak surface area electrical signal during the exhaustion phase of the asymmetric load bench press offset test for each group (specifically, the final four bench presses) (Krzysztofik et al., 2021). Raw electromyographic signals were refined using an 8–450 Hz bandpass filter (a Butterworth second-order bandpass filter)

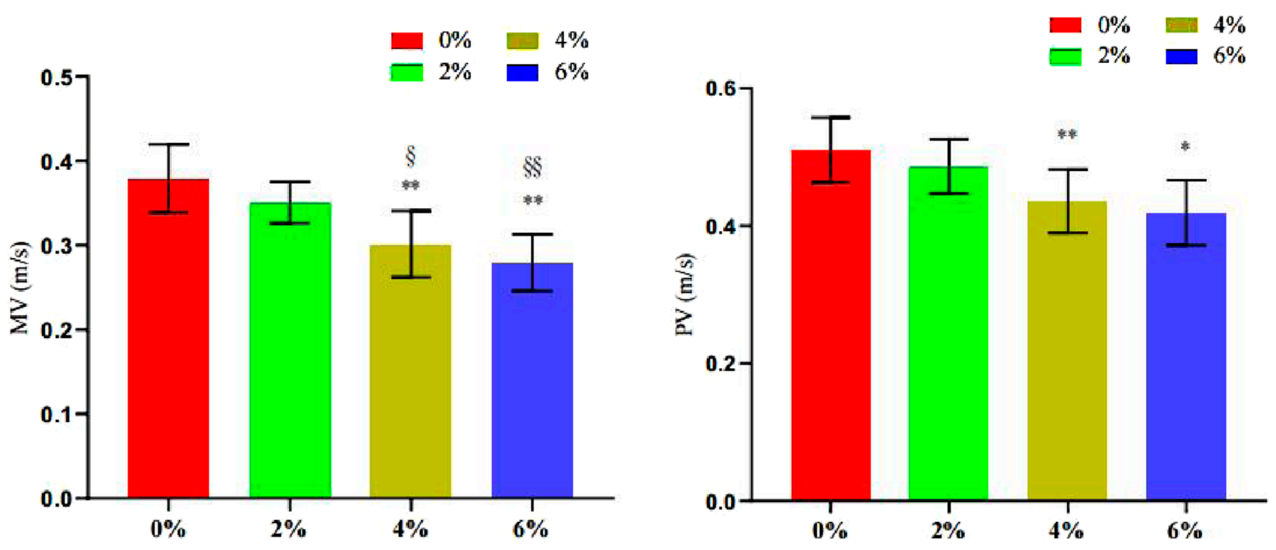

FIGURE 9
The change of barbell speed during bench press offset training with different asymmetrical loads.

TABLE 5 Summary of changes in barbell motion power index in bench press offset training with different asymmetric loads (n = 10).

	0% asym	2% asym	4% asym	6% asym	F
MP	437 ± 53.70	416 ± 48.70	371 ± 43*	357 ± 43**§	7.01
PP	332 ± 51.60	308 ± 46.10	261 ± 45.80*	242 ± 45.70**§	5.73

Note:*indicates a significant difference in the change of index values compared to the 0% asymmetric intervention group (*.p < 0.05;**.p < 0.01), and § indicates a significant difference in the change of index values compared to the 2% asymmetric intervention group (§.p < 0.05; §§.p < 0.01).

and full-wave rectification to derive the RMS for each target muscle throughout the bench press. For the MVIC test, electromyographic signals from 0.5 s before and after the maximum value were processed in the aforementioned manner to ascertain the RMS of each target muscle during the MVIC. The desired standardized RMS, denoted as MVIC%, was calculated by dividing the RMS from the bench press phase for each target muscle by the RMS from the MVIC test. This metric indicates the activation level of the target muscles. To determine the MDF index value, the time-domain signal was transformed into a frequency-domain signal *via* fast Fourier transform (FFT). The power of each frequency component was then computed. The resulting power spectrum was aggregated to derive the cumulative power distribution, with the MDF representing the frequency value that accounts for 50% of the total power in this distribution.

(4) Experimental Control: 1. Timing Control: To ensure that differences in training times do not affect the results, all subjects will complete each experimental test during the same morning timeframe, from 8:30 to 11:30. This approach minimizes the impact of circadian rhythms on the findings. Additionally, a 48-h washout period is implemented between the asymmetric load bench press training sessions of varying degrees to eliminate cumulative effects, thereby ensuring the objectivity of the experimental outcomes.2. Physical Activity and Dietary Control: Throughout the washout period, participants were barred from engaging in additional physical exercise to mitigate the impact of extraneous physical activity on athletic performance and minimize the risk of sports injuries. This measure ensured reduced inconsistencies in experimental conditions among individuals. Furthermore, the experiment was structured as a self-controlled crossover acute study, necessitating each participant's attendance five times—once for a bench press 1 R M test and four times for varying degrees of asymmetric load bench press offset training tests. Consequently, stringent records of daily intake of three meals were maintained by test personnel throughout the entire experimental duration to ensure consistency in dietary intake among all subjects. Additionally, participants were imperatively required to abstain from consuming any drugs or sports supplements that could potentially enhance athletic performance during the experimental period, thereby minimizing the risk of additional variables influencing athletic performance.

2.3 Statistical analysis

The data were statistically analyzed using SPSS 26.0 software and graphed using Graphpad Prism 8.0. The original data are expressed in the form of mean ± standard deviation (M±SD). After the homogeneity of variance test, for univariate analysis, independent sample t-tests were used for comparisons between two groups, and paired sample t-tests were used for within-group comparisons; one-way repeated measures ANOVA was used for multiple group

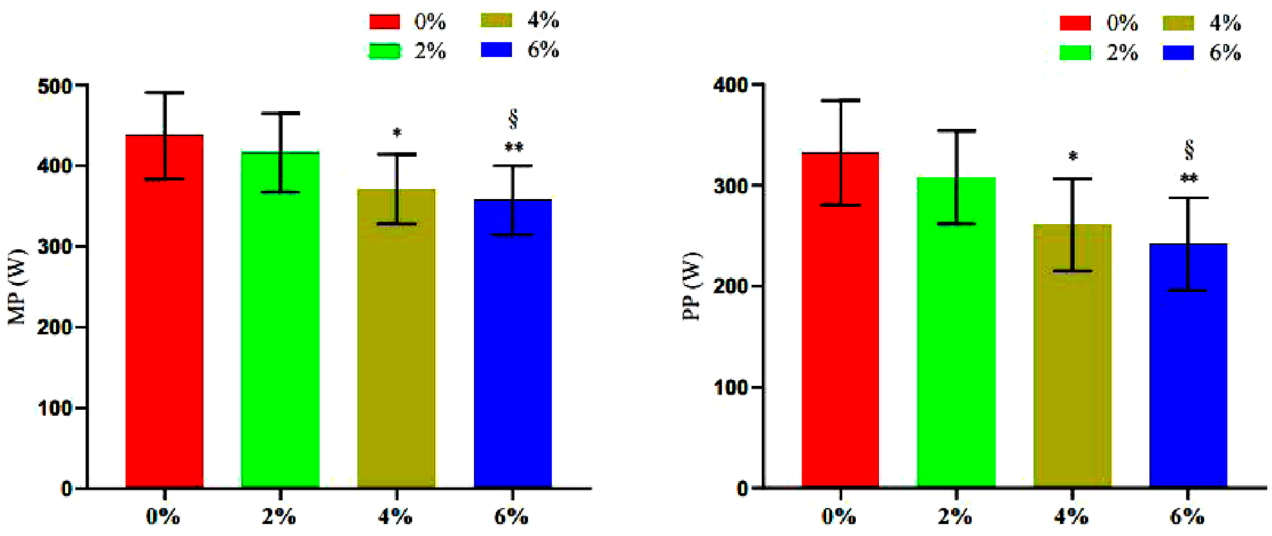

FIGURE 10
Changes in the number of bench press repetitions and time under tension during different asymmetric load shift training.

TABLE 6 Summary of changes in bench press repetitions and time under tension in different asymmetric load offset training (n = 10).

	0% asym	2% asym	4% asym	6% asym	F
Number of repetitions	13.90 ± 2.52	11.80 ± 3.19	8.53 ± 2.67**	6.63 ± 2.40**§§	15.65
TUT	48 ± 4.71	44.20 ± 7.35	39.40 ± 6.55*	33.90 ± 5.72**§	12.12

Note:*indicates a significant difference in the change of index values compared to the 0% asymmetric intervention group (*.p < 0.05;**.p < 0.01), and § indicates a significant difference in the change of index values compared to the 2% asymmetric intervention group (§.p < 0.05; §§.p < 0.01).

comparisons. The statistical significance level was set at $p < 0.05$; a very significant level was $p < 0.01$.

3 Results

3.1 Raw EMG of the target muscles when subjects performed the asymmetrical load bench press offset training

Specific experimental results are shown in Figure 6.

3.1.1 Variations in the MVIC% values of the targeted muscle groups during asymmetric load bench press offset training

The results in Table 2 and Figure 7 indicate that bilateral muscle group comparisons within the group revealed the following: The MVIC% values of the non-dominant side pectoralis major (P = 0.009) and anterior deltoid (P = 0.038) were significantly lower than those on the dominant side when training with 0% asymmetry. With 6% asymmetry, the MVIC% value of the non-dominant side external oblique muscle was significantly higher than the dominant side (P = 0.004), while no significant differences were observed in other groups. When comparing intervention groups for the same muscle group asymmetry, it was found that the MVIC% values of the non-dominant side pectoralis major (P = 0.035) and anterior deltoid (P = 0.022) at 6% asymmetry were both significantly higher than those of the 0% load group; moreover, the activation level of the non-dominant side external oblique muscle was not only significantly higher than the 0% load group (P < 0.001), but also significantly better than the 2% load group (P = 0.005), with no significant differences between other groups.

3.2 Changes in the MDF values of the target muscle groups in different asymmetric load bench press offset training

The findings from Table 3 and Figure 8 indicate that in within-group bilateral muscle group comparisons, the mean difference force (MDF) values for the non-dominant pectoralis major (P = 0.002) and anterior deltoid (P = 0.002) at 0% asymmetry were notably higher on the non-dominant side during asymmetrical bench pressing. The MDF value of the non-dominant anterior deltoid at 2% asymmetry was significantly elevated compared to the dominant side (P = 0.017). Conversely, the MDF value of the non-dominant external oblique muscles at 6% asymmetry was substantially reduced in comparison to the dominant side (P < 0.001). No significant disparities were observed in other groups. When comparing intervention groups with identical muscle group asymmetry, it was determined that: the MDF values of the pectoralis major at 4% (P = 0.01) and 6% asymmetry (P = 0.002) were both significantly diminished relative to the 0% load group; the MDF values of the anterior deltoid at 4% (P < 0.001) and 6% asymmetry

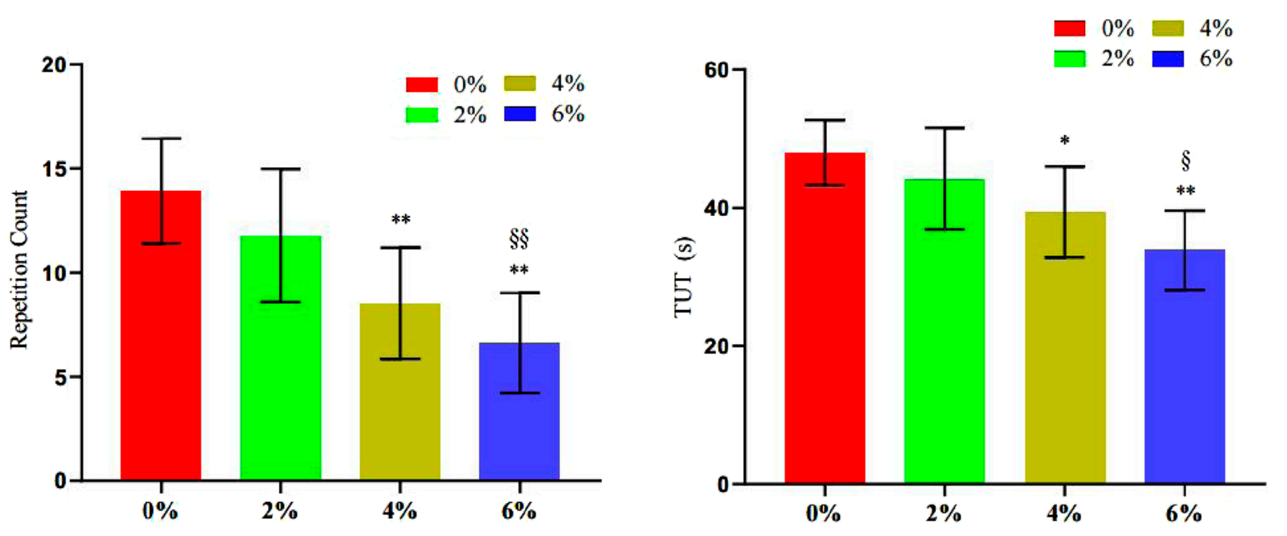

FIGURE 11
Changes in the number of bench press repetitions and time under tension during different asymmetric load shift training.

TABLE 7 Summary of changes in blood lactic acid before and after bench press offset training with different asymmetric loads (n = 10).

	0% asym	2% asym	4% asym	6% asym	F
Pre-test	1.83 ± 0.24	1.8 ± 0.31	1.78 ± 0.31	1.68 ± 0.32	0.459
Post-test	9.88 ± 0.75	9.14 ± 0.71	7.43 ± 1.57**§	7.42 ± 1.59**§	10.406

Note:*indicates a significant difference in the change of index values compared to the 0% asymmetric intervention group (*.p < 0.05;**.p < 0.01), and § indicates a significant difference in the change of index values compared to the 2% asymmetric intervention group (§.p < 0.05; §§.p < 0.01).

(P < 0.001) were not only significantly reduced compared to the 0% load group but also significantly lower than the 2% asymmetry (P = 0.001); furthermore, the MDF value of the external oblique muscles at 6% asymmetry was significantly decreased compared to the 0% load group (P = 0.002), with no significant differences noted between other groups.

3.3 Variations in bench press movement performance-related indicators under different asymmetrical load bench press offset trainings

3.3.1 Variations in the movement speed of the barbell

The findings from Table 4 and Figure 9 indicate that the mean velocity (MV) values for both 4% asymmetry (P = 0.002) and 6% asymmetry (P < 0.001) were significantly lower than that of 0% asymmetry during the asymmetrical bench press. Furthermore, the MV values for these two groups were also significantly lower than that of 2% asymmetry (4% asymmetry P = 0.019, 6% asymmetry P < 0.001). The peak velocity (PV) values for 4% asymmetry (P = 0.011) and 6% asymmetry (P = 0.002) were significantly lower than that of 0% asymmetry, with the PV value for 6% asymmetry also significantly lower than that of 2% asymmetry (P = 0.014). No significant differences were observed in the other groups.

3.3.2 Changes in the power of barbell movement

The findings presented in Table 5 and Figure 10 indicate that the Mean Pairwise (MP) values for 4% asymmetry (P = 0.034) and 6% asymmetry (P = 0.009) are significantly lower than that of 0% asymmetry. Furthermore, the MP value for 6% asymmetry is significantly lower than that of 2% asymmetry (P = 0.046). The Pairwise Proportion (PP) values for 4% asymmetry (P = 0.02) and 6% asymmetry (P = 0.003) are also significantly lower than that of 0% asymmetry. Additionally, the PP value for 6% asymmetry is significantly lower than that of 2% asymmetry (P = 0.023). No significant differences were observed in the other groups.

3.3.3 Changes in the number of repetitions and duration under tension in the bench press exercise

The findings presented in Table 6 and Figure 11 indicate that the repetition times values for 4% asymmetry (P = 0.001) and 6% asymmetry (P < 0.001) were significantly lower than those for 0% asymmetry. Furthermore, the repetition times value for 6% asymmetry was notably lower than that for 2% asymmetry (P = 0.004). Similarly, the TUT values for 4% asymmetry (P = 0.018) and 6% asymmetry (P < 0.001) were significantly lower than that of 0% asymmetry. The TUT value for 6% asymmetry was also significantly lower than that for 2% asymmetry (P = 0.013). No significant differences were observed in the other groups.

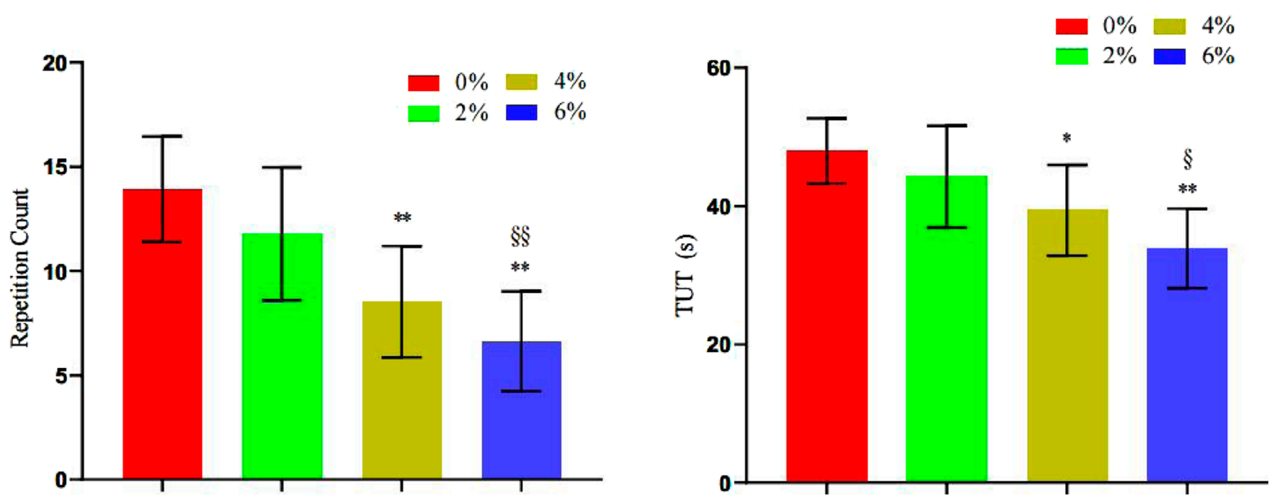

FIGURE 12
Changes in the number of bench press repetitions and time under tension during different asymmetric load shift training.

TABLE 8 Summary of heart rate changes before and after bench press offset training with different asymmetric loads (n = 10).

HR	0% asym	2% asym	4% asym	6% asym	F
Pre-test	70.6 ± 4.58	67 ± 4	65.3 ± 4.39	69.4 ± 3.99	2.76
0min	166 ± 14.5	153 ± 19.3	142 ± 21.1*	125 ± 14.4**§	12.85
1min	140 ± 15.8	132 ± 6.57	115 ± 13.7**§	106 ± 10.2**§§	19.04
3min	122 ± 20.8	115 ± 12.4	96.2 ± 8.91*§§	94.3 ± 5.69*§§	11.42
5min	109 ± 18.5	92.6 ± 8.13	93.1 ± 9.43	88.7 ± 8.09*	3.34

Note:*indicates a significant difference in the change of index values compared to the 0% asymmetric intervention group (*.p < 0.05;**.p < 0.01), and § indicates a significant difference in the change of index values compared to the 2% asymmetric intervention group (§.p < 0.05; §§.p < 0.01).

3.4 Changes in physiological indicators before and after bench press training with different asymmetrical loads

3.4.1 Changes in blood lactate

The findings from Table 7 and Figure 12 reveal that the blood lactate values for both the 4% asymmetry (P = 0.003) and 6% asymmetry (P = 0.003) groups post-asymmetrical bench press were notably lower than those of the 0% asymmetry group after the same exercise. Furthermore, the blood lactate levels for the 4% asymmetry (P = 0.036) and 6% asymmetry (P = 0.037) groups post-exercise were significantly reduced compared to the 2% asymmetry group's post-exercise values. No significant differences were observed in the other groups.

3.4.2 Changes in heart rate

The results of Table 8 and Figure 13 showed that compared with 0% asymmetry, the HR values were significantly increased at 0 min 4% asymmetry (P = 0.047) and 6% asymmetry (P < 0.001); 1 min 4% asymmetry (P = 0.006) and 6% asymmetry (P < 0.001); 3 min 4% asymmetry (P = 0.016) and 6% asymmetry (P = 0.01); and 5 min 6% asymmetry (P = 0.029). Compared with 2% asymmetry, the HR values were significantly increased at 0 min 6% asymmetry (P = 0.01); 1 min 4% asymmetry (P = 0.0015) and 6% asymmetry (P < 0.001); 3 min 4% asymmetry (P = 0.006) and 6% asymmetry (P = 0.002), and no significant differences were found in the other groups.

4 Discussion

4.1 Effects of symmetric load bench press training on muscle activation and exercise-induced fatigue

Inter-limb asymmetry serves as the theoretical foundation for offset training. Extensive research has demonstrated that inter-limb asymmetry, characterized by significant disparities in muscle activation between bilateral limbs, occurs not only in elite weightlifters (Golas et al., 2018) but also in general fitness populations (Krzysztofik et al., 2021). However, whether bodybuilders exhibit such asymmetry remains inconclusive. This study simulated symmetric load bench press training (0% asymmetry) to investigate its effects on muscle activation and exercise-induced fatigue in bodybuilders. The results revealed significant inter-limb asymmetry during symmetric loading (70% 1 R M), with the dominant-side pectoralis major (PM: 51 ± 6.82 vs 35 ± 5.32, p = 0.009) and anterior deltoid (AD: 48.2 ± 5.05 vs 32.6 ± 9.21, p = 0.038) exhibiting higher MVIC% values than the non-dominant side. These findings align with studies by Golas et al. (2018) and Krzysztofik et al. (2021). For instance, Golas et al. (2018)

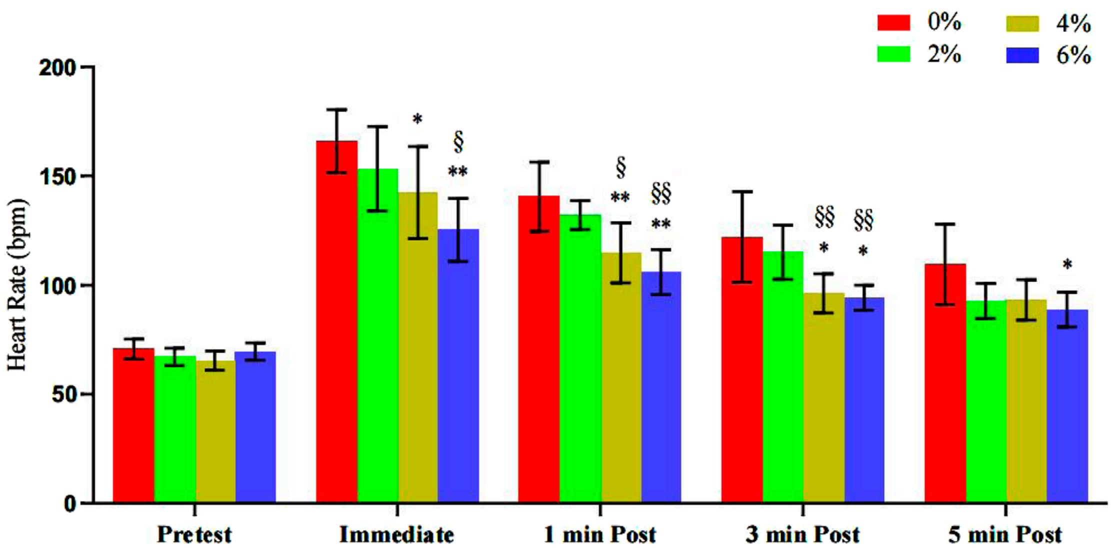

FIGURE 13
Changes before and after bench press offset training with different asymmetric loads.

observed that elite powerlifters under 70% and 90% 1 R M loads demonstrated significantly higher total electromyographic (EMG) peaks on the dominant side, particularly exceeding 100% MVIC for the anterior deltoid and triceps brachii at 90% 1 R M. Similarly, resistance-trained individuals with over 6 years of experience showed dominant-side dominance in anterior deltoid and triceps activation across low (50% 1 R M) and high (90% 1 R M) loads ($p < 0.001$), though no significant differences were observed in PM activation ($p = 0.168$) (Krzysztofik et al., 2021). Collectively, these results underscore the prevalence of inter-limb asymmetry across populations, reinforcing the necessity of asymmetric load interventions to mitigate long-term performance deficits and injury risks.

Notably, unlike previous studies emphasizing triceps asymmetry, this study identified PM and AD as the primary asymmetrical muscles in bodybuilders. This discrepancy may stem from training specialization: Bodybuilders prioritize targeted muscle recruitment over maximal load lifting. Despite the bench press engaging PM, AD, and triceps brachii (TB), PM contributes most significantly to the movement (Padulo et al., 2015), making its asymmetry more pronounced in this population. To evaluate exercise-induced fatigue, median frequency (MDF), blood lactate, and heart rate were systematically analyzed. MDF reflects muscle fatigue, with declining values indicating increased low-frequency EMG components due to metabolic byproduct accumulation and impaired neuromuscular conduction (Daniel and Małachowski, 2023). Dominant-side PM and AD exhibited lower MDF values, suggesting higher fatigue levels. Post-exercise blood lactate increased from 1.83 ± 0.24 mmol/L to 9.88 ± 0.75 mmol/L, and heart rate rose from 70.6 ± 4.58 bpm to 166 ± 14.5 bpm, though trends lacked statistical significance. Elevated lactate correlates with glycolytic metabolism during high-intensity exercise, exceeding lactate clearance thresholds and inducing central fatigue (Hideaki and Yusuke, 2013). Heart rate modulation, governed by autonomic nervous system activity, aligns with sympathetic activation during exertion and parasympathetic recovery post-exercise (Marasingha-Arachchige et al., 2020). Overall, non-dominant muscles exhibited greater fatigue, yet symmetric loading did not induce significant exercise-induced fatigue.

4.2 Effects of graded asymmetric load bench press offset training on muscle activation and fatigue

Current research focuses on identifying optimal asymmetric load thresholds to enhance non-dominant muscle activation while minimizing compensatory fatigue. Jarosz et al. (2020) demonstrated that acute asymmetric loading (0%–7.5% 1 R M) at 70% 1 R M significantly improved non-dominant PM and AD activation, particularly at 7.5%. Conversely, Saeterbakken et al. (2020b) observed that higher asymmetric loads (5%–10% 1 R M) reduced non-dominant PM and AD activation but increased external oblique (EO) activity by 280%–320%, indicating core compensation. In this study, 0%–6% asymmetric loads were applied, with non-dominant loading and dominant unloading to maintain total load at 70% 1 R M. Moderate interventions (2%–4%) effectively reduced asymmetry by elevating non-dominant PM and AD activation (6% PM: 54.4% ± 8.46% vs 0%: 35 ± 5.32, $p = 0.035$), consistent with Jarosz et al. (2020). However, activation plateaued at higher loads (6%), suggesting a 4% threshold for maximizing non-dominant recruitment. Excessive loading (6%) triggered core compensation (non-dominant EO: 31.1% ± 12.3% vs 0%: 12.8 ± 3.34, $p < 0.001$), diverting effort from primary movers and contradicting training objectives.

Performance metrics (barbell velocity, power, repetitions, time under tension) and physiological markers (blood lactate, heart rate) deteriorated progressively with higher asymmetry. For example, 6% loading reduced mean velocity (MV: 0.28% ± 0.03% vs 0%: 0.38 ± 0.04, $p < 0.001$) and increased post-exercise lactate

(7.42% ± 1.59% vs 0%: 9.88 ± 0.75, $p = 0.003$). These findings align with Matthew Sharp et al. (2022), where 5% asymmetric loading enhanced hypertrophy and strength but increased perceived exertion, highlighting trade-offs between efficacy and fatigue.

Recent evidence has shed light on the neural control mechanisms underlying limb dominance, which is highly relevant to understanding the enhanced non-dominant muscle activation observed in our study. Lecce et al. (2025) demonstrated that dominant muscles exhibit greater MVF compared to non-dominant muscles, associated with higher motor unit discharge rates and a greater proportion of common synaptic inputs. This suggests that the higher strength and activation levels in dominant limbs are primarily driven by increased neural drive due to greater shared synaptic inputs rather than differences in intrinsic motoneuron properties. Similarly, our study found that non-dominant muscles under asymmetric loading showed increased activation, which may be attributed to altered neural drive mechanisms. The application of asymmetric loads could potentially modulate the distribution of synaptic inputs, enhancing the neural drive to the non-dominant limb and thereby improving its activation levels.

Moreover, the phenomenon of cross-education, where unilateral training induces adaptations in the contralateral untrained limb, has been increasingly explored. Lecce et al. (2024) highlighted that unilateral resistance training can lead to significant strength gains in the non-trained contralateral limb, mediated by motor unit adaptations. This cross-education effect may be explained by neural adaptations occurring at both spinal and supraspinal levels, including enhanced interhemispheric communication and reduced inhibitory mechanisms. In the context of asymmetric load training, the increased activation of non-dominant muscles might be influenced by similar cross-education mechanisms. The neural drive to the non-dominant limb could be potentiated through the coordinated activation of neural pathways, even in the absence of direct physical training, leading to improved muscle activation and force generation.

These neural adaptations may also play a role in the observed performance metrics and physiological fatigue markers in our study. The progressive decline in barbell velocity, power output, and repetitions with higher asymmetry levels could be partly due to the neural challenges of maintaining stability and coordination under asymmetric loading. Additionally, the increased blood lactate and prolonged heart rate recovery in the 6% asymmetry group suggest that the enhanced neural drive to muscles comes at the cost of increased metabolic and cardiovascular stress. This aligns with the notion that greater neural activation can lead to higher energy demands and faster fatigue onset.

In conclusion, the integration of recent findings on neural control mechanisms and cross-education provides a more comprehensive understanding of the enhanced non-dominant muscle activation and the associated physiological responses observed during asymmetric load bench press training. These insights not only enrich the interpretation of our results but also highlight the potential for targeted neural adaptations through asymmetric training protocols, which could be further explored in future research.

4.3 Study limitations

This study has several limitations.

(1) The acute experimental design involved short-term interventions of asymmetrical load bench press training with lateral displacement, which may not fully capture long-term adaptive changes. Chronic training could induce structural muscle remodeling, enhanced neuromuscular control, and sustained performance improvements—effects unobservable in acute experiments. Future studies should adopt longitudinal intervention designs to track participants' adaptations over weeks or months, thereby comprehensively evaluating the long-term impacts of asymmetrical load training.
(2) The sample comprised only 10 collegiate bodybuilders, a limited and specific population, which restricts the generalizability of findings. Responses to asymmetrical load training may vary across athletes of different ages, training levels, and genders. Expanding the sample size to include participants with diverse backgrounds and training experiences would enhance the representativeness and external validity of results.
(3) Exercise-induced fatigue was primarily assessed using median frequency (MDF), blood lactate, and heart rate. These metrics may inadequately reflect the multidimensional complexity of fatigue. Future research should incorporate additional indicators, such as muscle strength/endurance tests, neuromuscular control assessments, psychological fatigue questionnaires, creatine kinase (to evaluate skeletal muscle damage), and oxidative stress markers (e.g., malondialdehyde [MDA] and superoxide dismutase [SOD]), to holistically assess the effects of asymmetrical load training on fatigue.

4.4 Innovations and contributions

This study revealed significantly higher activation levels in the dominant-side pectoralis major and anterior deltoid compared to the non-dominant side. In contrast to previous findings showing no significant pectoralis major asymmetry but notable differences in anterior deltoid and triceps activation, this discrepancy may stem from bodybuilders' compensatory activation patterns due to prolonged symmetric bench press training. Regarding intervention efficacy, both 2% and 4% asymmetrical loads effectively reduced inter-limb asymmetry, with 2% demonstrating optimal training efficacy based on muscle activation and performance metrics. Notably, the 6% load partially mitigated asymmetry but yielded no significant additional benefits, aligning with Saeterbakken et al.'s conclusion that excessive asymmetry triggers compensatory core muscle recruitment to maintain stability, contradicting the intervention's original intent.

Key contributions include: (1) First systematic investigation of asymmetrical load bench press models in bodybuilders, uncovering latent inter-limb asymmetry under conventional symmetric training. (2) Empirical evidence for precision training protocols by quantifying how load gradients modulate target muscle activation. (3) Multidimensional insights (sport biomechanics, electromyographic, and physiological) advancing the understanding of neuromuscular coordination mechanisms during asymmetrical training. (4) Future research should integrate muscle function metrics, neuromuscular control parameters, biochemical markers, and psychophysiological indices to comprehensively evaluate exercise-induced fatigue.

5 Conclusion

This study explored the effects of graded asymmetrical load bench press training on muscle activation and exercise-induced fatigue in bodybuilders. Key findings include:

Inter-limb asymmetry exists in bench press training, with significantly lower activation levels in non-dominant pectoralis major and anterior deltoid.

2%, 4%, and 6% asymmetrical loads ameliorated asymmetry and enhanced non-dominant muscle activation. The 2% load demonstrated optimal efficacy with minimal performance impairment and fatigue.

Excessive asymmetry (6%) induced core muscle compensation and pronounced fatigue, detrimentally affecting performance. These findings highlight the importance of load optimization in asymmetrical training protocols to balance efficacy and physiological strain.

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 Henan Sport 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

BY: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Writing – original draft. SY: Investigation, Resources, Writing – review and editing. JZ: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Supervision, Writing – original draft. CL: Data curation, Investigation, Methodology, Project administration, Software, Writing – original draft. TH: Formal Analysis, Investigation, Supervision, Validation, Writing – review and editing. QH: Conceptualization, Data curation, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review and editing. KL: Software, Validation, 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.2025.1592477/full#supplementary-material

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Acute modulation of common synaptic inputs and motor unit discharge rates following neuromuscular electrical stimulation superimposed onto voluntary contractions

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Introduction: Superimposing neuromuscular electrical stimulation (NMES) onto voluntary contractions induces specific neuro-physiological adaptations that may have a direct effect on force related outcomes. This study investigated motor unit discharge characteristics and force steadiness following three acute experimental conditions: NMES superimposed onto isometric contractions (NMES + ISO), passive NMES, and isometric contractions only (ISO).

Methods: Seventeen healthy volunteers participated in the study. Each condition involved 20 intermittent (6s contraction/6s rest) isometric ankle dorsi flexions at 20% of their maximum voluntary contraction (MVIC). NMES was delivered to the tibialis anterior (TA) during NMES and NMES + ISO. High-density surface electromyography (HDsEMG) was used to record myoelectric activity in the TA during steady force-matching contractions, at 10% MVIC, performed immediately after each experimental condition. Motor unit discharge rate (DR) and inter-spike variability (ISIvar) were analyzed from decomposed HDsEMG signals. Coherence analysis was performed to evaluate the strength of common synaptic input across different frequency bands and the proportion of common synaptic input (pCSI) received by spinal motoneurons. Force steadiness was evaluated using the coefficient of variation of force ($Force_{CoV}$).

Results: NMES + ISO significantly increased motor unit DR compared to baseline and post-intervention NMES. NMES + ISO also induced an increase in pCSI compared to baseline, ISO and NMES. $Force_{CoV}$ was reduced after NMES + ISO compared to all experimental conditions, indicating improved force steadiness.

Discussion: These results suggest that superimposing NMES onto voluntary contractions can enhance motor unit firing rate and pCSI at low force levels. These adaptations seem to positively contribute to force steadiness, likely by engaging filtering mechanisms which minimize the independent synaptic noise affecting motor control. These findings provide new perspectives on the adaptations induced by NMES exercise, highlighting some of the neuro-physiological mechanisms involved and enriching our knowledge of how the neuromuscular system responds and adapts to NMES-based interventions.

KEYWORDS

electrical stimulation, motor unit, common synaptic input, force steadiness, neural drive, coherence analysis, HDsEMG

Introduction

Neuromuscular electrical stimulation (NMES) has proven to be highly effective in maintaining, restoring, and improving muscle mass and function in both healthy individuals and those with injuries (Vanderthommen and Duchateau, 2007; Maffiuletti, 2010). In rehabilitation settings, NMES can assist in recovering muscle function and motor control following injury or surgery, facilitating the relearning of effective muscle force generation and modulation capabilities (Herzig et al., 2015; Labanca et al., 2018; 2022). In sports training, NMES can complement conventional strength training methods, offering a targeted approach to enhance force control in specific muscle groups (Filipovic et al., 2011). Notably, superimposing NMES onto voluntary muscle contractions (NMES+) has yielded even greater improvements in muscle function and performance than NMES alone, due to specific neurophysiological adaptations (Paillard, 2018; Borzuola et al., 2023a). Recent studies exhibited that NMES+ has a facilitatory effect on both spinal and cortical responses (Lagerquist et al., 2012; Borzuola et al., 2020; 2023c; 2024; Scalia et al., 2023) compared to passive NMES and voluntary contractions alone, indicating significant modulation of these pathways through both peripheral and central mechanisms. However, these studies involved the assessment of evoked responses, which do not reflect changes in volitional neural activity.

Volitional neural activity could be achieved non-invasively by evaluating the behavior of large populations of motor units (MUs) through decomposition of high-density surface electromyography (HDsEMG) (Holobar and Zazula, 2007; Merletti et al., 2008). Several studies indicated that this technique allows for a reliable measurement of MUs discharge characteristics and estimation of the synaptic input received by spinal motor neurons (Del Vecchio et al., 2019b). Interestingly, a recent study carried out by our research group exhibited that short bouts of NMES+ can acutely increase MU firing rates at high force levels, suggesting an enhanced neural drive which could positively impact force generating capacities and control (Borzuola et al., 2023b). However, the impact of NMES+ on MU behavior as well as on the shared inputs received by motor neurons during low-force contractions, where coordinated force production is required, remains unclear.

The generation and control of muscle force rely on the activation of spinal motor neurons, which integrate a mix of excitatory and inhibitory signals originating from spinal, supraspinal, and sensory pathways. These signals include both independent and common synaptic inputs to motor neurons, although, notably, during tasks requiring force control (i.e., force-matching tasks), it is the common component within the low-frequency band (<5 Hz) that predominantly controls force generation (Farina and Negro, 2015; Castronovo et al., 2018). Coherence analysis allows to evaluate the correlations in MU spike trains within (intramuscular coherence - IMC) and between (intermuscular coherence) muscles in the frequency domain and can be used to estimate the strength of the common synaptic input (CSI) in specific frequency bandwidths such as delta (0–5 Hz), alpha (6–12 Hz) and beta (15–35 Hz) (Castronovo et al., 2018). Peak coherence values within these bands are typically analyzed to infer the level of shared inputs that modulate various aspects of neuromuscular function such as force control (delta), afferent and spinal circuits (alpha) and corticospinal pathways (beta) (Castronovo et al., 2015). Force control is inherently linked to the proportion of common synaptic input (pCSI) received by spinal motoneurons (i.e., proportion between the common inputs to the motor neurons with respect to the independent synaptic inputs at low frequencies) as it influences their collective behavior, contributing to coordinated muscle contractions and force steadiness (Negro et al., 2009; Hug et al., 2023). Thus, an increase in pCSI suggests a higher level of synchronization among motor units, which can reduce synaptic independent noise likely improving the precision of force control (Farina and Negro, 2015).

The effect of NMES on force control is multifaceted and depends on various factors, including stimulation parameters, muscle characteristics, and individual responsiveness. Research indicates that NMES can lead to improvements in force production, endurance, and coordination, thereby enhancing force control capacities (Bezerra et al., 2011). These enhancements are attributed to several underlying mechanisms, including neural adaptations, muscle hypertrophy, and changes in motor unit recruitment patterns (Maffiuletti et al., 2006). Neural adaptations induced by NMES+ involve modifications in motor neuron excitability, synaptic efficacy, and intermuscular coordination (Borzuola et al., 2023a). A recent study which investigated the effect a combination of electrical stimulation and vibration (noise stimulation) on neural plasticity, reported an improvement in motor control strategies and as well as in the ability to regulate force output accurately (Chou et al., 2023). Nevertheless, while previous work has examined MU discharge characteristics following NMES at moderate to high contraction levels, no study has yet evaluated the effects of NMES+ on common synaptic input and force steadiness at low contraction levels, where shared synaptic inputs are particularly relevant.

Therefore, the present study aims to investigate the acute effects of NMES+ on motor unit firing patterns, the proportion and strength of common synaptic inputs to spinal motoneurons, and force steadiness, in comparison to passive NMES and voluntary isometric contractions alone (ISO). Based on the findings of our previous study we hypothesized that NMES + ISO would result in an enhancement of MU discharge rate (DR), pCSI and IMC in the delta band greater than in the other two conditions with a concomitant improvement in force steadiness. By elucidating the relationship between force control and pCSI, this study aims to provide critical insights into the acute neuromuscular responses that are induced by NMES+.

Methods

Participants

Seventeen young healthy volunteers (12 males and 5 females, mean ± SD age: 28 ± 5 years, mass: 71 ± 10 kg, height: 1.75 ± 0.7 m), with no history of neurological or orthopedic disorders, participated in the study. A statistical power analysis was performed *a priori*, using a repeated measures approach (ANOVA: Repeated measures, within factors), to determine the sample size (G*Power software version 3.1.9.4; α = 0.05, power = 0.85, effect size = 0.35, sample size = 14) as indicated by Cohen (1992) based on previous works investigating motor unit discharge properties following exercise (Semmler et al., 2004; Borzuola et al., 2023b; Lecce et al., 2023; Nuccio et al., 2024). Specifically, mean motor unit discharge served as primary outcome measure for the power analysis, with pooled effect size estimated from these studies. The participants did not have any experience with NMES exercise before performing the experimental session and were asked not to engage in any strenuous activity 24 h before the experimental session. All procedures were approved by the Internal Review Board of the University of Rome "Foro Italico" (CAR 86/2021) and adhered to the standards defined by the *Declaration of Helsinki*. Written informed consent was obtained from all participants before their first experimental session.

Experimental procedures

The experimental session (Figure 1) lasted about 2 h and consisted of three experimental conditions: (a) NMES applied on the tibialis anterior muscle (NMES) (b) NMES superimposed onto voluntary isometric contraction of the ankle dorsi flexor muscles (NMES + ISO) and (c) voluntary isometric contraction of the ankle dorsi flexor muscles only (ISO). In addition, participants underwent a baseline resting condition, during which they did not perform any exercise. Experimental conditions, including baseline were administered in random order. During each exercise condition participants performed 20 intermittent contractions at 20% of maximal voluntary isometric contraction (MVIC) (6 s contraction/6 s rest), for a total duration of 4 min. The number and duration of these contractions was chosen to prevent the onset of muscle fatigue (Neyroud et al., 2014; Grosprêtre et al., 2018), while at the same time promoting neural adjustments as indicated in previous research (Lagerquist et al., 2012; Borzuola et al., 2020; Borzuola et al., 2023c). During baseline, participants remained seated at rest for 4 min. A recovery interval of 10 min was provided between each experimental condition to minimize carryover effects. All the procedures were conducted on participants' dominant limb which was determined as the limb preferred for hopping or kicking a ball (Holmbäck et al., 2003). Following each condition, participants performed steady force-matching contractions at 10% MVIC while we assessed tibialis anterior muscle myoelectrical

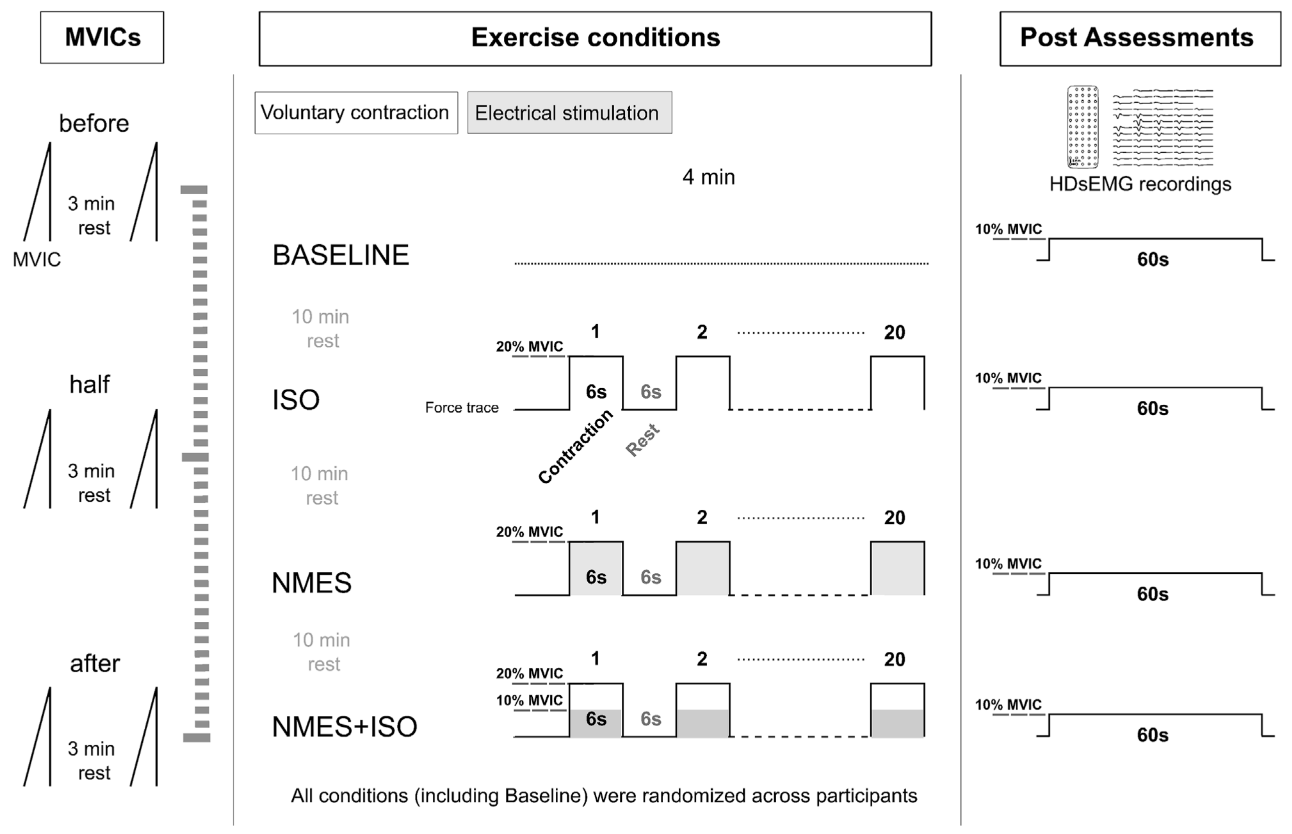

FIGURE 1
Experimental protocol

activity with high-density surface EMG (HDsEMG). Real-time visual feedback of both the force output and the expected trajectory were provided to participants at a constant visual gain. MVIC assessments were repeated at three separate times (before, at half and at the end of the experimental conditions) to monitor if any fatigue had arisen throughout the protocol.

Force recordings and analysis

During the experimental procedures, participants sat comfortably in a chair that was firmly fixed to an adjustable ankle dynamometer (OT Bioelettronica, Turin, Italy). The setup ensured that knee and hip joints were maintained at 90° flexion (with 0° representing full extension and a neutral position, respectively), and the ankle was positioned at 0° of ankle plantar-dorsi flexion (0° = foot orthogonal to the shank axis). The ankle and the foot were firmly strapped to the footplate of the dynamometer using padded Velcro straps to minimize movement, while the non-dominant leg rested on a footrest. The foot plate was connected to a calibrated force transducer (CCT Transducer, Turin, Italy), which was mounted perpendicularly beneath the footplate. The analogue signal from the transducer was amplified with a 500 gain, sampled at 2,000 Hz, and converted to digital data by a 16-bit external analogue-to-digital converter (Sessantaquattro, OT Bioelettronica, Turin, Italy). Force and HDsEMG signals were acquired with the software OTbiolab (OT Bioelettronica, Turin, Italy). Prior to maximal testing, participants completed a warm-up and familiarization protocol involving 20 submaximal isometric dorsiflexions (about 50% of perceived maximal contraction). The MVIC assessment consisted of progressively increasing the force of the dorsi flexor muscles from zero to a maximum over 3 s and maintaining the maximal value for ~3 s before relaxing. Participants were given verbal encouragement to promote their maximal effort. Two MVIC attempts were performed, each spaced 3 min apart to minimize the effect of fatigue. MVIC was chosen as the largest 500 ms average achieved within a force recording. Assessment of MVIC was then used to define a target isometric dorsi flexion force as 20% MVIC, which was used for the exercise conditions, and the steady force level at 10% MVIC. The steady force-matching contractions at 10% MVIC had a duration of 60 s. The magnitude of the force fluctuations around the target force was quantified by computing the coefficient of variation for force ($Force_{CoV}$: ratio of standard deviation relative to the mean). A moving 20 s window (100 ms increments) was used to identify the steadiest 20 s (lowest coefficient $Force_{CoV}$) of each 60 s trial (Tvrdy et al., 2025).

NMES

NMES was delivered over the TA muscle using a portable muscle electrical stimulator (Chattanooga Wireless Professional, DJO Global, Vista, CA, United States). NMES was applied either passively or superimposed onto voluntary contraction of the dorsi flexor muscle. The stimulator produced a rectangular, balanced biphasic pulse and was constantly handled and controlled by the operator. Two self-adhesive electrodes (Compex Dura-Stick plus, 50 × 50 mm, DJO Global, Vista, CA, United States) were used to deliver the stimulation. The anode was placed over the motor point of the tibialis muscle, while the cathode was placed distally on the same muscle, about 6 cm from the anode, as illustrated in Figure 2. The motor point of the tibialis anterior muscle was identified at the beginning of the experimental session with a hand-held anode ball electrode in accordance with the electrical stimulator user's guide. NMES was administered with a pulse frequency of 50 Hz and a pulse width of 400 µs per phase to generate higher forces while promoting the highest comfort during electrical stimulation, as reported in previous investigations (Baldwin et al., 2006; Wiest et al., 2017). The current pulse intensity of the stimulation was manually adjusted in accordance with each participant's tolerance. Before the beginning of the experimental conditions, participants familiarized with the electrical stimuli for about 10 min at low intensity. In the NMES condition, current pulse intensity was increased (average NMES intensity: 20.4 mA; range 10.5–32.2 mA) until the passively stimulated ankle dorsi flexion reached the target force at 20% MVIC. During ISO, participants were required to match the target force of 20% MVIC by voluntarily contracting their dorsi flexor muscles. During NMES + ISO, current pulse intensity was set to produce half of the target force (10% MVIC; average NMES intensity: 15.1 mA; range 8.6–26.9 mA) and participants were asked to voluntarily contract their dorsi flexor muscles to achieve the full target of 20% MVIC. In this condition, participants were asked to relax their tibialis anterior muscle before the first and after the 10th contraction while the investigator adjusted the current intensity to make sure that the force produced by the stimulator alone corresponded to half of the target force throughout the entire NMES + ISO condition.

HDsEMG recordings

HDsEMG signals were acquired in monopolar derivation from the TA muscle using a high-density adhesive grid of 13 × 5 equally spaced electrodes (gold-coated, 1 mm diameter, 8 mm inter-electrode distance (IED); GR08MM1305, OT Bioelettronica, Turin, Italy). A trained operator first located the perimeter of the muscle by manual palpation and, then, positioned the grid over the most innervated areas of the distal area of the TA muscle (Figure 2), as indicated in previous works (Del Vecchio et al., 2019a; Casolo et al., 2020; Borzuola et al., 2023b). The area of the skin where the grid was applied was shaved, lightly abraded, and cleansed with 65% ethanol to optimize electrode-skin conductivity. The grid was applied over the skin of tibialis anterior muscle parallel to the lateral margin of the tibia with a bi-adhesive foam layer designed to match the HDsEMG grid (SpesMedica, Battipaglia, Italy). The cavities of the foam layer were filled with conductive paste (SpesMedica) to obtain skin-electrode contact. The reference electrode of the grid was positioned on the medial malleolus of the tested leg with a moistened ankle strap while the electrode grid was connected to a multichannel amplifier (Sessantaquattro, OT Bioelettronica, Turin, Italy).

The HDsEMG signals were sampled at 2,000 Hz, band-pass filtered (3 dB bandwidth, 10–500 Hz), converted to digital data by the multichannel amplifier, and visually inspected to detect and exclude channels with noise. On average, 2.6 ± 1.1 channels per grid were excluded before decomposition.

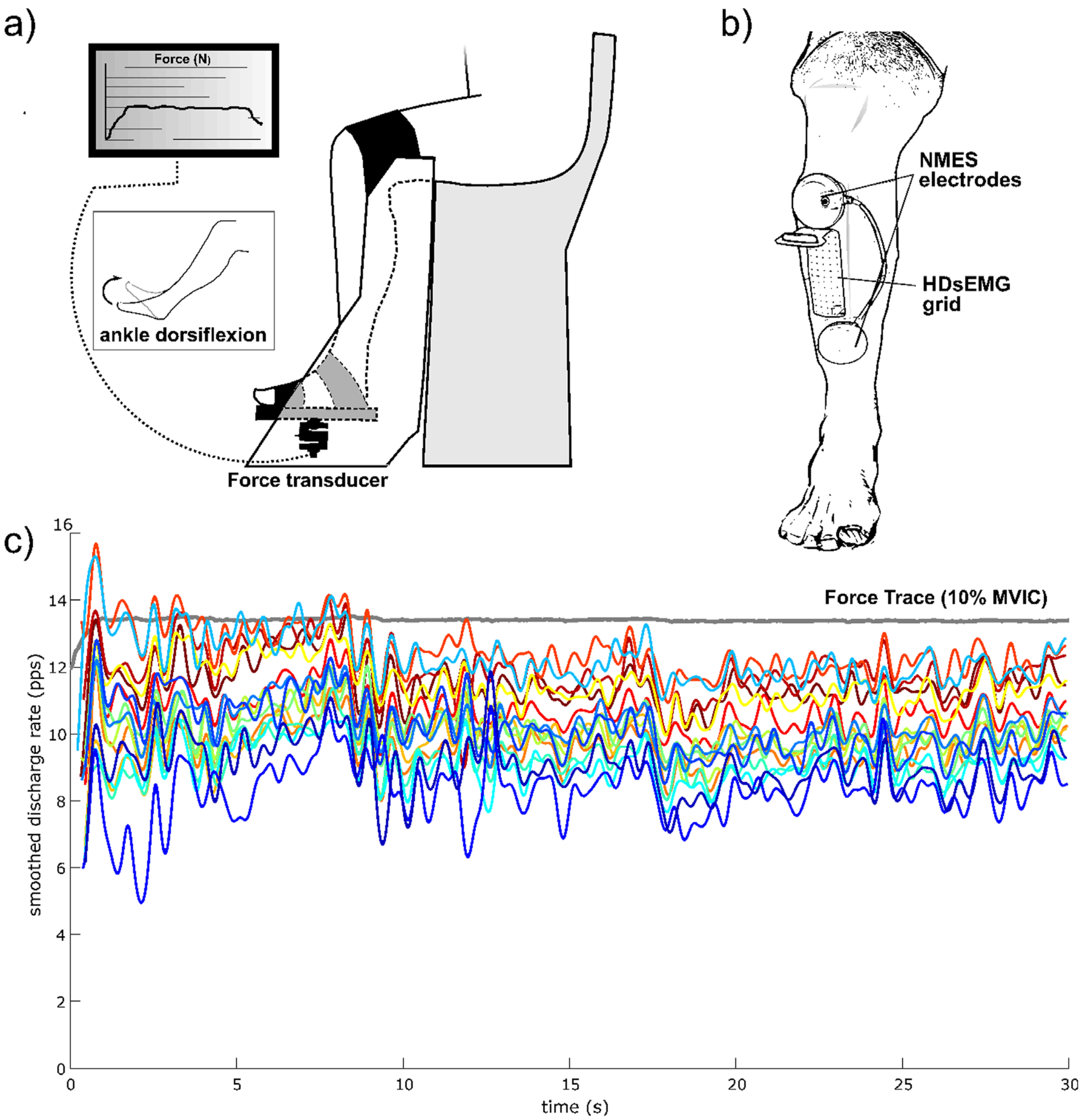

FIGURE 2
Experimental setup and HDsEMG recording. **(a)** Participants' position on the dynamometer; **(b)** NMES electrodes and HDsEMG positioning on the TA muscle; **(c)** Example of smoothed discharge rate of all identified MUs of one trial, from one participant, during the steady force-matching isometric contraction at 10% MVIC.

Motor unit decomposition and analysis

Then, HDsEMG signals were decomposed into individual MU discharge times using a validated convolutive blind source separation method (Holobar and Zazula, 2007), which was implemented in a MATLAB (R2022a; The MathWorks, Natick, MA) tool (v. 4.9; DEMUSE; The University of Maribor, Slovenia). The discharge times of individual MUs were then converted into binary spike-trains, which were then visually inspected by the investigator to remove MUs showing a pulse-to-noise ratio (PNR) ≤30 dB or an inter-spike time interval higher than 2 s (Holobar and Farina, 2014). MUs were tracked across conditions using a widely validated procedure (Martinez-Valdes et al., 2017). To examine the discharge characteristics of the identified MUs the average MU discharge rate

(DR) and the variability for the Inter-spike Interval (ISI_{var}) were estimated during the 20 s time window of the steady force-matching contraction that was selected for computing the $Force_{CoV}$.

Intramuscular coherence (IMC)

A coherence analysis was performed on cumulative spike trains (i.e., index of the neural drive to the muscle; CSTs). Specifically, intramuscular coherence (IMC) was estimated by cross-correlating CSTs from increasing groups of MUs (e.g., eight identified MUs were pooled within two groups including up to four MUs each) using a Welsh periodogram with non-overlapping 1 s Hanning windows. The number of MUs in each of the two groups varied from 1 to the maximum number (half of the total number of identified MUs). One hundred random permutations of the identified MUs were performed for each iteration, and the average of all permutations was extracted and used for further analysis. The coherence profile was estimated within the full-frequency bandwidth (Farina et al., 2017). The coherence in each frequency band was estimated as the integral of the coherence estimates within delta (1–5 Hz), alpha (6–12 Hz), and beta (15–30 Hz) bands. The average coherence in the frequency range 100–250 Hz was set as the *bias* level and therefore subtracted from the analyses of coherence profiles (Del Vecchio et al., 2019b). To compare IMC across limbs and groups, we considered a minimum of six MUs for each submaximal isometric task. All seventeen subjects had at least six matched Mus for each isometric task. The Fisher "z-transform" was applied to the coherence estimates C(f) to obtain a normally distributed variable Z(f), as illustrated in Equation 1 (Halliday and Rosenberg, 2000).

$$Z(f) = \sqrt{2n}\, tanh^{-1}\sqrt{C(f)} \quad (1)$$

Where n represents the number of time segments that were used for the analysis.

pCSI

The proportion of common synaptic input (pCSI) received by spinal motoneurons was estimated by computing the slope (rate of change) of the relation between average coherence values in the delta band and the number of identified MUs (Farina et al., 2017). This analysis was performed on the low-frequency delta bandwidth (1–5 Hz), as it has been shown to be the main determinant of the force output (Farina et al., 2017). The pCSI reflects the fraction of the total input that is shared between motoneurons and that is unrelated with the independent components of the synaptic input.

Statistical analysis

Statistical analysis was performed using IBM SPSS 24.0 (IBM Corp., Armonk, NY, United States) and Jamovi 2.2.5 (The Jamovi project, Sydney, Australia). The Shapiro-Wilk test was used to assess the normality of distribution of the reported variables. When variables did not show a normal distribution, these were log-transformed to meet the assumption of normality before applying the statistical test. To analyze differences in DR and ISIvar of MUs, separate linear mixed-effects models (GAMLj pack: General Analyses for the Linear Model in Jamovi) were used to account for the hierarchical structure of the data (Tenan et al., 2014; Héroux, 2021). Condition (Baseline, ISO, NMES, NMES + ISO) was considered as a fixed effect while participant-specific variability was modeled with random intercepts, and restricted maximum likelihood estimation (REML) was applied to fit the models. The analysis was performed using only tracked MUs which were identified in all four conditions. Significance of the fixed effect was assessed by an F-test using Satterthwaite's approximation for the degrees of freedom. A Bonferroni-Holm correction was applied to account for multiple comparisons. A one-way repeated measurement ANOVA was used to detect differences in $Force_{CoV}$, pCSI, and IMC within the delta, alpha, and beta bands between conditions (Baseline, ISO, NMES, NMES + ISO). The same analysis was performed to evaluate differences between the three MVIC assessments (before, half and end). The Mauchly's test was used to assess sphericity of the analyzed variables, and the Greenhouse-Geisser correction was applied if sphericity was violated. A Bonferroni-Holm correction was applied when needed to account for multiple comparisons. In addition, to investigate the relationship between Force CoV (dependent variable) and pCSI, DR, ISIvar, and IMC in the different frequency bands, linear mixed-effects models were used. These models included subject as a random effect (intercept) to account for repeated measures design. Model fit and power were evaluated using marginal R^2 (variance explained by fixed effects) and conditional R^2 (variance explained by both fixed and random effects). Residual plots were inspected to assess assumptions of linearity and homoscedasticity. For all statistical tests, the significance level was set to 0.05. Data are reported as means ± SD unless stated elsewhere.

Results

MVIC and force steadiness

The repeated measures ANOVA revealed no significant differences between the MVIC assessments (before: 222 ± 81 N; half: 219 ± 78 N; end: 220 ± 82 N) suggesting that no fatigue had arisen throughout the experimental protocol.

The repeated measures ANOVA indicated a significant effect of Condition ($F = 5.34$; $\eta_p^2 = 0.25$; $P = 0.003$). Post-hoc tests showed a decrease in $Force_{CoV}$ following NMES + ISO (0.93% ± 0.30%) compared to baseline (1.19% ± 0.41%; −21.8%; $d = 0.66$; $P = 0.013$; Confidence Interval (CI) [−0.393, −0.109]), ISO (1.04% ± 0.35%; -10.6%; $d = 0.35$; $P = 0.02$; CI [−0.199, −0.019]) and NMES (1.12% ± 0.46%; −16.9%; d ≈ 0.55; $P = 0.001$; CI [−0.333, −0.045]). Data are illustrated in Figure 3 and reported in Table 1.

Motor unit properties

Number of identified MUs

A total of 1009 MUs were identified in the TA with an average of 59.3 ± 14.8 MUs per participant. Of all MUs, 220 MUs (about 22%) were tracked across all four conditions (Baseline, ISO, NMES, NMES + ISO), with an average number of 12.9 ± 3.3 tracked MUs per participant.

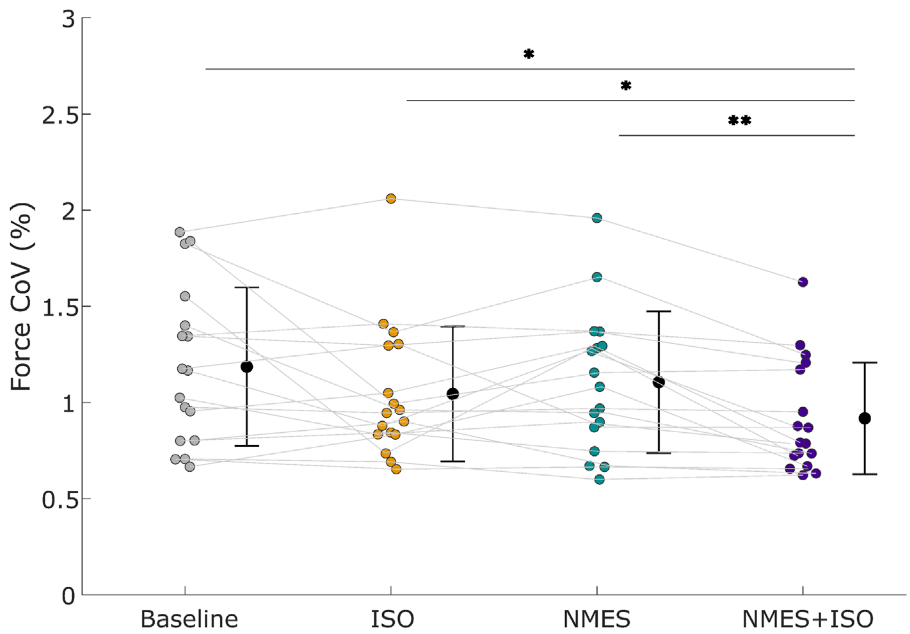

FIGURE 3
Force steadiness. Force coefficient of variation ($Force_{CoV}$) across different conditions. Black circles and error bars indicate means ± SD. Individual participant data (*n* = 17 participants) are presented as different color dots for each experimental condition. Mean values are represented by a black dot with SD black bars. *$P < 0.05$, **$P < 0.01$.

TABLE 1 Data and statistical results from force and electromyographic recordings.

	$Force_{COV}$ (%)	DR (pps)	ISIvar (%)	IMC (z-score)			pCSI
				Delta	Alpha	Beta	
Baseline	1.19 ± 0.41	10.09 ± 0.98	10.55 ± 2.02	6.05 ± 0.98	2.44 ± 1.29	1.48 ± 0.95	0.44 ± 0.13
ISO	1.04 ± 0.35	10.44 ± 1.10	10.90 ± 1.45	6.37 ± 0.95	2.65 ± 1.08	1.66 ± 0.67	0.46 ± 0.13
NMES	1.12 ± 0.46	10.38 ± 1.24	11.00 ± 2.14	6.07 ± 1.21	2.42 ± 1.18	1.56 ± 0.79	0.44 ± 0.14
NMES + ISO	0.93 ± 0.31	10.51 ± 1.02	11.36 ± 3.11	6.37 ± 1.03	2.42 ± 1.09	1.53 ± 0.56	0.50 ± 0.14
Baseline vs. ISO (P-value)	(0.09)	**(0.002)**	(0.98)	(0.11)	(0.15)	(0.12)	(0.22)
Baseline vs. NMES (P-value)	(0.42)	(0.06)	(0.30)	(0.94)	(0.89)	(0.58)	(0.86)
Baseline vs. NMES + ISO (P-value)	**(0.01)**	**(0.001)**	(0.83)	(0.12)	(0.85)	(0.50)	**(0.001)**
ISO vs. NMES (P-value)	(0.19)	(0.28)	(0.31)	(0.21)	(0.14)	(0.29)	(0.33)
ISO vs. NMES + ISO (P-value)	**(0.02)**	(0.26)	(0.85)	(0.99)	(0.08)	(0.18)	**(0.03)**
NMES vs. NMES + ISO (P-value)	**(0.001)**	**(0.03)**	(0.42)	(0.09)	(0.98)	(0.18)	**(0.02)**

Data are presented as group means ± standard deviation. In bold statistically significant differences between conditions.

DR and ISIvar

The fixed-effects omnibus test indicated a significant effect of Condition (F = 9.52; P < 0.001) on MU DR. Post-hoc analysis showed that MU DR was significantly increased following NMES + ISO (10.51 ± 1.02 pps) compared to both baseline (10.09 ± 0.98 pps, +4.2%, *d* = 0.52, P = 0.001, CI [0.365, 0.810]) and NMES (10.38 ± 1.24 pps, +1.25%, *d* = 0.26, P = 0.038, CI [0.022, 0.562]). Moreover, MU DR was significantly greater after ISO (10.44 ± 1.10 pps) compared to baseline (10.09 ± 0.98 pps, +3.5%, *d* = 0.37, P = 0.002, CI [0.193, 0.637]). There was no significant main effect of Condition (F = 0.47; P = 0.701) on ISIvar. Data are illustrated in Figure 4 and reported in Table 1.

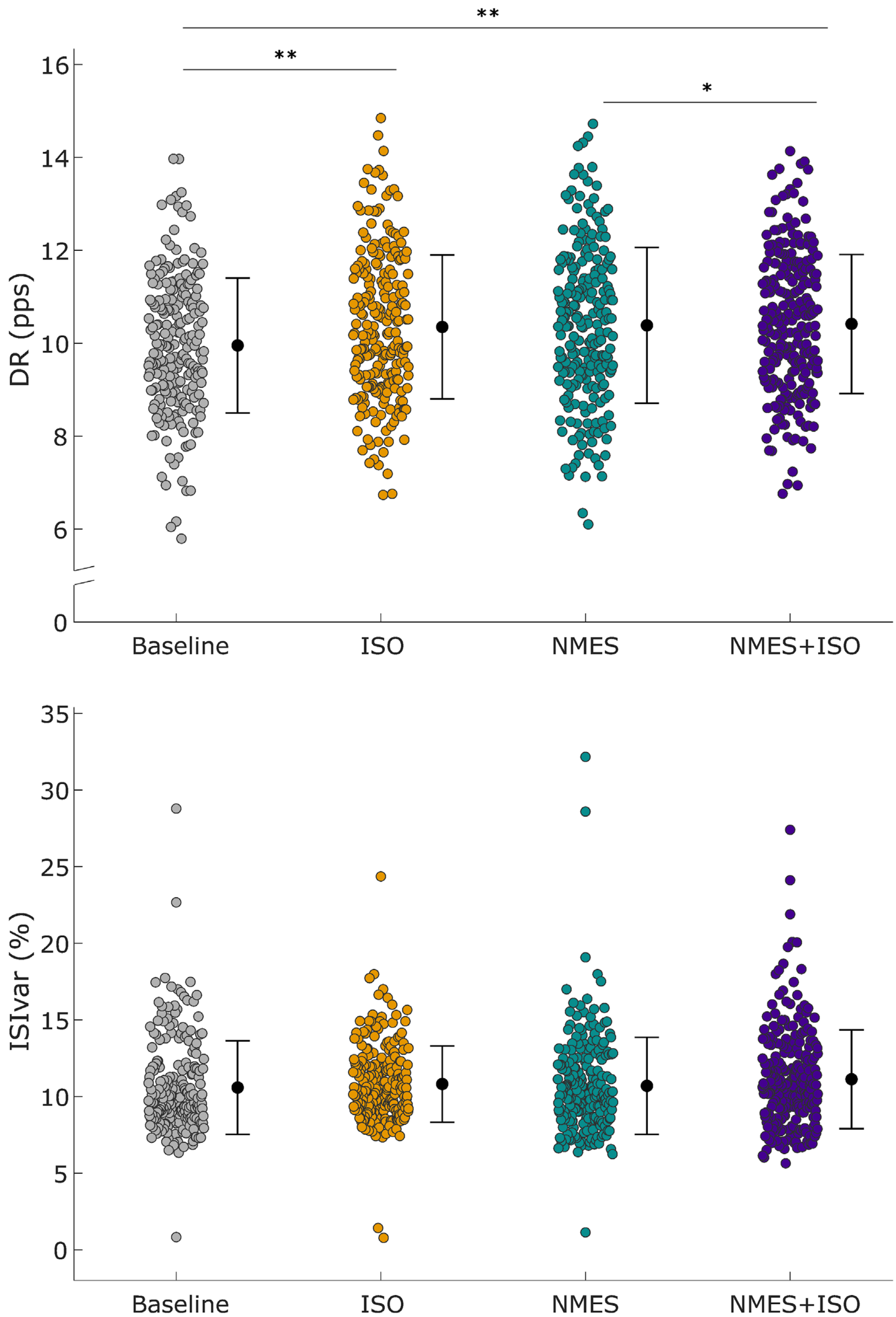

FIGURE 4
Differences in motor unit discharge rate (DR) and inter-spike variability (ISIvar). Upper panel: Distribution of DR of all MUs that were identified in the TA muscle. DR values are represented by using different color-filled circles for each experimental condition. Lower panel: Distribution of ISIvar of all identified MUs. ISIvar values are represented using different color-filled circles for each experimental condition. Mean values are represented by a black dot with SD black bars. $^{*}P < 0.05$, $^{**}P < 0.01$.

IMC

Profiles of intramuscular coherence for each experimental condition are illustrated in Figure 5. When analyzing IMC within each frequency band, no significant differences emerged for any frequency band following the experimental conditions. Data are reported in Table 1.

pCSI

There was a significant effect of Condition (F = 3.39; η_p^2 = 0.18; P = 0.025) for pCSI. Post-hoc analyses showed a significantly higher pCSI of the TA muscle after the NMES + ISO condition (0.50 ± 0.14) compared to baseline (0.44 ± 0.13; *d* = 0.45, P = 0.001, CI [0.028, 0.090]), ISO (0.46 ± 0.13; *d* = 0.22, P = 0.037, CI [0.002, 0.058]) and NMES (0.44 ± 0.13; *d* = 0.40, P = 0.020, CI [0.010, 0.098]) conditions (Figure 6).

Linear regression analysis

When evaluating the relationship between pCSI and $Force_{CoV}$, the linear mixed-effects model revealed a statistically significant model (F(1,42.9) = 16.40, P < 0.001). The marginal R^2 was 0.26 suggesting that pCSI accounts for approximately 26% of the variance in $Force_{CoV}$, while the while the conditional R^2 was 0.61, reflecting additional variance explained by random effects. The regression equation was $Y = -1.31^*X + 1.07 + \varepsilon$. The 95% CI for the slope ranged from −2.07 to −0.72, suggesting that for each unit of increase in pCSI, $Force_{CoV}$ decreases by about 0.72–2.07 units.

When considering the relationship between IMC in the delta band and $Force_{CoV}$, the analysis revealed a statistically significant model (F(1,66.6) = 4.44, P = 0.039). The marginal R^2 was 0.07 and the conditional R^2 was 0.62. The regression equation was $Y = -0.09^*X + 0.07 + \varepsilon$, while the 95% CI for the slope ranged from −0.18 to −0.01 suggesting that, for each unit of increase in IMC in the delta band, $Force_{CoV}$ decreases by about 0.01–0.18 units. None of the other independent variables that were evaluated exhibited a statistically significant linear mixed-effects model. Data are presented in Figure 7.

Discussion

The main finding of this study was that NMES + ISO significantly increased motor unit discharge rate (DR) in the TA muscle during low-intensity ankle dorsi flexions, compared to baseline levels and passive NMES. Furthermore, pCSI was greater following NMES + ISO compared to baseline, NMES and voluntary isometric contractions alone. Finally, NMES+ led to a reduction in the $Force_{CoV}$ compared to all the experimental conditions, indicating improved force steadiness. No differences between conditions were found in the IMC in different frequency bands. These results partially confirm our hypothesis and highlight the potential of NMES+ to enhance motor unit firing rates and optimize force control, particularly through the modulation of common synaptic inputs.

The significant increase in DR following NMES+ aligns with previous research indicating that NMES can enhance motor unit recruitment and firing rates (Borzuola et al., 2023b), although the present study revealed this change also at lower force levels (i.e. 10% MVIC). This likely results from the combined effects of voluntary effort and superimposed NMES, facilitating greater motor unit activation and leading to a more substantial neural input to the muscles compared to NMES and voluntary contraction alone. The enhanced DR might ensure that MUs fire at an optimal rate to maintain force output, possibly contributing to improved muscle force production and steadiness.

The significant increase in pCSI that was observed in this study reflects the degree of synchronized input received by motor neurons, which is crucial for coordinated muscle contractions and force control (Farina and Negro, 2015). An increased pCSI indicates enhanced synchronization of motor unit discharge, improving the precision and stability of force production. This enhancement might be attributed to the integrated effect of voluntary contraction and electrical stimuli, which is likely to promote the recruitment of additional motor units, thereby increasing overall synaptic input to the motor neuron pool and leading to greater synchronization of motor unit activity. Moreover, some researchers suggested that increased pCSI acts as a filter by attenuating independent synaptic noise (Farina et al., 2014). This mechanism ensures that motor neurons receive consistent and coordinated signals, thus reducing force variability and improving steadiness (Negro et al., 2009). This synchronization is particularly important during low-force tasks, in which small variations in neural input can lead to noticeable fluctuations in force production (Enoka and Farina, 2021).

The reduction in $Force_{CoV}$ following NMES+ indicates a relevant improvement in force steadiness, which is critical for performing precise motor tasks (Enoka and Duchateau, 2017). The improved force steadiness can be explained by an enhanced synchronization of motor unit activity, whereas increased pCSI leads to coordinated firing of motor units, reducing variability in force production (Farina and Negro, 2015). This association was confirmed by the linear mixed-effects model analysis that was conducted in the present study, which revealed a moderate relationship between $Force_{CoV}$ and pCSI. As previously discussed, the recruitment of additional motor units during NMES+ may further contribute to force steadiness by distributing the workload across a larger pool of motor units, reducing the relative load on individual motor units and enhancing overall muscle performance (Gregory and Bickel, 2005).

The IMC within the delta, alpha and beta bands were similar following the four experimental conditions. The absence of differences in the delta band does not agree with our hypothesis as an increase in the strength of the common synaptic input in the low frequency band was expected, with a similar trend as pCSI. However, while both pCSI and IMC in the delta bands both measure aspects of motor unit synchronization, each of these variables focuses on different mechanisms of neural control. pCSI represents the proportion of input that motor neurons receive from common sources, reflecting the degree of shared synaptic input among motor neuron, whereas IMC in the delta band highlights low-frequency coordination of motor units but may not directly indicate the source or proportion of synaptic input (Del Vecchio et al., 2023; Hug et al., 2023). The observed increase in pCSI with no change in delta band IMC in this study suggests that NMES + ISO enhances force

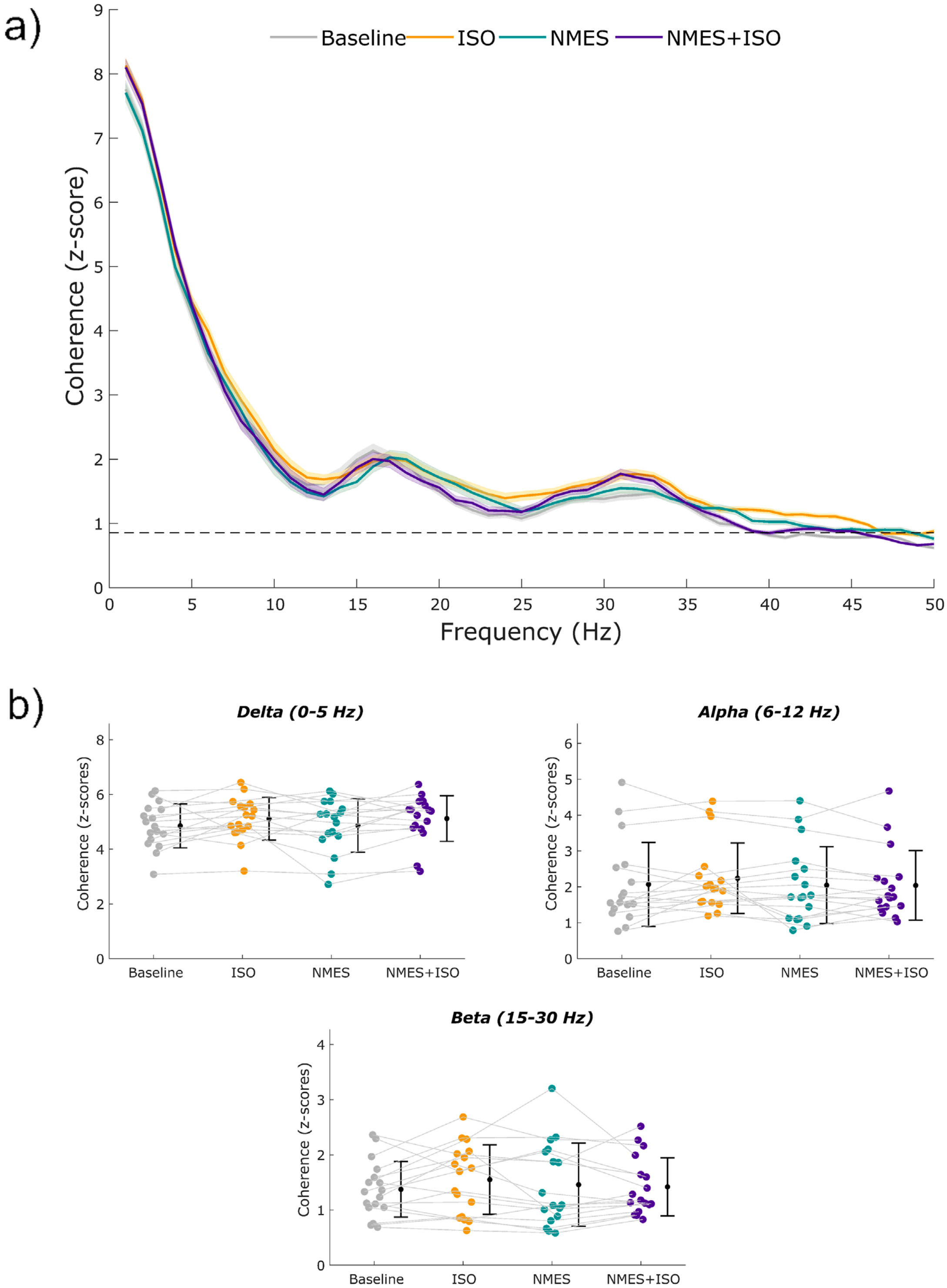

FIGURE 5
Profiles of intramuscular coherence (IMC) and IMC across frequency bands. **(a)** Mean IMC across MUs of the TA during a sustained contraction at 10% MVIC. The shaded areas represent the standard error of the mean. **(b)** Individual values of intramuscular coherence within the delta (1–5 Hz), alpha (6–12 Hz), and beta (15–30 Hz) bands. Participant-specific values are represented using color-filled circles for each experimental condition. Mean coherence values are represented by a black dot with SD black bars.

steadiness through increased proportion of common synaptic input with respect to independent synaptic input, rather than altering low-frequency coherence patterns. Nevertheless, we found a weak but significant linear association between $Force_{CoV}$ and IMC in the delta band, reinforcing the established view that increased coherence in low-frequency bandwidths might enhance force steadiness.

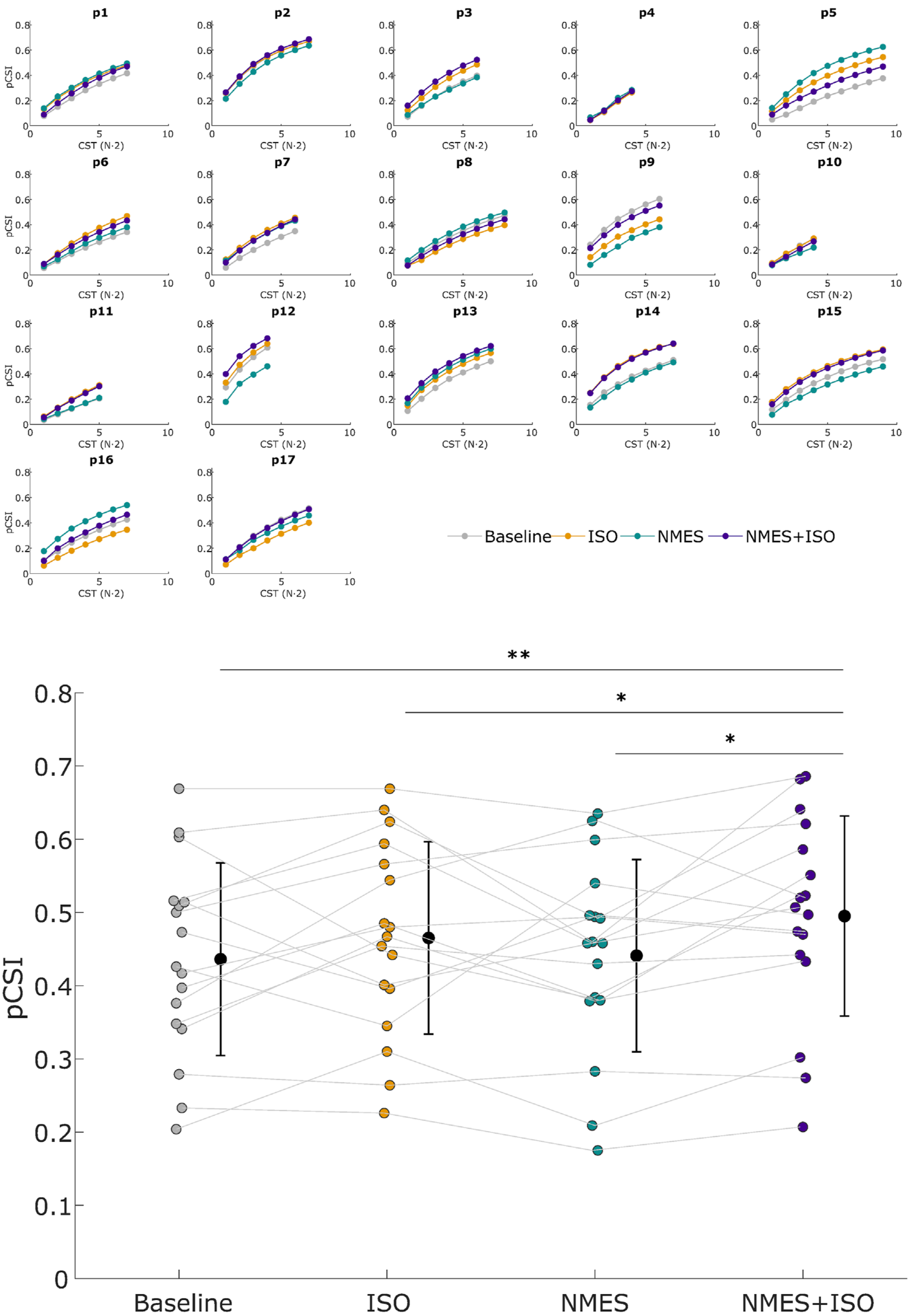

FIGURE 6
Proportion of common synaptic input (pCSI). Upper panel: pCSI of all subjects across all conditions. pCSI was derived from coherence between Cumulative Spike Trains (CST), with CST (N·2) referring to the number of pairwise combinations of MUs spike trains used for the calculation (N = number of MUs). Lower panel: Mean pCSI of each experimental condition. Participant-specific values are represented using color-filled circles for each experimental condition. Mean pCSI values are represented by a black dot with SD black bars. *P < 0.05, **P < 0.01.

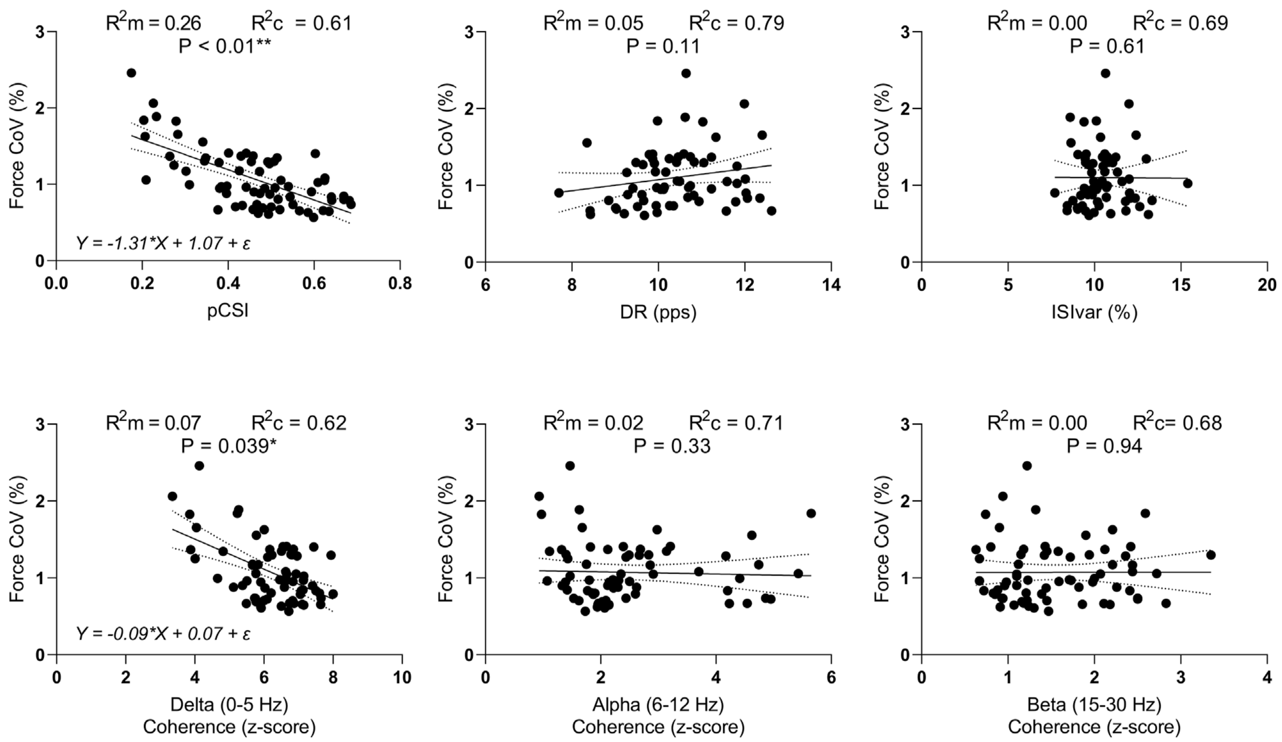

FIGURE 7
Linear mixed-effects models. Scatterplots of $Force_{CoV}$ in function of pCSI, DR, ISIvar, and IMC in the delta, alpha, and beta bands. R^2m = marginal R-squared; R^2c = conditional R-squared $^*P < 0.05$, $^{**}P < 0.01$.

Some authors have indicated that neural oscillation in the alpha band are associated with physiological tremor, which can ultimately affect force steadiness and generation capacity (Enoka and Farina, 2021; Lecce et al., 2023; Nuccio et al., 2024). Alteration of afferent inputs and spinal reflex excitability appears to be associated with such involuntary synaptic noise, which characterize alpha oscillation (Nuccio et al., 2024). Nonetheless, despite previous studies which indicated an acute effect of NMES+ on spinal and supraspinal activity (Borzuola et al., 2020; Borzuola et al., 2023c), no acute changes in the IMC in the alpha band emerged after the experimental conditions. This suggests that short bouts of exercise, including NMES+, might not be sufficient to induce the neural plasticity that is required to significantly alter the synchronized neural activity in the alpha band. An alternative explanation might involve the differences in cortico-motoneuronal connectivity between the tibialis anterior (TA) and other muscles (Lauber et al., 2018). For instance, the effects of NMES+ on spinal excitability were commonly evaluated in the soleus muscle (Borzuola et al., 2020; Scalia et al., 2023; Scalia et al., 2024), which primarily relies on spinal mechanisms (Lagerquist et al., 2012). As a result, this muscle might show larger alpha band oscillations compared to the tibialis anterior (TA), which has stronger cortico-motoneuronal connectivity and potentially greater supraspinal control (Lauber et al., 2018).

IMC in the beta bands appears to be linked to corticospinal transmission and motor control (Watanabe and Kohn, 2015). However, some authors indicated that, as muscles act as low-pass filters, beta inputs are thought to have only limited influence on voluntary force production (Farina and Negro, 2015). Specifically, recent evidence revealed that small changes in muscle force can only be determined by bursts of beta activity which, due to its irregular nature, may only have a minimal impact on controlling voluntary force (Zicher et al., 2023). The findings of the present study are in line with these results as no changes in beta IMC was found after the experimental conditions.

The effects of NMES+ on force control and neural drive are mediated by both peripheral and central mechanisms. Peripherally, NMES+ induces muscle contractions through direct stimulation of motor axons (Collins, 2007). This direct activation bypasses the usual voluntary pathways and can lead to greater motor unit recruitment, including the MUs that are not typically recruited during voluntary contractions (Bickel et al., 2011). Centrally, NMES+ can induce plastic changes in the neural pathways involved in motor control (Carson and Buick, 2021). The increased motor neuron excitability and synchronization that were found following NMES+ suggest that this intervention can modulate both spinal and supraspinal pathways. The facilitatory effects on spinal and cortical responses that were observed in previous studies (Borzuola et al., 2020; Borzuola et al., 2023c; Scalia et al., 2023) support this notion. These central adaptations likely contribute to the enhanced neural drive and improved force steadiness as indicated in the present study.

Improvements in force steadiness are crucial in rehabilitation settings for the recovery of fine motor skills, as well as in athletic contexts, where greater force steadiness can translate into improved precision and control during sports activities requiring fine motor coordination. The findings of the present study indicate that NMES+ could significantly enhance neural drive and improve force steadiness making it a valuable tool for rehabilitation and performance enhancement.

While this study provides valuable insights into the neuromuscular adaptations induced by NMES+, further research is needed to elucidate the underlying mechanisms fully. Longitudinal studies investigating the chronic effects of NMES+ on motor unit behavior and muscle performance would provide a more comprehensive understanding of its benefits. Exploring the effects of different NMES parameters, such as frequency, intensity, and duration, could help to optimize NMES protocols for various applications. Investigating the effects of NMES+ in different populations, including older adults and individuals with neuromuscular disorders, would also be valuable, as these populations may significantly benefit from the enhanced neural drive and improved force steadiness associated with NMES+. Moreover, understanding how NMES+ influences muscle function and force control in these groups could inform the development of tailored rehabilitation protocols.

This study has several limitations that should be considered. First, the sample size was relatively small. Although sample size was defined through an appropriate statistical power analysis based on preliminary data and previous study with similar experimental protocols, increasing the number of participants as well as involving different populations (i.e., older adults, individuals with neuromuscular impairments) could support the generalizability of the findings. Second, in this study a relatively low force level was used. The level for force was chosen, as suggested in previous research studies, to improve the accuracy of decomposition (Negro et al., 2009). However, at 10% MVIC it could be argued that only a subset of MUs could be analyzed thus hindering the ability to evaluate coherence and neural drive in a larger cohort of MUs. Finally, the study did not explore the underlying molecular and cellular mechanisms driving the observed neuromuscular adaptations. As suggested by some authors (Al-Majed et al., 2004; Guo et al., 2021), assessing the molecular and cellular changes in muscle and neural tissues in response to NMES could provide deeper insights into the mechanisms driving the observed adaptations, such as how NMES+ influences neuromuscular junction plasticity, axonal integrity, muscle fiber type distribution, and intracellular signaling pathways involved in muscle growth and adaptation. Further investigation into these mechanisms could provide a deeper understanding of how NMES+ influences muscle and neural function at a fundamental level.

In conclusion, this study demonstrates that NMES+ significantly enhances motor unit discharge rate and the proportion of common synaptic input to spinal motoneurons, leading to improved force steadiness. These findings suggest that NMES+ can optimize neural drive and motor unit synchronization, contributing to more efficient and stable force production. The enhanced force control observed following NMES+ has important implications for rehabilitation and performance enhancement, providing a foundation for developing more effective NMES-based interventions. Further research is needed to explore the long-term effects and optimize the application of NMES+ across different populations and settings.

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 University of Rome Foro Italico. 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.

Author contributions

RB: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review and editing. SN: Conceptualization, Formal Analysis, Investigation, Methodology, Validation, Writing – original draft, Writing – review and editing. AD: Conceptualization, Formal Analysis, Methodology, Writing – original draft, Writing – review and editing. IB: Conceptualization, Supervision, Writing – original draft, Writing – review and editing. FF: Conceptualization, Supervision, Writing – original draft, Writing – review and editing. GD: Conceptualization, Supervision, Writing – original draft, Writing – review and editing. AM: Conceptualization, Funding acquisition, Project administration, Resources, 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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Cardiopulmonary and hemodynamic responses to *Baduanjin* exercise and cycle ergometer exercise among chronic heart failure patients: a comparison

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Objective: *Baduanjin* is a traditional Chinese exercise and serves as an alternative to conventional cardiac rehabilitation in China. In this study, we compare the cardiopulmonary and hemodynamic responses of *Baduanjin* to those of cycle ergometer exercise in chronic heart failure patients.
Methods: For this cross-sectional study design, following baseline data collection, participants underwent a series of tests including impedance cardiography (ICG) and a maximal cardiopulmonary exercise test (CPET) to determine peak exercise capacity. Participants then engaged in 9-min of *Baduanjin* exercise. The average oxygen consumption (EqualVO_2) during *Baduanjin* was calculated. Participants then engaged 9 min of constant-load cycling at 60 rpm at an intensity which elicited the EqualVO_2. Cardiopulmonary and hemodynamic data were measured continuously during both Baduanjin and cycling exercise.
Results: A total of 30 participants were included. Although *Baduanjin* and cycling exercise showed similar VO_2 levels (8.2 ± 1.3 vs. 8.4 ± 1.4, p = 0.339, respectively), there was a bimodal distribution during *Baduanjin* exercise compared to a unimodal distribution during cycling exercise. Compared to conventional cycling, *Baduanjin* demonstrated lower respiratory burden which is associated with greater ventilatory efficiency as evidenced by lower respiratory rate values (p = 0.003), minute ventilation (p < 0.001), end-tidal carbon dioxide pressure (p < 0.001), and minute ventilation to carbon dioxide production ratio (p < 0.001). In terms of hemodynamic response, *Baduanjin* is demonstrated significantly lower cardiac output (p = 0.017) and elevated arterial-venous oxygen difference (p = 0.036).
Conclusion: Our study offers novel insight into the cardiopulmonary and hemodynamic differences between *Baduanjin* and cycling when performed

at consistent intensity levels. *Baduanjin* demonstrates an intermittent intensity pattern and increased peripheral oxygen utilization, which is attributed to more pronounced muscle activation. Furthermore, *Baduanjin* has been linked to a reduction in both cardiac and respiratory burdens.

KEYWORDS

chronic heart failure, *Baduanjin*, cycle ergometer exercise, cardiopulmonary response, hemodynamic response

1 Introduction

Comprehensive exercise-based cardiac rehabilitation (CR) is a Class 1A recommend therapy for patients with chronic heart failure (HF) (Pelliccia et al., 2020; McDonagh et al., 2023; Ponikowski et al., 2016). Patients with HF who engage in exercise based CR demonstrate improved quality of life, reduced hospitalization, and lower mortality rates (Molloy et al., 2024-03; Bozkurt et al., 2021). However, these CR programs are underutilized, with participation rates ranging from 10% to 30% worldwide (Beatty et al., 2023; Ozemek and Squires, 2021; Balady et al., 2011; Grace et al., 2008-10; Sanderson et al., 2003). In China, primary barriers to participation in CR have been identified and include resource scarcity and limited healthcare funding (Zhang et al., 2023; Zhang et al.). Therefore, solutions to improving CR uptake HF patients must be tailored to these barriers. In addition to overcoming the above noted barriers, resource-adapted CR programs must be sensitive to the cultural context in which they are embedded.

Commonly accepted as beneficial to one's health, traditional Chinese exercise is a form of exercise embedded within communities throughout different regions of mainland China for nearly sixteen centuries (Wang et al., 2016; Health Qigong Management Center, 2003). Thus, this equipment-free exercise may be ideal for hospitals with limited resources (Sun, 2015), as well as patients, because it can be practiced at home, reducing barriers such as weather, transportation, and cost (Deka et al., 2017; Conraads et al., 2012). *Baduanjin*, translated as "eight silken movements", is one form of traditional Chinese exercise which has been practiced for over 1,000 years. It is characterized by slow movements (physical training) synchronized with meditation (mindfulness-based training) and regulated breathing (respiratory training) to achieve a harmonious flow of energy (*qi*) in the body (Zou et al., 2017). *Baduanjin* is easy to learn, with minimal physical or cognitive demands, as it only entails eight simple movements based on traditional Chinese medicine theory. Moreover, it is an adaptable form of exercise that can be practiced in any location, at any time, without any special equipment, and requires minimal time investment (Chen et al., 2022). Hence, it is easily incorporated into daily routines and could easily be integrated into a comprehensive CR program.

Moderate intensity continuous aerobic exercise is the most widely researched type of exercise in CR and has been shown to be efficient, safe, and well-tolerated by patients with HF (Molloy et al., 2024-03). Historically, *Baduanjin* has been considered light-intensity exercise, regardless of the individual's physical fitness. In contrast, our group has recently demonstrated that *Baduanjin* exercise falls within the moderate intensity aerobic exercise classification, based on the percent of measured oxygen consumption (VO_2), particularly for deconditioned patients such as those with HF (Chen et al., 2020). However, to date there is a lack of evidence comparing *Baduanjin* with conventional moderate intensity aerobic exercise such as cycle ergometer exercise, among CHF patients. This highlights a key knowledge gap for referring physicians. Therefore, the purpose of this study was to 1) compare the cardiopulmonary responses between *Baduanjin* and cycle ergometer exercise; and 2) compare the hemodynamic responses between *Baduanjin* and cycle ergometer exercise, in patients with CHF.

2 Methods

2.1 Participants

We utilized a cross-sectional design to recruit patients from the chronic disease management cohort at the Heart Failure Center at Guangdong Provincial Hospital of Chinese Medicine, between June 2023 and January 2024. Eligible participants included stable heart failure patients aged 18–85 years, classified as New York Heart Association (NYHA) class II or III, who had practiced *Baduanjin* for at least 3 months. The exclusion criteria for the trial included conditions that contraindicate exercise testing. Inclusion and exclusion criteria details are listed in Supplementary S1.

2.2 Data collection

2.2.1 Procedures, equipment, and requirements

Our study was conducted in the CR department at the Heart Failure Center at Guangdong Provincial Hospital of Chinese Medicine. The main process of this study included three steps (Figure 1). First, after collecting the baseline information (i.e., medical history, physical examination, anthropometric measurements, and echocardiograph data), we conducted a maximal cardiopulmonary exercise test to determine individual maximal exercise capacity (e.g., VO_2 peak). Second, we conducted a real-time monitoring test of cardiopulmonary and hemodynamic metrics during *Baduanjin* exercise. Third, we conducted a real-time monitoring test of the same cardiopulmonary and hemodynamic metrics during cycle ergometer exercise. Details of data collection were listed in Supplementary S2. All of the hemodynamic data collected and constructed by PhysioFlow are listed below with their clinical meanings listed in Table 1.

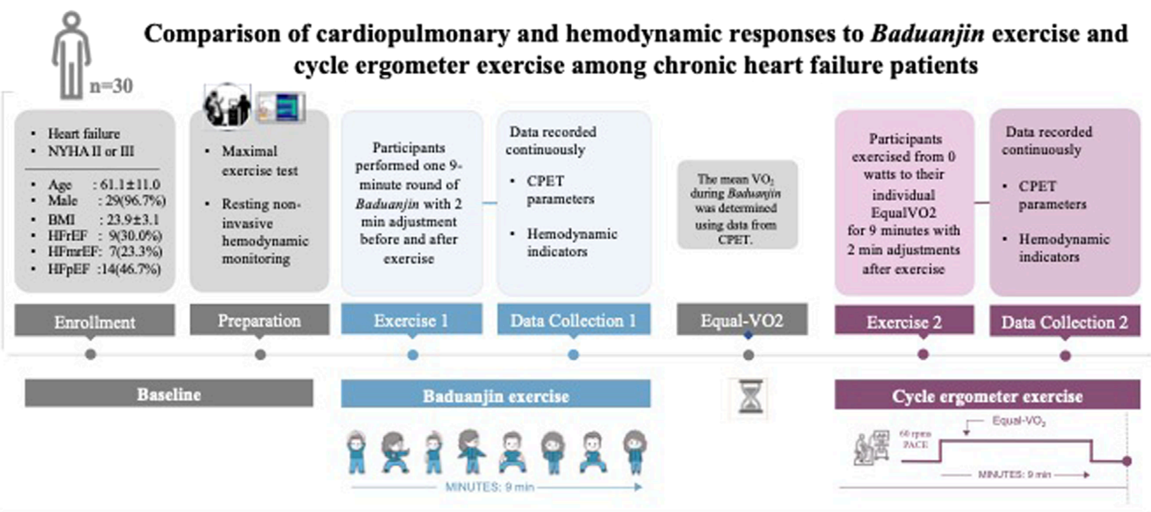

FIGURE 1
Study procedures Legends: NYHA, New York Heart Association; BMI, body mass index; HFrEF, heart failure with reduced ejection fraction; HFmrEF, heart failure with middle ranged ejection fraction; HFpEF, heart failure with perceived ejection fraction; VO_2, volume of Oxygen; EqualVO2, the average oxygen consumption; CPET, cardiopulmonary exercise testing.

2.3 Statistical analysis

We adopted statistical analyses similar to those described in our previous work (Chen et al., 2020). Data from the maximal exercise test as well as the average cardiorespiratory and hemodynamic parameters obtained during *Baduanjin* exercise and cycle ergometer exercise were summarized as mean and standard deviation (SD). The mean VO_2 and HR collected during *Baduanjin* exercise and cycle ergometer exercise were compared to individual maximum exercise capacity measured during the cardiopulmonary exercise test and reported as a percentage (expressed as $\%VO_{2max}$ and $\%HR_{max}$). In order to categorize the exercise intensity, we referred to a position statement on exercise intensity terminology (Norton et al., 2010). Moreover, in order to explore the cardiopulmonary response patterns throughout the session, all cardiopulmonary parameters were summarized at 10-s intervals as mean ± SD, and plotted over time. All statistical procedures were performed with SPSS (version 18.0, Chicago, IL, USA).

3 Results

3.1 Participant characteristics

The participants (n = 30, 29 male and 1 female, ages 61.1 ± 11.0 years) had a clinical history of heart failure for a median of 3.5 years and were classified as either New York Heart Association (NYHA) II (n = 19, 63.3%) or NYHA III (n = 11, 36.7%). The mean left ventricular ejection fraction (LVEF) was 49.4% ± 13.4%, and they were either with reduced LVEF (HFrEF, n = 9, 30.0%), middle ranged LVEF (HFmrEF, n = 7, 23.3%), or preserved LVEF n (HFpEF, n = 14, 46.7%). In addition, 96.7% of the participants (n = 29) had been taking β-blockers. Spirometry showed that 66.7% (n = 20) of participants had normal lung function; and 26.7% (n = 8), 3.3% (n = 1), and 3.3% (n = 1) showed restrictive, obstructive, and mixed pulmonary ventilatory dysfunction, respectively. Details on demographic and anthropometry characteristics, medical history, heart failure status, and comorbidities are presented in Table 2.

3.2 Results of maximum exercise tests and resting hemodynamic status

As shown in Table 3, the results of the maximum exercise test revealed that the average RER of the 30 participants was 1.1 ± 0.1. All participants stopped testing due to leg muscle fatigue. VT was detected in all cases. Participants had an impaired exercise capacity with a mean VO_{2max} of 18.4 ± 4.2 mL/kg/min and demonstrated an elevated V_E/VCO_2 slope (30.8 ± 5.8).

The results of hemodynamic assessment indicated that this sample exhibited normal resting SV at 76.6 ± 14.4 mL, CO at 5.2 ± 1.1 L/min, $C_{(a-v)}O_2$ at 5.18 ± 2.2 mL/dL, and SVR with a median of 2,202.0 dyn·s/cm^5. Additional details regarding hemodynamic indices are presented in Table 3.

3.3 Comparison of the average cardiopulmonary and hemodynamic responses between *Baduanjin* exercise and cycle ergometer exercise

For the average cardiopulmonary responses (Table 4), the intensity of the two exercises are similar. During exercise, the average VO_2 during *Baduanjin* was 44.6% of VO_{2max} compared to 45.7% of VO_{2max} during cycling with no statistically significant difference between the two groups (8.2 ± 1.3 vs. 8.4 ± 1.4, $p = 0.339$, respectively; Table 4). For ventilatory and metabolic measures,

TABLE 1 Cardiopulmonary and hemodynamic parameters collected in this study.

A. Hemodynamic parameters			
	Parameters	Abbreviations	Clinical meaning
Left Ventricular Ejection Function	Stroke Volume	SV (mL)	The amount of blood pumped out by the heart with each contraction
	Cardiac Output	CO (L/min)	The amount of blood the heart pumps per minute, CO = SV*HR
Myocardial Contraction	Contractility Index	CI	An index to evaluate heart contraction function
Preload	Early Diastolic Filling Rate	EDFR (%)	The rate of left ventricular filling in the early diastolic phase
Afterload	Systemic Vascular Resistance	SVR (dyn·s/cm^5)	The systemic peripheral vessels' resistance to cardiac pumping
Peripheral oxygen utilization	Arterial-venous oxygen difference	$C_{(a-v)}O_2$ (mL/dL)	The difference in oxygen content between arterial and venous blood, reflecting the balance between oxygen delivery and consumption at the tissue level
B. Cardiopulmonary parameters			
Exercise Tolerance	Load	Load (W)	The load imposed on the body during exercise
	Maximum Oxygen Consumption	VO_{2max} (mL/kg/min)	The amount of oxygen consumed per minute during maximum intensity exercise
	Anaerobic Threshold	AT	The critical point at which anaerobic metabolism exceeds aerobic metabolism during exercise
	Respiratory Exchange Ratio	RER	The ratio of carbon dioxide production to oxygen consumption during respiration
	Metabolic Equivalents	METs	The multiple of metabolic rate during exercise compared to the rate at rest, indicating the relative energy metabolism level
Circulatory Function	Heart Rate	HR (bpm)	The number of heart beats per minute
	Maximum Heart Rate	HR_{max} (bpm)	The highest heart rate that can be achieved during maximum exercise intensity
	Oxygen Pulse	O_{2pulse} (ml/beat)	The amount of oxygen consumed by the body per heartbeat, calculated from VO_2/HR
	Systolic Blood Pressure	SBP (mmHg)	Blood pressure value during heart contraction
	Diastolic Blood Pressure	DBP (mmHg)	Blood pressure value during heart relaxation
	1-min Heart Rate Recovery	HRR_1 (bpm)	An index of parasympathetic activity
Ventilation Function	Minute Ventilation	V_E (L/min)	The amount of gas exhaled per minute
	Respiratory Rate	RR (bpm)	The number of breaths per minute
Gas Exchange	End-Tidal Carbon Dioxide Pressure	$P_{ET}CO_2$ (mmHg)	The carbon dioxide pressure in the terminal airways during exhalation
	Ventilation/Carbon Dioxide Production	V_E/VCO_2	The ratio of ventilation per carbon dioxide production
	Ventilation/Carbon Dioxide Production Slope	V_E/VCO_2 slope	The rate of increase in ventilation per unit increase in carbon dioxide production

TABLE 2 Participants' characteristics (n = 30).

Parameters	Mean ± SD or number (%) (n = 30)
Demographic and anthropometrical characteristics	
Male	29 (96.7%)
Age, years	61.1 ± 11.0
BMI	23.9 ± 3.1
Smoker	10 (33.3%)
Drinker	5 (16.7%)
Heart failure characteristics	
Heart failure history, years	3.5 (2.0, 6.0) ▲
NYHA classification	
- NYHA II	19 (63.3%)
- NYHA III	11 (36.7%)
LVEF classification	
-HFrEF	9 (30.0%)
-HFmrEF	7 (23.3%)
-HFpEF	14 (46.7%)
HR, bpm*	67.7 ± 10.8
SBP, mmHg*	108.8 ± 14.1
DBP, mmHg*	66.8 ± 9.8
NT-proBNP, pg/mL	394.0 (189.5,855.1) ▲
LVEF, %	49.4 ± 13.4
PASP, mmHg	25.2 ± 5.9
β-blocker users	29 (96.7%)
Comorbidities	
Coronary heart disease	21 (70.0%)
Previous MI	12 (40.0%)
Atrial fibrillation	6 (20.0%)
Hypertension	14 (46.7%)
Type 2 diabetes	14 (46.7%)
Chronic kidney disease	7 (23.3%)
Peripheral vascular disease	14 (46.7%)
Lung function	
FVC(%)	84.2 ± 11.7

(Continued on the following page)

TABLE 2 (*Continued*) Participants' characteristics.

Parameters	Mean ± SD or number (%) (n = 30)
FEV_1 (%)	84.9 ± 10.5
FEV_1/FVC(%)	105.2 ± 7.4
MVV(%)	96.6 ± 17.5

▲*Median* (P_{25}, P_{75}).
*Collected by the research nurse using an electronic sphygmomanometer as the baseline information.
Abbreviations: bpm, beats per minute; BMI, body mass index; DBP, diastolic blood pressure; EF, ejection fraction; FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity; HFrEF, heart failure with reduced ejection fraction; HFmrEF, heart failure with middle ranged ejection fraction; HFpEF, heart failure with perceived ejection fraction; HR, heart rate; LVEF, left ventricular ejection fraction; MI, myocardial infarction; MVV, maximum voluntary ventilation; NYHA, new york heart association; NT-proBNP, N-terminal B-type natriuretic peptide; PASP, pulmonary artery systolic pressure; SBP, systolic blood pressure; SD, standard deviation.

Baduanjin demonstrated significantly lower RR, V_E, $P_{ET}CO_2$, and $V_{E/}VCO_2$ (all $P < 0.001$), compared to the cycling exercise (Table 4).

For the average hemodynamic responses (Table 4), the average HR during *Baduanjin* exercise was significantly higher when compared to cycling (Table 4). Similarly, the peak heart rate during *Baduanjin* was significantly higher than during cycle exercise (93.9 bpm *versus* 86.0 bpm, $P < 0.001$, Table 4). Furthermore, our data indicate that SBP was significantly lower during *Baduanjin* compared to cycling while DBP was not different between the two activities (Table 4). In addition, the average SV and CO during *Baduanjin* exercise (SV: 64.5 ± 11.3 mL, CO: 5.2 ± 0.8 L/min) were both significantly lower than cycle exercise (SV: 70.9 ± 10.4 mL, $P = 0.001$; CO: 5.6 ± 0.9 L/min, $P = 0.017$). Moreover, significantly higher $C_{(a-v)}O_2$ ($P = 0.036$) and SVR ($P = 0.036$) were found during *Baduanjin* exercise than during cycle exercise.

3.4 Comparison of the real-time cardiopulmonary and hemodynamic responses between *Baduanjin* exercise and cycle ergometer exercise

The VO_2 responses are shown in Figures 2a,b. The VO_2 response curve of the cycle exercise is smooth with no obvious peaks. After the cycle ergometer exercise reached moderate intensity in the second minute, it leveled off and remained at moderate intensity. However, the fluctuations in VO_2 during the *Baduanjin* exercise are greater than those during the cycle exercise. The VO_2 responses exhibited a bimodal distribution during *Baduanjin*. The VO_2 increased during the first 3 min when a hemi-squat posture was involved (second posture), followed by a small drop in VO_2 after the transition to third posture. The intensity reached the second peak at the seventh minute during an additional two hemi-squat postures (fifth and seventh). It then dropped to the baseline during the resting phase. Overall, the absolute VO_2 response remained under the VT (Figure 2a) and the $\%VO_{2max}$ response remained within the moderate-intensity range (Figure 2b).

The HR responses are shown in Figures 2c,d. Similar to the VO2 response, the HR response was smooth during cycle exercise and exhibited a bimodal distribution with smaller magnitudes during *Baduanjin* (Figures 2c,d). Overall, the absolute HR response remained under the equivalent HR for the VT (Figure 2c) and the %HRmax response remained within the moderate-intensity range (Figure 2d).

Figure 3 shows the participants' ventilatory responses, including respiratory rate (Figure 3a), V_E (Figure 3b), $P_{ET}CO_2$ (Figure 3c), and V_E/VCO_2 (Figure 3d), during *Baduanjin* and cycling exercise. All three response lines from *Baduanjin* were lower than those from cycling.

Figure 4 illustrates the real-time hemodynamic responses during *Baduanjin* and cycle exercise. Overall, during cycling, hemodynamics initially increased from a low value and then stabilized, while *Baduanjin*'s SV and CO response lines showed fluctuations with time and movement changes. Compared to cycle exercise, the SV and CO response were both lower during *Baduanjin* (Figures 4a,b), while the $C_{(a-v)}O_2$ and SVR response was higher during *Baduanjin* (Figures 4c,d).

4 Discussion

This is the first study to compare chronic heart failure patients' cardiopulmonary and hemodynamic responses to *Baduanjin* exercise to their responses to constant-load moderate intensity cycle exercise. The intensity of both exercise modalities was calibrated according to VO_2, resulting in comparable average VO_2 for each modality. In terms of the cardiopulmonary response, *Baduanjin* exercise is characterized by a bimodal distribution of VO_2 responses as well as a lower respiratory burden, which is associated with greater ventilatory efficiency compared to conventional cycling. In terms of hemodynamic response, *Baduanjin* is demonstrated significantly lower cardiac output and elevated arterial-venous oxygen difference. These cardiopulmonary and hemodynamic responses to *Baduanjin* may be attributed to a higher degree of muscle engagement compared to cycle ergometer exercise.

The strength of this study lies in its comparison of the cardiopulmonary and hemodynamic differences between *Baduanjin* exercise and cycle exercise during matched intensity levels. Our study suggests that *Baduanjin* is a moderate-intensity aerobic exercise suitable for CHF patients, similar to our prior findings (Chen et al., 2020). However, there is a lack of research on real-time physiological responses comparing these two exercise modalities. When studying the cardiopulmonary and hemodynamic responses to different exercises, maintaining a consistent intensity level is crucial (Taylor et al., 2021). In a previous study, exercise intensity was matched based on heart rate response (Gary et al., 2019), while in this study, mean VO_2 during *Baduanjin* exercise was used for match intensity. As such, there was no significant difference in average VO_2

TABLE 3 Ventilation and gas exchange data during maximal exercise and resting hemodynamic data.

Parameters	Values (Mean ± SD)
Load (W)_MAX	91.7 ± 30.4
A. Ventilation and Gas Exchange during maximal exercise	
Maximum RER	1.1 ± 0.1
Maximum VO_2 (mL/kg/min)	18.4 ± 4.2
Maximum METS	5.2 ± 1.2
Maximum RR (bpm)	33.4 ± 5.0
Maximum V_E (L/min)	48.1 ± 10.4
Maximum $P_{ET}CO_2$ (mmHg)	37.4 ± 5.6
VE/VCO_2 slope$^{\triangle}$	30.8 ± 5.8
B. Hemodynamics during rest	
Resting HR (bpm)*	70.2 ± 8.2
Resting SV (mL)	76.6 ± 14.4
Resting CO (L/min)	5.2 ± 1.1
Resting CI	152.8 ± 54.6
Resting O_2 pulse (mL/beat)	4.3 ± 1
Resting EDFR (%)	63.6 (49.4, 71.4)$^{\blacktriangle}$
Resting SBP (mmHg)*	117.3 ± 22
Resting DBP (mmHg)*	73.3 ± 17.8
Resting SVR (dyn·s/cm^5)	2202.0 (1948.0, 2376.0)$^{\blacktriangle}$
Resting $C_{(a-v)}O_2$ (mL/dL)	5.18 ± 2.2

$^{\blacktriangle}$*Median* (P_{25}, P_{75}).
$^{\triangle}$from rest to maximum.
*Collected during the "Maximal exercise test".
Abbreviations: bpm, beats per minute; CI, contractility index; CO, cardiac output; $C_{(a-v)}O_2$, arterial-venous oxygen difference; DBP, diastolic blood pressure; EDFR, early diastolic filling rate; HR, heart rate; MAX, maximal intensity; METs, metabolic equivalents; O_2 pulse, oxygen pulse (oxygen consumption to heart rate ratio); $P_{ET}CO_2$, end-tidal carbon dioxide partial pressure; RR, respiratory rate; RER, respiratory exchange ratio; SBP, systolic blood pressure; SD, standard deviation; SV, stroke volume; SVR, systemic vascular resistance; V_E, minute ventilation; V_E/VCO_2 slope, ventilation efficiency for carbon dioxide elimination; VO_2, oxygen consumption.

between the two modes of exercise. This suggests that VO_2 as a parameter is a good tool for balancing determining exercise intensity as complexities may arise when using HR due to the HR-modulating effect of pharmacotherapies commonly prescribed for CHF patients, such as β-blockers.

While average VO_2 levels were comparable between the two modes of exercise, distinct differences emerged in the intensity response curves. Cycle exercise plateaued in intensity due to a consistent power output, whereas *Baduanjin* exhibited an intermittent pattern with notable fluctuations, leading to a bimodal response curve. The bimodal VO_2 response observed during *Baduanjin* exercise is a reflection of the unique characteristics of this traditional Chinese practice, likely attributed to its structured sequence of movements with varying intensities. The presence of two VO_2 peaks corresponds to movements involving semi-squat postures, indicating that *Baduanjin* offers a distinctive form of moderate-intensity intermittent training. Moderate-intensity intermittent physical activity has been shown to be associated with improved executive function in older adults (MacDonald et al., 2024). Furthermore, a systematic review demonstrated that following training, moderate-intensity intermittent training results in greater reductions in fat mass, as well as improved performance on functional tests for elderly women, compared to moderate-intensity continuous training (Coswig et al., 2020/02). Therefore, *Baduanjin* exercise may be particularly suitable for heart failure patients with impaired executive function or functional performance, as well as for those aiming to achieve fat loss.

Baduanjin exercise imposes a lower respiratory burden by enhancing ventilatory efficiency compared to conventional cycle exercise. Similarly, a meta-analysis has also demonstrated that *Baduanjin* improves ventilatory efficiency (Zou et al., 2017). Patients with CHF typically exhibit an exaggerated ventilatory response for a given metabolic demand during exercise (Dubé et al., 2016-09). Our study's findings indicate that during *Baduanjin* exercise, the respiratory rate is lower than that observed during cycle exercise at the same intensity, suggesting a more stable exercise-induced respiratory response during *Baduanjin*. This can be particularly advantageous for individuals with heart failure working to improve exercise endurance. In addition, our study show that both V_E and V_E/VCO_2 were lower during *Baduanjin* exercise, compared to cycle exercise. V_E quantifies the total volume of gas inhaled or exhaled per minute and is influenced by respiratory rate and tidal volume. The V_E/VCO_2 ratio indicates the proportion of ventilation relative to carbon dioxide production. The observed decrease in V_E and V_E/VCO_2 during *Baduanjin* exercise suggests that less ventilation is needed for the same amount of carbon dioxide production. This indicates a higher efficiency for gas exchange per breath compared to cycle exercise. *Baduanjin* exercise involves movements that elongate respiratory muscles, enhance thoracic compliance and mobility, reduce respiratory center stimulation, and reduce exertional dyspnea (Xie et al., 2022). Additionally, it incorporates respiratory muscle and breathing training to increase respiratory muscle strength and endurance, decrease mechanical loads such as chest wall stiffness, and facilitate deeper, slower breathing for improved gas exchange efficiency.

Baduanjin exercise imposes a lower cardiac demand with increased peripheral oxygen utilization, compared to cycling. Our results demonstrate a significantly lower CO response during *Baduanjin* compared with cycling. This reduction in CO, which represents the volume of blood the heart pumps per minute, suggests that *Baduanjin* imposes less cardiac demand than cycling. Moreover, applying the Fick principle, the $C_{(a-v)}O_2$ was significantly higher during *Baduanjin* exercise when compared to the cycling. The $C_{(a-v)}O_2$., which quantifies the oxygen concentration disparity between arterial and venous blood post-circulation through active muscle, indicates the efficiency with which peripheral organs, tissues, and cells extract oxygen from the mitochondria. Thus, patients engaged in *Baduanjin* exercise may experience improved

TABLE 4 Comparison of cardiopulmonary and hemodynamic responses to *Baduanjin* exercise or cycle exercise.

Parameters	*Baduanjin* (Mean ± SD)	Cycling (Mean ± SD)	*P*-value
Load (W)	—	21.9 ± 8.4	-
A. Ventilation and Gas Exchange			
VO_2 (mL/kg/min)	8.2 ± 1.3	8.4 ± 1.4	0.339
METs	2.3 ± 0.4	2.4 ± 0.4	0.299
RR (bpm)	21.1 ± 4.6	23.2 ± 3.3	0.003*
V_E (L/min)	18.8 ± 4.5	21.3 ± 3.9	<0.001*
$P_{ET}CO_2$ (mmHg)	31.6 ± 3.2	34.0 ± 3.4	<0.001*
$V_{E/}VCO_2$	39.5 ± 5.4	42.0 ± 5.4	<0.001*
B. Hemodynamics			
HR (bpm)	81.8 ± 9.7	79.9 ± 10.2	0.005*
HR_{max} (bpm)	93.9 ± 12.0	86.0 ± 11.9	<0.001*
HRR_1 (bpm)	5.0 (2.0, 8.0)▲	5.0 (3.0, 8.0)▲	0.343
SV (mL)	64.5 ± 11.3	70.9 ± 10.4	0.001*
CO (L/min)	5.2 ± 0.8	5.6 ± 0.9	0.017*
CI	145.9 ± 57.8	176.9 ± 63.4	<0.001*
O_2 pulse (ml/beat)	6.8 ± 1.5	7.2 ± 1.4	0.001*
EDFR (%)	60.1 (56.4, 68.2)▲	59.5 (53.1, 69.6)▲	0.586
SBP (mmHg)	109.1 ± 16.4	113.1 ± 15.7	0.021*
DBP (mmHg)	65.9 ± 8.1	65.9 ± 10.1	0.544
SVR (dyn·s/cm^5)	1,451.4 (1,198.7, 1663.7)▲	1,140.1 (1,040.9, 1220.9)▲	<0.001*
$C_{(a\text{-}v)}O_2$ (mL/dL)	11.2 ± 3.5	10.4 ± 2.6	0.036*

▲*Median* (P_{25},P_{75}).
Abbreviations: bpm, beats per minute; $C_{(a\text{-}v)}O_2$, arterial-venous oxygen difference; CI, contractility index; CO, cardiac output; DBP, diastolic blood pressure; EDFR, early-diastolic filling rate; HR, heart rate; HR_{max}, maximum heart rate during exercise; HRR_1, 1-min heart rate recovery; METs, metabolic equivalents; O_2 pulse, oxygen pulse (oxygen consumption to heart rate ratio); $P_{ET}CO_2$, end-tidal carbon dioxide partial pressure; RR, respiratory rate; SBP, systolic blood pressure; SD, standard deviation; SV, stroke volume; SVR, systemic vascular resistance; V_E, minute ventilation; V_E/VCO_2 slope, ventilation efficiency for carbon dioxide elimination; VO_2, oxygen consumption.

peripheral oxygen extraction, potentially due to the engagement of multiple muscle groups characteristic of this form of exercise.

Baduanjin has been recognized for its comprehensive muscle training program which targets both the upper and lower extremities. In contrast to cycle exercise, which involves simple movements with less muscle mass engagement, *Baduanjin* incorporates a diverse range of movements that engage muscles throughout the body. For instance, postures such as the horse-riding stance in Postures 2, 5, and 7 can be likened to targeted quadriceps training, effectively strengthening the thigh muscles. Additionally, dynamic movements involving the forearms and fists in Postures 1, 2, 3, and 7 provide comprehensive upper extremity training, enhancing strength and coordination in the arms and hands. Furthermore, *Baduanjin* emphasizes high-impact and weight-bearing exercises, as illustrated in Posture 8 where practitioners push upward from their toes and land forcefully on their feet. Thus, this holistic approach to physical conditioning extends beyond the focus on lower body muscle endurance typically associated with cycle exercise. However, our current data do not allow us to distinguish perfusion changes specifically in the upper or lower extremities. The higher SVR observed during *Baduanjin* compared to that during cycle ergometer exercise may suggest greater muscular engagement, further evidenced by high $C_{(a\text{-}v)}O_2$. Previous research demonstrated that a single bout of resistance training elevates systemic peripheral resistance (Wakeham et al., 2025a; Wakeham et al., 2025b; Dawson et al., 1985; Miles et al., 1987). Therefore, the engagement of multiple muscle groups in *Baduanjin* contributes to its therapeutic benefits,

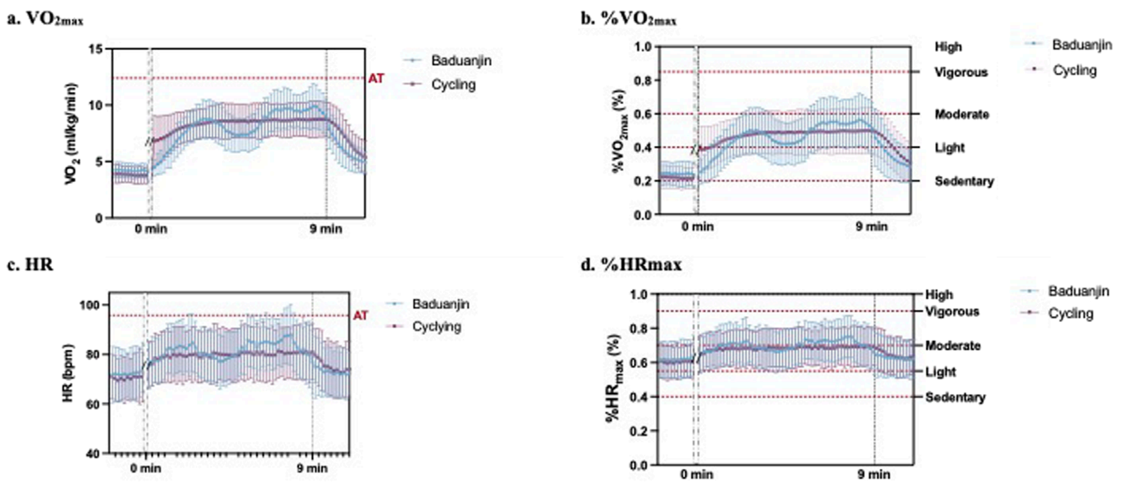

FIGURE 2
Comparison of the real-time cardiopulmonary responses of **(a)** VO_2max, **(b)** %VO_2max, **(c)** HR, and **(d)** %HRmax between Baduanjin exercise and cycle ergometer exercise.

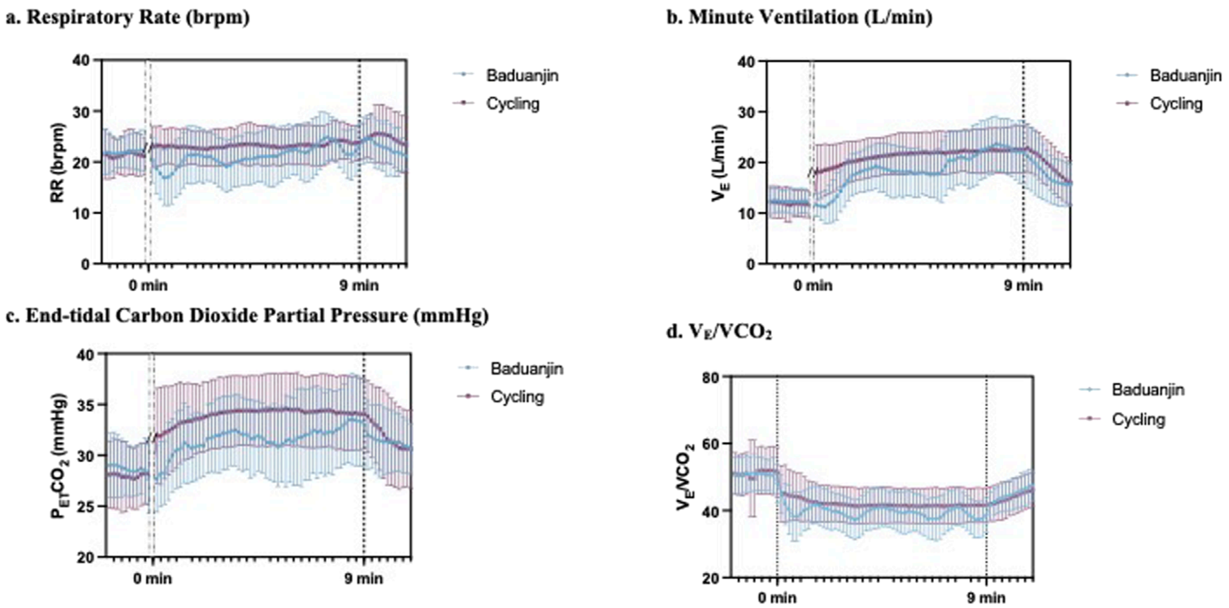

FIGURE 3
Comparison of the real-time pulmonary responses of **(a)** respiratory rate, **(b)** minute ventilation, **(c)** end-tidal carbon dioxide partial pressure, and **(d)** V_E/VCO_2 between Baduanjin exercise and cycle ergometer exercise.

particularly in expanding practitioners' functional capacity and overall muscle strength (Esposito et al., 2011).

4.1 Study limitations

As with any study, this study has potential limitations. Firstly, the sample size was small and we were unable to perform a sample size calculation, as we did not find adequate data for our research question and study design *a priori*. Although the number of participants was low, the within-subject repeats narrowed the estimates' confidence intervals. Secondly, the interpretability and generalizability of the results are limited by the analyzed population's clinical characteristics; our study population included mainly NYHA II CHF patients, and only one female. Therefore, our findings are specific to the population studied. Thirdly, our research employed a non-invasive technique known as ICG, which offers benefits for patients. However, ICG also has limitations regarding specific hemodynamic measurements (such as volume and contractility) that need to be estimated or recalculated. Fourthly, it is crucial to recognize that *Baduanjin* exercise encompasses elements of strength training and balance training in addition

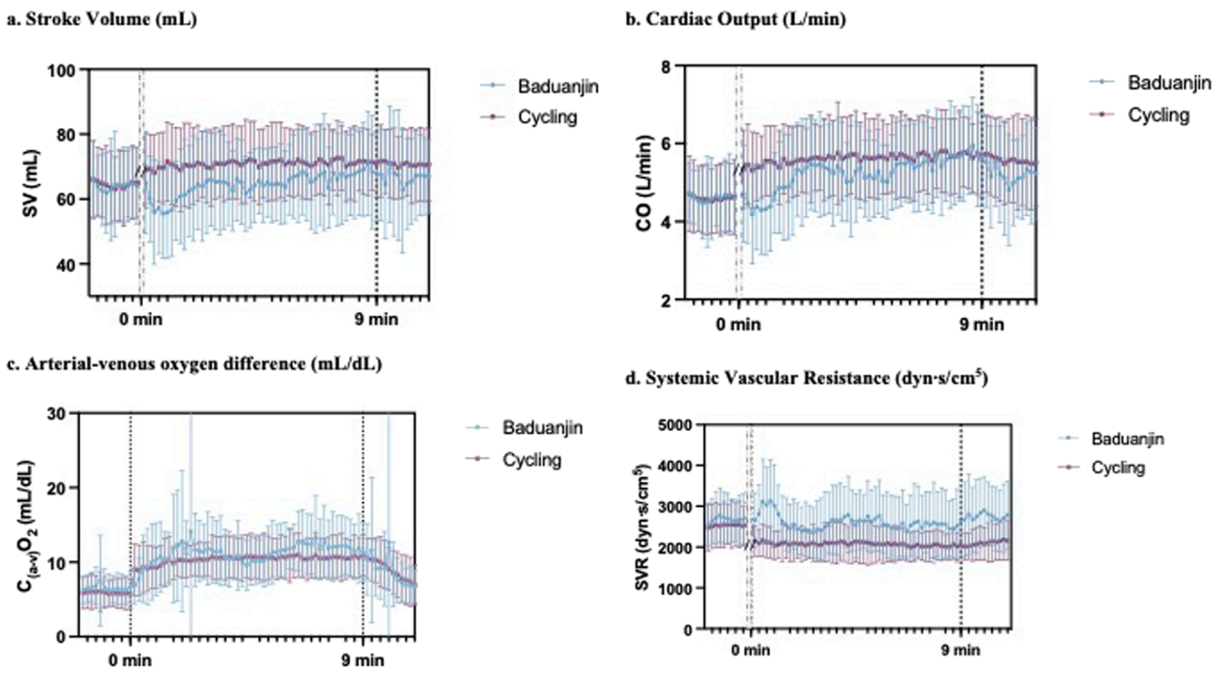

FIGURE 4
Comparison of the real-time hemodynamic responses of **(a)** stroke volume, **(b)** cardiac output, **(c)** arterial-venous oxygen difference, and **(d)** systemic vascular resistance between Baduanjin exercise and cycle ergometer exercise.

to endurance exercise training. This multifaceted nature sets *Baduanjin* apart from endurance cycling, which primarily focuses on cardiovascular endurance. As such, the unique combination of strength, balance, and endurance components in *Baduanjin* requires careful consideration when interpreting the results and comparing it to other forms of exercise. Fifth, this study was specifically designed to observe the gas and hemodynamic changes during the two types of exercise. We did not measure the changes in peak VO_2 or VO_2 at the first ventilatory threshold following the two types of exercise in this study. However, these parameters are crucial for reflecting improvements in endurance capacity (Christou et al., 2024). Comparing these two parameters would be valuable for further elucidating the differences between the two exercises.

5 Conclusion

Our study offers novel insight into the cardiopulmonary and hemodynamic differences between *Baduanjin* and cycle ergometer exercise when performed at consistent intensity levels. Unlike the steady intensity of cycle exercise, *Baduanjin* exhibits an intermittent intensity pattern which is the result of more prominent muscle activation during various postures. Additionally, *Baduanjin* is associated with superior improvement in oxygen respiratory efficiency and increased peripheral oxygen utilization, which is crucial to CHF patients' health. Furthermore, *Baduanjin* reduces cardiac and respiratory burden, providing a more comfortable exercise experience. From the clinical perspective, the practice's ease-of-use and flexibility regarding time commitment and space requirements make it an attractive option for cardiac rehabilitation programs. Given these advantages, *Baduanjin* would be particularly effective for inclusion in cardiac rehabilitation programs for CHF patients in China, where it is widely practiced and culturally familiar.

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 research protocol was approved by the Ethics Committee at Guangdong Provincial Hospital of Chinese Medicine under ethical approval number YF2023-119-01. Prior to participation, each subject received an oral explanation of the study and provided written and verbal informed consent.

Author contributions

XC: Conceptualization, Data curation, Formal Analysis, Methodology, Project administration, Writing – original draft, Writing – review and editing. XH: Data curation, Formal Analysis, Writing – original draft, Writing – review and editing. TO: Writing – review and editing. YQ: Data curation, Writing – review and editing. HZ: Writing – review and editing. ZW: Writing – review and editing. HC: Funding acquisition, Writing – review and editing. WL: Funding acquisition, Writing – review and editing. WJ: Conceptualization, Methodology, 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.2025.1620785/full#supplementary-material

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Glossary

CHF	chronic heart failure
ICG	impedance cardiography
CPET	cardiopulmonary exercise testing
NYHA	New York Heart Association
EqualVO_2	the average oxygen consumption
VO_2	volume of oxygen
V_E	minute ventilation
CO	cardiac output
EBCR	exercise-based cardiac rehabilitation
HF	heart failure
HR	heart rate
SV	stroke volume
CI	contractility index
EDFR	diastolic filling rate
SVR	systemic vascular resistance
VO_2max	maximum oxygen consumption
RER	respiratory exchange ratio
METs	metabolic equivalents
HRmax	maximum heart rate
O_2pulse	oxygen pulse
SBP	systolic blood pressure
DBP	diastolic blood pressure
HRR_1	minute heart rate recovery
RR	respiratory rate
$P_{ET}CO_2$	end-tidal carbon dioxide pressure
VE/VCO_2	ventilation/carbon dioxide production
VE/VCO_2 slope	ventilation/carbon dioxide production slope
VT	ventilatory threshold
AT	anaerobic threshold
VCO_2	volume of carbon dioxide
LVEF	left ventricular ejection fraction
SD	standard deviation
C(a-v)O_2	elevated arterial-venous oxygen difference
BMI	body mass index
bpm	beats per minute
NT-proBNP	N-terminal B-type natriuretic peptide
PASP	pulmonary artery systolic pressure
MI	myocardial infarction
MAX	maximal intensity
O_2 pulse	oxygen pulse (oxygen consumption to heart rate ratio)
FEV_1	forced expiratory volume in 1 s
FVC	forced vital capacity
MVV	maximum voluntary ventilation

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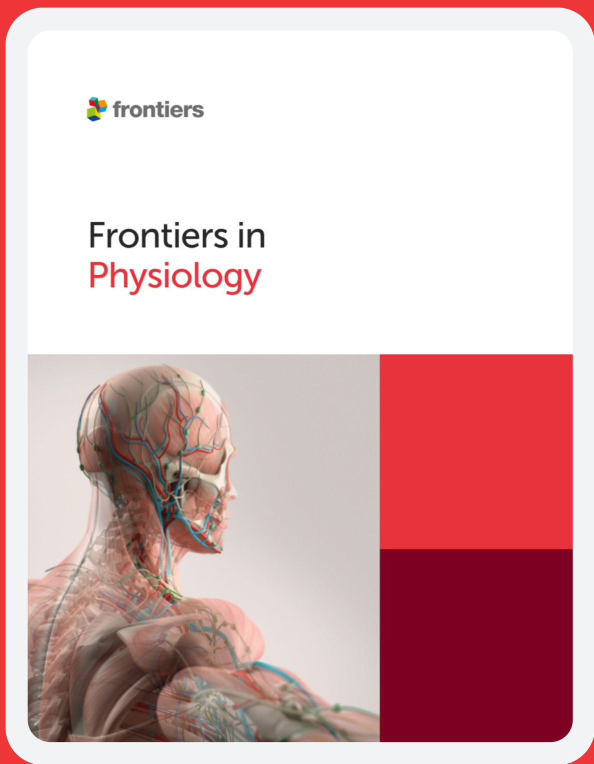

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