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Muscle and tendon injuries in sporting and tactical populations: mechanisms, prevention and rehabilitation

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Muscle and tendon injuries in sporting and tactical populations: mechanisms, prevention and rehabilitation

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Recovery from sport-induced muscle damage in relation to match-intervals in major events

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Muscle damage could affect the next match performance in sports when the time to recover from a previous match is shorter. We examined the interval between matches in nine team sports (e.g., soccer, rugby, field hockey, basketball, volleyball, baseball) and two racket sports (badminton, tennis) in World Cups held in 2022-2023, 2020 Tokyo Olympic Games and Gland Slam in 2023. We then performed narrative review using three electronic databases (PubMed, Scopus, Google Scholar) to get information about muscle damage and recovery in the 11 sports, and discussed whether the intervals in the events would be enough for athletes. We found that the match intervals varied among sports and events ranging from 0 to 17 days. The interval was the shortest for softball (0–2 days) and the longest (5–17 days) for rugby. Regarding muscle damage, changes in muscle function and/or performance measures after a match were not reported for cricket, volleyball and softball, but some information was available for other sports, although the studies did not necessarily use athletes who participated in the major events. It was found that recovery was longer for soccer and rugby than other sports. Importantly, the match-intervals in the events did not appear to accommodate the recovery time required from the previous match in many sports. This could increase a risk of injury and affect players' conditions and health. Changing the match-intervals may be difficult, since it affects the budget of sporting events, but an adequate interval between matches should be considered for each sport from the player's and coach's point of view.

KEYWORDS
World Cup, Olympic Games, grand slam, delayed onset muscle soreness, muscle function, performance, injury

1 Introduction

Major sporting events such as World Cups, Olympic Games, and Gland Slam in tennis attract millions of people worldwide (1). In these events, athletes perform multiple matches in a certain time period, especially when they progress to quarterfinal, semifinal and final matches. However, it is not necessarily clear how matches are scheduled in the sporting events. Limited information is available for the recovery time in relation to the match schedule.

Movements consisting of eccentric (lengthening) contractions (i.e., eccentric-biased movements) of leg and other muscles are performed in sports, which could induce muscle damage representing by delayed onset muscle soreness (DOMS) and prolonged decreases in muscle functions, even for well-trained athletes (2–4). Muscle damage impairs performance for several days, affecting subsequent training sessions and next matches (5–9). For example, Chou et al. (3) reported that it took 4–5 days for maximal voluntary isometric contraction (MVIC) strength of the knee extensors and flexors and performance measures such as Yo-Yo intermittent recovery test level one to return to baseline following a simulated soccer (football) match using a 90 min Loughborough Intermittent Shuttle Test (LIST) performed by elite female soccer players. Since it is likely that official soccer matches are more demanding than the LIST, it is assumed that soccer players require at least 4 days between matches to be ready for the next match (8). However, the interval between soccer matches does not necessarily appear to be longer than 4 days in major events such as World Cups and Olympic Games.

The time taken for recovery from a match varies among sports (3, 5, 10–26). For example, Souglis et al. (5) compared soccer, basketball, volleyball and handball at an elite competitive level for muscle damage and inflammatory indices. They showed that soccer produced the greatest increases in inflammatory markers, creatine kinase (CK) and lactate dehydrogenase (LDH) activities in the blood, and these were smallest after volleyball. Abián et al. (20) reported no significant changes in MVIC strength of the knee extensors and badminton-specific running and movement velocity after a 45 min simulated badminton match, although some increases in plasma CK activity and myoglobin concentration were observed. A simulated single badminton match played by state-level male players decreased muscle strength, voluntary activation, and muscle soreness of the knee extensors and flexors at immediately after and 1 h after the match, but they returned to the baseline by 1 day after the match (26). A simulated 3 h tennis match played on a hard court induced small increases in muscle soreness at 1–2 days post-match, and decreased muscle function assessed by one repetition maximum (1-RM) squat strength (35%), squat jump (7%), and counter movement jump (10%) at immediately post-match, and at 1 day post-match to a smaller extent (17). However, it is not known the level of muscle damage experienced by elite players who played longer singles matches in the grand slam tennis events in which some matches exceed 3 h.

It is likely that muscle damage carries over in the next match when a time to recover from a previous match was not long enough for some team sports such as soccer and rugby, and racket sports such as tennis. However, it is not known how these are considered for match intervals during official tournaments such as World Cups and Olympic Games. It is important to clarify the recovery time after a match, and examine a match interval in sports, starting from some major events. Therefore, we analyzed the interval between matches of men and women in team sports and racket sports (singles) in major sporting events held in 2021–2023, and reviewed literatures to find information about muscle damage and recovery in these sports to examine whether a recovery time required from a previous match are considered in a match schedule.

2 Methods

The study was approved by the Research Ethics Committee of National Taiwan Normal University (Approval #: 202311HS022). The procedures used in the study adhered to the tenets of the Declaration of Helsinki.

2.1 Interval between matches

We included soccer, rugby, field hockey, basketball, handball, volleyball, baseball, cricket, softball, badminton and tennis in this study. We focused on top-level competitions of these sports and examined the events held in 2022 and 2023 for the World Cups, 2020 Tokyo Olympic Games held in 2021, and singles in four major tournaments in tennis (Australia Open, French Open, Wimbledon and US Open) held in 2023. The 2023 World Baseball Classic was used for baseball, and the 2023 World Cup for cricket. The sporting events included in the present study are shown in Table 1. We obtained the information about intervals between matches from the websites of the above events held in 2022 and 2023 (e.g., 2023 FIFA women world cup: https://en.wikipedia.org/wiki/2023_FIFA_Women%27s_World_Cup), and 2020 Tokyo Olympic Games (e.g., https://en.wikipedia.org/wiki/Football_at_the_2020_Summer_Olympics). We analyzed the intervals (days) between matches of men and women in these sporting events, identified the ranges, and calculated mean ± SD interval for each sport event.

2.2 Literature review

We conducted a narrative literature review to obtain information about muscle damage and recovery relating to soccer/football, rugby, field hockey, basketball, handball, volleyball, badminton, tennis, baseball, cricket, and softball. The literature search focused on peer-reviewed journal articles published up until June 2024 using three databases (PubMed, Scopus, Google Scholar). Search keywords included: “soccer/football,” “rugby,” “field hockey,” “basketball,” “handball,” “volleyball,” “badminton,” “tennis,” “baseball,” “cricket,” “softball,” “match,” “game,” AND “muscle function,” “muscle dysfunction,” “muscle damage,” “muscle injury,” “MVIC strength,” “muscle strength,” “strength,” “isometric strength,” “delayed onset muscle soreness,” “muscle soreness,” “muscle pain,” “range of motion,” “countermovement jump,” “vertical jump,” AND “recovery”. We searched articles written in English related to ‘muscle damage’ and/or ‘recovery’ for the sports included in the analyses of match-intervals (i.e., soccer/football, rugby, field hockey, basketball, handball, volleyball, badminton, tennis, baseball, cricket, softball). We focused on changes in muscle functions [e.g., MVIC strength, range of motion, countermovement jump (CMJ)], delayed onset muscle soreness (DOMS)/muscle soreness] and their time course of recovery following a single match due to these variables are the main indirect markers of eccentric exercise-induced muscle damage used in previous studies (2, 6, 7). If studies only measured dependent variables (i.e., muscle function, performance) at one time-point post-match, they were excluded since no information of recovery from a match could be obtained.

TABLE 1 The sporting events analyzed for intervals between matches in the present study.

Sport	World cup		Olympic	
	Men	Women	Men	Women
Soccer	2022 FIFA Men's World Cup	2023 FIFA Women's World Cup	2020 Tokyo	2020 Tokyo
Rugby	Rugby World Cup 2023 (Rugby 15)	Women's Rugby World Cup 2022	—	—
Field Hockey	2023 Men's FIH Indoor Hockey World Cup	2023 Women's FIH Indoor Hockey World Cup	2020 Tokyo	2020 Tokyo
Basketball	2023 FIBA Basketball Men's World Cup	2022 FIBA Women's Basketball World Cup	2020 Tokyo	2020 Tokyo
Handball	2023 IHF Men's World Championship	2023 IHF Women's World Championship	2020 Tokyo	2020 Tokyo
Volleyball	2022 FIVA Volleyball Men's World Cup	2023 FIVA Volleyball Women's World Cup	2020 Tokyo	2020 Tokyo
Badminton -Singles	2023 BWF World Championships	2023 BWF World Championships	2020 Tokyo	2020 Tokyo
Tennis -Singles	—	—	2020 Tokyo	2020 Tokyo
	2023 Australian Open	2023 Australian Open	—	—
	2023 French Open	2023 French Open	—	—
	2023 Wimbledon	2023 Wimbledon	—	—
	2023 US Open	2023 US Open	—	—
Baseball	2023 World Baseball Classic	—	2020 Tokyo	—
Cricket	2023 ICC Men's Cricket World Cup	2023 ICC Women's Cricket World Cup	—	—
Softball	2022 WBSC Men's Softball World Championship	2021 WBSC Women's Softball World Cup	—	2020 Tokyo

BWF, badminton world federation; FIBA, fédération international de basket-ball; FIFA, fédération internationale de football association; FIH, international hockey federation; FIVA, federation internationale de volleyball; ICC, international cricket council; IHF, international handball federation; US, United States; WBSC, world baseball softball confederation.

2.3 Statistical analyses

The descriptive data are presented as ranges and their mean ± SD for each sport event. All statistical analyses were performed using the Microsoft Excel Version 2023.

3 Results

3.1 Match interval

Table 2 shows the intervals (days) between matches (range, mean ± SD) in the sporting events for each sport. The match-intervals differ largely among sports ranging from 0 day to 17 days. The longest match-interval was found for rugby (5–17 days), and the shortest interval was seen for softball (0–2 days).

3.2 Muscle damage and recovery

Table 3 shows changes in muscle functions and/or performance measures after a match or a simulated match of each sport. In many of the studies, a full time-course of the recovery was not investigated (e.g., 10–14, 16, 17, 19, 21–23, 25, 26), thus the time for the measures to return to the baseline was not clear for many sports. No previous study has investigated changes in muscle function and/or performance measures after a match of volleyball, softball and cricket (Table 3). Based on the available information, the recovery is shorter for badminton, when compared with soccer and rugby, and the longest recovery time was found for rugby (Table 3).

TABLE 2 The rest interval (days) between matches (range, mean ± SD) in sports included in the world cups (2022–2023) and Tokyo Olympic games (2021), and the four grand slam events in tennis (Australia open, French open, wimbledon and US open).

Sport	World cup		Olympic	
	Men	Women	Men	Women
Soccer	2–7	3–7	3–4	3–4
	4.1 ± 0.7	4.9 ± 0.8	3.0 ± 0.2	3.1 ± 0.2
Rugby	5–15	6–8	5–17	6–17
	8.2 ± 1.6	6.9 ± 0.6	10.7 ± 4.7	10.7 ± 4.7
Field Hockey	2–7	1–7	1–2	1–2
	3.1 ± 1.2	2.6 ± 1.3	1.6 ± 0.5	1.7 ± 0.5
Basketball	1–3	1–2	2–3	2–3
	2.0 ± 0.4	1.3 ± 0.5	2.7 ± 0.5	2.7 ± 0.5
Handball	2–3	2–3	2–2	2–2
	2.0 ± 0.1	2.1 ± 0.0	2.0 ± 0.0	2.0 ± 0.0
Volleyball	1–3	1–3	2–2	2–2
	1.4 ± 0.6	1.5 ± 0.6	2.0 ± 0.0	2.0 ± 0.0
Badminton	1–2	1–2	1–4	1–4
	1.4 ± 0.5	1.2 ± 0.4	2.0 ± 1.0	1.8 ± 0.9
Tennis	—	—	1–3	1–2
			1.7 ± 0.6	1.3 ± 0.5
Australia Open	1–3	0.5–4	—	—
	1.9 ± 0.3	1.9 ± 0.7		
French Open	1–4	1–5	—	—
	2.3 ± 0.6	2.3 ± 0.5		
Wimbledon	1–3	1–4	—	—
	1.8 ± 0.8	2.2 ± 1.0		
US Open	1–3	1–6	—	—
	2.2 ± 0.5	2.1 ± 0.6		
Baseball	1–3	—	1–4	—
	1.5 ± 0.9		1.7 ± 0.7	
Cricket	3–9	1–5	—	—
	4.5 ± 1.4	2.8 ± 1.0		
Softball	1–1	0–1	—	1–2
	1.0 ± 0.0	0.9 ± 0.3		1.2 ± 0.4

TABLE 3 The information of gender, age, performance level, duration of a match, and muscle function and/or performance variables, and delayed onset muscle soreness (DOMS) after a match of each sport in the studies. The last time taken the measurements (time of the last measure) and when the measurements were returned to the baseline (time of recovery) are shown.

Sport	Study	Sex age (y)	Performance level	Duration (min)	Variables	Time of the last measure (h)	Time of recovery (h)
Soccer match	Tanabe et al. (27)	Male 20.0 ± 1.0	15 university soccer players	90	CMJ DOMS RJ-index	48 48 48	0.5 Not full recovery 48
Soccer match	Junior et al. (28)	Female 23.6 ± 5.4	10 Brazilian professional soccer players	90	CMJ 10 m sprint 20 m sprint DOMS	48 48 48 48	48 24 24 Not full recovery
Soccer match	Dewangga et al. (29)	Female ≤ 17.0	20 U17 soccer players	90	Vertical jump	48	24
Friendly match	Marqués-Jiménez et al. (30)	Male 22.9 ± 2.4	10 semi-professional soccer players		RSA	48	24
Soccer (LIST)	Chou et al. (3)	Female 21.0 ± 1.1	12 elite university soccer players	90	MVIC-KE	120	120
					MVIC-KF	120	120
					CMJ	120	120
					30 m sprint	120	72
					Balance	120	120
					Agility *T*-test	120	120
					6 × 10 m	120	120
					YYIR1	120	96
					DOMS-KE	120	120
					DOMS-KF	120	120
Soccer (LIST)	Thomas et al. (23)	Male 21.0 ± 1.0	15 semi-professional players	90	MVIC-KE	72	Not full recovery
					CMJ	72	Not full recovery
					RSI	72	72
					Broad jump	72	48
					DOMS-KE	72	72
Soccer (LIST, match)	Magalhães et al. (12)	Male 21.3 ± 1.1	16 soccer players from 2nd and 3rd Portuguese divisions	90	MVIC-KE	72	Not full recovery
					MVIC-KF	72	Not full recovery
					CMJ	72	Not full recovery
					20 m sprint	72	Not full recovery
					DOMS	72	Not full recovery
Soccer (match)	Ispirlidis et al. (10)	Male 20.2 ± 0.8	12 elite soccer players	90	1RM	144	96
					20 m Sprint	144	120
					CMJ	144	72
					ROM-KE	144	96
					DOMS	144	96
Soccer (friendly match)	Brownstein et al. (22)	Male 21.0 ± 1.0	16 semi-professional players	90	MVIC-KE	72	72
					CMJ	72	48
Rugby (professional rugby league match)	McLellan et al. (13)	Male 24.3 ± 3.6	12 professional rugby league players	80	DOMS-KE ftCMJ rpCMJ DOMS	72 144 144 144	72 144 Not full recovery 96
Rugby (professional rugby league match)	McLellan et al. (14)	Male 19.0 ± 1.3	17 elite Rugby League players	80	pfCMJ	120	24
					RFD-CMJ	120	48
					ppCMJ	120	48
Rugby (match)	Roe et al. (21)	Male 17.4 ± 0.8	14 academy rugby union players	80	CMJ	72	72
					Plyometric push-up	72	48
Rugby (rugby union match)	Silva et al. (31)	Male 28.9 ± 3.5	14 amateur rugby players	80	10 m sprint	96	72
					L-shape run test	96	Not full recovery
Rugby (RLMSP)	Twist and Sykes (15)	Male 23.5 ± 2.3	10 university rugby players	86	MVIC-KE	48	48
					MVIC-KF	48	Not full recovery
					CMJ	48	48
					DOMS	48	Not full recovery
Field hockey (match)	Burt et al. (24)	Male 20.0 ± 2.4	11 field hockey players	70	MVIC-KE	48	No change
					MVIC-KF	48	No change
					CMJ	48	No change
					DOMS	48	48

(*Continued*)

TABLE 3 Continued

Sport	Study	Sex age (y)	Performance level	Duration (min)	Variables	Time of the last measure (h)	Time of recovery (h)
Basketball (match)	Moreira et al. (18)	Female 27.4 ± 4.8	11 elite professional basketball players	40	1RM leg press	24	24
					1RM bench press	24	24
					Agility *T*-test	24	24
					DOMS-KF	48	Not full recovery
Basketball (simulated match)	Pliauga et al. (19)	Male 21.5 ± 1.7	10 first in the Lithuanian National Basketball division players	40	CMJ	48	Not full recovery
					10 m sprint	48	Not full recovery
Volleyball	No study						
Handball (match)	Chatzinikolaou et al. (16)	Male 22.8 ± 1.4	24 elite adult team handball players	60	CMJ	144	48
					1RM-leg press	144	48
					1RM-bench press	144	48
					Handgrip	144	48
					10-m sprint	144	48
					Line drill test	144	48
					Agility *T*-test	144	48
					DOMS-KE	144	48
					DOMS-KF	144	72
					dROM-KJ	144	72
					ndROM-KJ	144	No change
Baseball-pitching (simulated pitching)	Reinold et al. (11)	Male 26.0 ± 4.9	67 professional baseball pitchers	50–60 pitches at full intensity	ROM-shoulder ER	48	No change
					ROM- shoulder IR	48	Not full recovery
					ROM- elbow flexion	48	No change
					ROM- elbow extension	48	Not full recovery
Softball	No study						
Badminton-singles (simulated match)	Lin et al. (26)	Male 26.4 ± 5.3	10 elite singles badminton players from the Western Australia badminton team	60	dMVIC-KE	24	24
					ndMVIC-KE	24	24
					dMVIC-KF	24	24
					ndMVIC-KF	24	No change
					DOMS	24	Not full recovery
Cricket	No study						
Tennis-singles (simulated 3 h tennis match)	Gomes et al. (17)	Male 17.6 ± 1.4	10 young tennis players from Brazil national junior ranking 10th–45th	180	1RM	48	24
					CMJ	48	24
					SJ	48	24
					DOMS	48	Not full recovery

LIST, Loughborough intermittent shuttle test; RLMSP, rugby league match simulation protocol (RLMSP is one of simulated rugby matches); CMJ, countermovement jump; d, dominant limb; DOMS, delayed onset muscle soreness; RSA, repeated sprint ability; ER, external rotation; nd, nondominant limb; ftCMJ, flight time of CMJ; IR, internal rotation; KE, knee extensors; KF, knee flexors; PF, plantar flexors; MVIC, maximal voluntary isometric contraction strength; pfCMJ, peak force of CMJ; ppCMJ, peak power of CMJ; 1-RM, one repetition maximum; RFD, rate of force development; RFD-CMJ, rate of force development during countermovement jump test; RJ-index, rebound jump index; ROM, range of motion; ROM-KJ, knee joint of ROM; rpCMJ, relative power of CMJ; RSI, reactive strength index; SJ, squat jump; YYIR1, yo-yo intermittent recovery running level 1.

4 Discussion

The match intervals varied among sports and events such that the intervals in World Cups and Olympic Games were the shortest for softball (0–2 days) and the longest (5–17 days) for rugby (Table 2). Soccer matches were generally scheduled with 2–7 days of rest between matches in the World Cups, but 3–4 days during the Olympic Games, and rugby had a longer interval for men (5–15 days) than women (6–8 days) in the World Cups (Table 2). It appears that the recovery time is somewhat considered in scheduling matches in the events, since the recovery takes longer after rugby or soccer matches than softball matches (Table 3). However, considering the wide range of intervals between matches, and possible large intra- and inter-individual variability in external and internal load in a competition, some athletes are unlikely to recover from a previous match, but still play a following match (e.g., 31).

As shown in Table 3, muscle function and/or performance parameters were impaired following a match for all sports, but the time for them to return to the baseline differed largely among sports. No information about changes in muscle function and/or performance after a match was found in published papers for volleyball, softball and cricket. The extent of decrement in muscle function that elite athletes experience after an official match is not necessarily clear, since many of the studies did not use them as participants (3, 10–12, 15–19, 21–27, 29, 30). Thus, in order to obtain the whole pictures of recovery after matches for elite athletes, more studies are required.

It is well-documented that muscle damage represented by DOMS and prolonged decreases in muscle function is induced by unaccustomed exercises consisting of large volume and/or high-intensity eccentric contractions, and the magnitude of muscle damage is reduced when the same exercises are repeated, known as the repeated bout effect (2, 32–34). In spite of the repeated bout effect, some muscle damage is still induced in well-trained athletes (3, 5, 8, 10, 13, 18, 27, 29, 30). The muscle damage impairs performance, which could last for several days (6–8, 35). It is important to note that muscle damage is induced to some extent even for well-trained athletes who are accustomed to most of the eccentric-biased movements performed in sports (5, 8, 10, 13, 18). It is likely that eccentric-biased movements performed in sports such as rapid deceleration, sudden stop, fast change of direction, landing, jumping, hopping, cutting, body collision/contact and preventing falls are the main causes of the decreases in muscle function and performance parameters (7, 36). It is likely that more strenuous eccentric-biased movements are required in a competitive match than in training and practice sessions, which could exceed the level of the repeated bout effect.

Fédération Internationale de Football Association (FIFA) sets each team must have at least 48 h of rest before the next match played in its official tournaments (https://digitalhub.fifa.com/m/2744a0a5e3ded185/original/FIFA-World-Cup-Qatar-2022-Regulations_EN.pdf). However, it seems possible that players required more than 48 h to recover from soccer matches even for well-trained players. Koyama et al. (37) showed that the relative external load of players increased when the competitive level of the opponents increased, suggesting that internal and external loads varied depending on contextual factors. It has been reported that external load and internal load differ between World Cup matches and friendly matches (38). Silva et al. (31) compared the impact of simulation matches and real matches in their systematic review article, and stated that the real matches (11 vs. 11 format) induced greater magnitude of DOMS and increased CK activity in the blood, although neuromuscular alterations were similar. Chou et al. (3) and Tseng et al. (9) reported that it took 4–5 days for elite female soccer players to restore MVIC strength of the knee extensors and flexors and performance measures such as Yo-Yo intermittent recovery test level 1 to the baseline levels following a 90 min LIST (3, 9). Thus, it seems likely that actual soccer matches could induce greater muscle damage than the LIST, because of other activities with a ball, and competitive nature of matches including contacts and impacts with opponents, thus the recovery takes longer. However, some studies reported that muscle soreness and some performance measures (sprint, vertical jump) fully returned to baseline at 24–48 h following a 90 min soccer match (27, 28, 30). It appears that many factors such as physical and mental demands in matches, environment and condition (e.g., temperature, humidity, ground condition) and the level of players affect the magnitude of muscle damage.

Based on the data from the female soccer players in the study by Chou et al. (3), and possible greater physical and physiological demands in competitive matches in major events such as World Cup, it is assumed that players need to have more than 4 days between matches. However, the interval between matches was 3–7 days for the group rounds, and that for the quarter finals, semifinals, third place and final was 3–6 days in the 2023 FIFA Women's World Cup. It is possible that a team that had a shorter interval between matches has disadvantage against a team that has a longer interval between matches. It is interesting to note that the interval between matches was not the same in 6 out of 8 matches in the quarter-final, semi-final, final and the third-place matches between teams, and 5 out of 6 matches (83%) were won by the teams who had a longer interval from the previous match in the 2023 FIFA Women's World Cup (8).

Although it is ideal to have the same match interval for the teams competing each other from the point of fairness, this would be almost impossible from the organizational perspective. Thus, it is important to find strategies to facilitate recovery after a match to prepare players for subsequent competition during sport events. One of the strategies is to use therapeutic modalities such as far-infrared ray (FIR) lamp therapy that has been shown to enhance recovery from muscle damage and performance parameters following a single bout (9) or multiple bouts of LIST (39).

It has been reported that basketball players in the National Basketball Association (NBA) teams scored more with a 2-day rest interval between matches when compared to consecutive matches (40), and had less successful three-point shots per 100 possessions and 20% less dunks during the fourth quarter compared to the first quarter when matches were played on consecutive days (41). The interval between matches in rugby (7–9 days) is longer than that in soccer (2–7 days) as shown in Table 2. The full recovery of muscle function and performance from a soccer (3–5 days) and rugby (2–6 days) match seems similar (Table 3). The playing time is shorter for rugby (80 min) than soccer (90–120 min); however, the total numbers of contact conditions and the extent of the contact impacts are likely to be greater for a rugby match (e.g., tackling: 156 times/match, scrums: 22 times/match, rucks: 16 times/match; total: 294 times/match) (42) than soccer (no tackling is allowed; ∼147 times body collision/match) (43). This may be a reason for a longer interval between matches in rugby than soccer. The full recovery of muscle function and performance after a field hockey match took about 1–48 h, while that following badminton and tennis singles matches took less than 2 days (Table 3). It is likely that the magnitude and volume of eccentric-biased movements are less for badminton and tennis than those in soccer and rugby. However, when a match duration is long such as more than 3 h in tennis for example, it is likely that a large amount of eccentric-biased movements contractions of lower limb muscles are performed, resulting in muscle damage and impaired performance. It is interesting to investigate how tennis players recover from a previous long match and are ready for the next match within 2 days. It is also possible that the interindividual responses differ in different conditions due to external-internal load influenced by match duration and contextual factors such as opponents' level and fixture congestion (44).

When players perform matches without full recovery from previous matches, it may result in accumulative physical and mental fatigue, compromise performance and increase injury risks of players (40, 45, 46). In fact, previous studies reported that a match congestion increased non-contact injuries in professional soccer players (45, 47–50), field hockey players (51) and basketball players (52). For example, Dupont et al. (45) reported that professional male soccer players played two matches per week without affecting the distance covered and the numbers of sprint during matches, but it increased the injury rate 6 folds when compared with a match per week. Mason et al. (51) showed that field hockey matches with 24 h interval had 3.8–6.8 times higher injury risks than matches with 3–7 days interval. Additionally, athletes have more risks of illness in congested match conditions (53–56). For example, Schwellnus et al. (55) stated that a congested match schedule increased risk of both subclinical immunological changes that could increase the risk of illness, and actual symptoms of illness or diagnosed illness. In the study of English Premier League, Morgans et al. (53) showed that playing 5 matches in 15 days led to large decreases in salivary immunoglobulin-A (SIgA) concentration (e.g., 2-day post-match 3: −68%, 2-day post-match 5: −71%). Therefore, it is important to examine adequate intervals between matches to minimize injury risks and illness of the players. Sport organizations and/or sports event organizers should consider the time taken for players to recover from a previous match.

It is also interesting to examine if a shorter interval between matches lowers the match quality, and higher quality matches can be seen when athletes are competing with enough recovery from previous matches. In fact, Folgado et al. (57) examined the physical and tactical performances of an English professional football team under congested (played one match every 3 days interval for 3 matches) and non-congested (played one match at least 6 days rest for 3 matches) fixture periods. They reported that no differences in the physical performances such as the total distance covered between congested and non-congested matches, but players spent more time for movement synchronized during the non-congested fixtures (lateral displacements: 41.3%, longitudinal displacements: 77.2%) when compared with congested fixtures (38.5%, 74.5%). The authors stated that the reduction of synchronization could be associated with an increased perception of fatigue (57).

It may be difficult to change match-intervals in sporting events, since it affects the budget and schedule of players in a season for other events. Pillay et al. (58) conducted a survey study of 1,055 professional male soccer players around the world, and found that 76% of them thought that there should be regulations in place to protect them from insufficient breaks (i.e., not enough rest in both off-season and in-season). Coaches and medical practitioners need to have strategies to reduce fatigue and muscle damage in matches, as well as facilitate the recovery of athletes after matches. It is necessary to have a simple measure to assess status of athletes including their readiness for the next match. In soccer, we reported that counter movement jump height could indicate recovery from a previous match well (3). Sporting organizations should communicate with coaches and athletes to set a schedule of events, and they should also seek medical and scientific guidance before making a match calendar (53). An adequate interval between matches should be discussed more openly for each sport. To minimize injuries and accumulative fatigue as well as prevent illness in sporting events, effective recovery strategies are important to be developed and established, warranting more studies. It is also important to monitor match intervals in upcoming major sporting events in 2024 such as the Olympic Games Paris and beyond.

There are several limitations in the present study. First, the present study included only 11 sports (soccer, rugby, field hockey, basketball, volleyball, baseball, cricket, handball, softball, badminton, tennis) among many, and focused on World Cups held in 2023, Olympic Games in 2021, and tennis gland slams in 2023. It is interesting to extend the analyses to previous events held before the ones included in the present study. Second, we searched articles relating to the 11 sports in which muscle damage and recovery were investigated using the literature review, but it was not based on a systematic review protocol. Thirdly, the present study included studies with participants who were not necessarily elite athletes. Since limited studies used elite athletes, and it is possible that they could recover from a match in a shorter time, actual recovery profiles of elite athletes who represent countries in the major sporting events are largely unknown. In order to better understand muscle damage and recovery in sporting events, more studies are required using top levels athletes, and barriers to conduct such studies requires good collaboration with teams, athletes and sporting organizations. Fourthly, LIST may not represent contemporary soccer matches and may demands of a female match-play. Magalhes et al. (12) reported that changes in muscle damage and performance parameters following a 90 min LIST played by male players of the second and third Portuguese divisions were similar to those after a 90 min soccer match. However, the LIST does not include soccer specific skills such as passing, kicking and heading a ball. Future studies are warranted to examine the effects of congested matches on muscle damage, fatigue, performance and health.

In conclusion, the present study showed that the interval between matches varied among sports and events, and the match intervals in the major sporting events were not necessarily long enough for the players to fully recover from the previous match in many cases. It may not be that sport organizations and event organizers can arrange the rest interval based on the full recovery time. More studies are warranted to investigate what the best rest interval is to be set between matches for each sport event such as World Cup and Olympic Games. Since the recovery time is crucial, it is necessary to for an event organiser to schedule matches to give the same match interval to the teams competing against at least.

Data availability statement

The datasets are presented in the article, further inquiries can be directed to the corresponding author.

Author contributions

KN: Writing – review & editing, Validation, Methodology, Investigation, Formal Analysis, Data curation, Conceptualization. TC: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Funding acquisition, Formal Analysis, Data curation, Conceptualization.

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Conflict of interest

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Individual factors determine landing impacts in rested and fatigued cheerleaders

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High vertical ground reaction forces (VGRF) during landings following acrobatic elements in artistic gymnastics is associated with trunk and lower extremity injury risk. As similar data regarding injury risk factors in cheerleading are scarce, the purpose of this study was to assess VGRF in pop-off dismounts of rested and fatigued flyers in cheerleaders. Fifteen German cheerleaders were recruited for this study, including seven female flyers and eight male bases. It was expected that performance would change in fatiguing athletes, potentially increasing the risk for injuries. However, neither the mean VGRF (rested: 6.0 ± 1.9 BW, fatigued: 6.2 ± 1.3 BW, overall range: 2.1–14.9 BW) nor the individual VGRF-time courses of the flyers changed significantly after the workout. Instead, we show that the flyers' ability to land – but not the bases' ability to catch – significantly influences the maximum and time-resolved impacts.

KEYWORDS

cheerleading, short recovery stress scale, Borg scale, statistical parametric mapping, ANOVA, force plate

1 Introduction

The International Olympic Committee (IOC) acknowledged the International Cheer Union (ICU) as the world governing body of cheerleading in July 2021, with the prospect of eventually becoming an Olympic sport. Contrary to the US, cheerleading is a fringe sport in Germany, yet growing in numbers. In recent years, a league system has been developed under the aegis of the "German Cheerleading and Cheerperformance Association" (Cheerleading und Cheerperformance Verband Deutschland, CCVD). During competitive championships, teams consisting of throwing (*bases*) and thrown members (*flyers*) perform routines with diverse elements – e.g. *(partner)stunts*, *pyramids*, or *baskets* (1, 2) – in order to obtain points by the judges. The permitted difficulty of stunts increases with athlete level (from 0 for beginners to 7 for professionals). The more complex and well-performed the routine, the more points for the team, particularly if the flyer does not *drop* (fall) (1). Hence, particular attention is directed to the smooth dismount of the flyer from great heights during training; more precisely, from one and a half body heights in partnerstunts and up to two and a half body heights in pyramids (1).

Landing from such great heights constitutes a huge injury risk factor for the flyers (3). In an attempt to mitigate these injury risks, the CCVD provides training guidelines to ensure a safe and preferably injury-free training practice (4). However, as cheerleading is a fringe sport in Germany, there is limited information related to frequency, severity and prevention of injuries (5). The same holds true for whole Europe: A PubMed search with keywords "`Cheerleading and injuries`" yielded 96 results of which 63 explicitly contained "`US or USA`" but none contained "`Germany or Europe`" (search results as of December 2023). Most injuries in US cheerleaders are strains and sprains in the ankle and lower extremities (3, 6–9). Approximately 17% of cheerleaders [193 out of 1,115, (10), Table 4] exhibited fractures, including stress fractures. The most catastrophic injuries occurred after landing on hard floors (11).

By the same token, injuries are predominantly linked to landings in floor exercises or dismounts in gymnastics (12–14) – a related sport. Hume et al. (15) further emphasize that uncontrolled and repetitive landings can lead to both acute and overuse injuries. It is hence unsurprising that the *Code of Points* for women's gymnastics stipulates a controlled landing on two feet for floor exercises (16, 17). According to Bradshaw and Hume (16), any modifications to the Code of Points should be made with athlete safety in mind, which in turn is linked to biomechanical considerations.

High impact forces during landing from great height are considered to be one of the leading biomechanical causes for injuries in athletes across disciplines (16, 18–20). Although some cheerleading-related injuries are known to occur during gymnastics parts, most happen during stunts (3, 21). These impact forces are commonly quantified by measuring the *vertical ground reaction forces* (VGRF) via force plates in various sports such as running, basketball, tennis, football, volleyball, skiing or gymnastics (20, 22). Depending on the injury risk assessment, one may be interested in peak VGRF, mean VGRF, or cumulative VGRF (impulse). For this study, we focus mainly on peak VGRF, i.e. the maximum recorded impact force over a certain time interval of interest. Peak VGRF during landing can range from four times the body weight (4 BW) after a 0.32 m jump to 11 BW after a 1.28 m jump (19). Hume et al. (15) reported VGRF of two-foot landings in gymnastics from 5 BW in training to 11 BW in competitions, and even up to 18 BW during unusual foot placement. To our knowledge, no measurements of VGRF during cheerleading stunts exist, where the flyers' landings are supported by their bases. Here, we present preliminary VGRF measurements after dismounting from a particular stunt, the so-called *pop-off*, where flyers drop-land on the ground after jumping straight from the outstretched arms of their bases. As studies suggest an association between athletes' fatigue and injury risk [see citations in Bagnulo (6)], stunts were performed by flyer-base pairs both in a rested state and after high-intensity workouts to measure the effect of fatigued stunt partners. Additionally, counter-movement jumps (CMJ) were utilized to measure the VGRF impacts of individual athletes to assess both their landing mechanics and their fatigue (23).

We aimed to address the following: (1) does a fatiguing workout alter the landing characteristics of the flyer or the catching ability of the base (2) is the landing impact determined predominantly by the base or the flyer (3) is there an association between two-foot landing impacts during CMJ and pop-off stunts, and, finally (4) monitor the effect of a fatiguing workout on VGRF landing profiles.

2 Method

2.1 Participants

We invited 15 level-6 athletes from a German coed team, with three to eleven years' experience in cheerleading. All athletes had already competed at national championships and had given their written informed consent to participate in this study.

The requirement for an approval was waived by the local ethics committee within the University of Koblenz. The seven flyers – denoted as F1,. . .,F7 – were exclusively female with a mean age of 24.6 ± 2.5 years (mean ± standard deviation). The eight bases – denoted as B1,. . .,B8 – were exclusively male with a mean age of 30.1 ± 4.2 years). Table 1 further summarizes data on the participants, such as age, mass, height, and performed pop-offs on each test day (see below). Mass and height were measured on site by the experimenters before the trials, using the force plate and measuring tape.

2.2 Technical description of the pop-off stunt

For this preliminary assessment of VGRF during cheerleading partnerstunts, the flyer-base pairs performed a standard pop-off technique, see picture sequence in Figure 1. The athletes were instructed to perform their routines as if they were training stunts. As the only exception, the teams were prompted to dismount the flyers onto the force plate, while mounting was conducted without constraints. With the flyer standing on their upward, outstretched arms, the bases dipped (bending the knees) both to signal the flyer to dismount and initiate the impetus. Subsequently, upon straightening the knees again, the flyer was thrown in the air, about 20–30 cm additional height. Before landing, the flyer tried to bring her hips forward and grab the wrists of the base. The base ought to decelerate the falling flyer by grabbing her hip thus supporting the landing. A representative impact signal upon landing is shown in Figure 2.

2.3 Test protocol and experimental set-up

All measurements were performed over three days in late June and early July 2023, at least two days after a regular training session. Upon arrival, participants were informed about data privacy and the planned stunt measurements and filled out both a case report as well as a detailed Acute Recovery and Stress Scale [ARSS, cf. (28, 29)] questionnaire to measure the psycho-physical effects of the fatiguing workout. The ARSS comprised

TABLE 1 Participants data sheet.

Role	Person	Sex	Age	Mass	Height	Pop-offs performed at		
	(identifier)		(years)	(kg)	(cm)	Day 1	Day 2	Day 3
Flyer	F1	female	25	54.1	155	–	–	13 {25}
	F2	female	27	52.2	163	–	–	32 {42}
	F3	female	25	48.5	159	–	36 {43}	–
	F4	female	21	58.0	169	–	–	14 {16}
	F5	female	25	57.9	158	8 {13}	–	–
	F6	female	21	54.0	167	11 {13}	–	16 {20}
	F7	female	28	46.3	167	–	–	21 {25}
All flyers			24.6	53.0	162.6	19 {26}	36 {43}	96 {128}
			± 2.5	± 4.1	± 5.0			
Base	B1	male	35	120.3	193	–	–	14 {16}
	B2	male	30	86.5	181	–	–	12 {17}
	B3	male	27	92.0	175	8 {13}	12 {13}	9 {16}
	B4	male	26	76.5	185	–	–	10 {16}
	B5	male	25	83.5	190	11 {13}	11 {17}	10 {16}
	B6	male	38	82.6	181	–	–	12 {16}
	B7	male	30	113.7	178.5	–	–	16 {16}
	B8	male	30	81.6	172	–	13 {13}	13 {15}
All bases			30.1	92.1	181.9	19 {26}	36 {43}	96 {128}
			± 4.2	± 15.0	± 6.7			
All athletes			27.5	73.8	172.9	Successful pop-offs: 151		
			± 4.5	± 22.6	± 11.3	Total pop-offs: {197}		

Pseudonymization of the seven female flyers (F1,…,F7) and eight male bases (B1,…,B8) together with their age, mass, and height. Mean values for flyers, bases, and all athletes are given alongside their standard deviation (± sign). Last three columns contain the number of successful and total {in curly brackets} pop-offs, respectively, for each athlete at the test days.

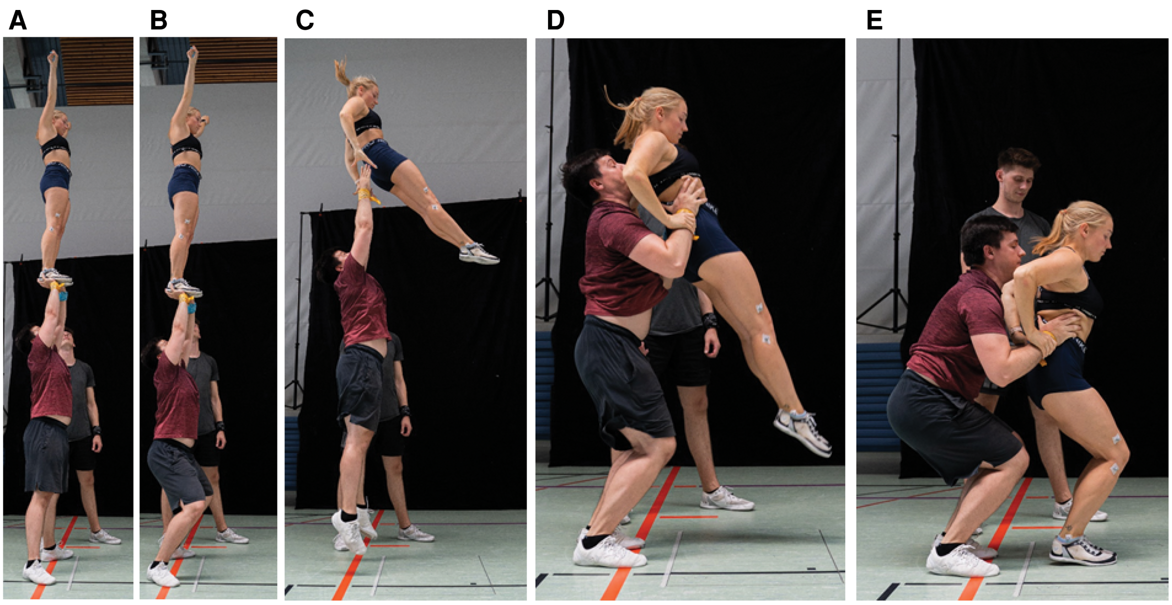

FIGURE 1
Pop-off technique in five sequences. (A) The flyer is in the extended position. (B) The base bends the knees to initiate the dismount and to signal the flyer. (C)–(D) the base grabs the hips and tries to decelerate the flyer, while the flyer grabs the wrists of the base. (E) The flyer lands on the force plate.

32 adjectives, categorized into four recovery items (R1: physical performance, R2: mental performance, R3: emotional balance, and R4: general recovery status) and four stress items (S1: muscular strain, S2: lack of activation, S3: emotional dysbalance, and S4: general stress level). All items were ranked by a seven-point Likert-type scale (ranging from 0 for "strongly disagree" to 6 for "strongly agree"). After an autonomous 10-min warm-up, the athletes were labeled as "rested". In this state, each athlete performed three counter-movement jumps (CMJ) as well as a sit-and-reach test, both serving as baseline references to asses the

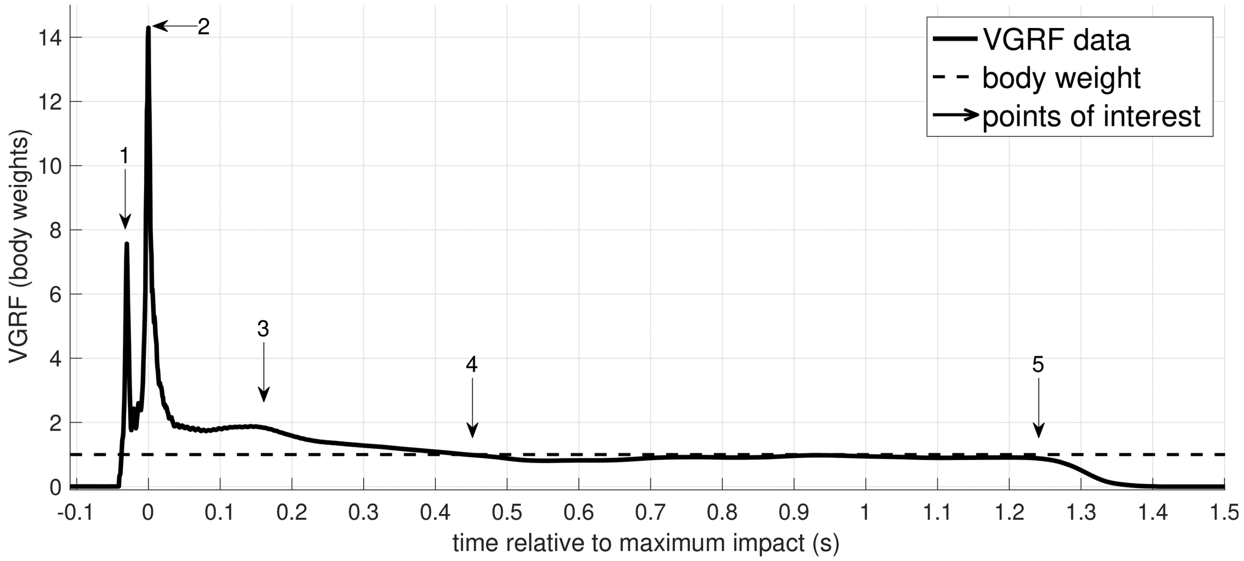

FIGURE 2
Exemplary measured VGRF-time course during “pop-off” landing. The graph gives a detailed overview of the landing impact, see Figure 1E. Points of interest are (1) toe strike, (2) heel strike, (3) minor peak presumably due to a combination of wobbling masses (24–26) and altered muscle activities (27), (4) reaching of BW, and (5) leaving the force plate.

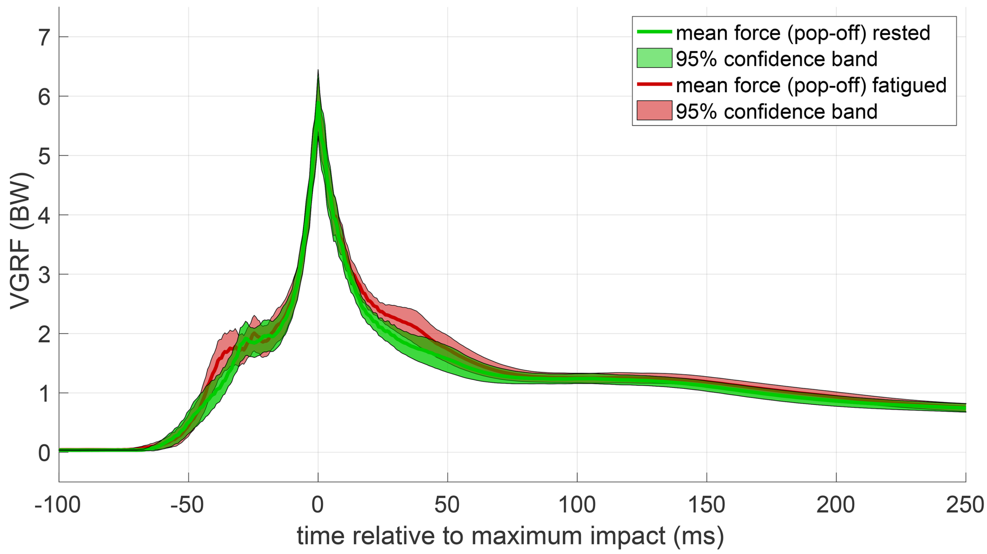

FIGURE 3
Mean VGRF-time courses of all flyers. Pop-off impact forces before (green) and after (red) the workout are juxtaposed. Lines show the mean force-time course and correspondingly shaded areas the 95% confidence bands.

effect of the fatiguing workout (23). Negative values for the sit-and-reach test indicate that athletes were not able to reach their toes. The flyer-base pair combinations for the pop-off measurements were chosen by the corresponding author, based on a predetermined succession that ought to ensure a smooth progress and multiple combinations. Due to time restrictions, each flyer did not conduct pop-offs with each base and vice versa. Only few (≤ 3) measurements of each pair were performed in a row to ensure low latency times for the other athletes. All VGRF measurements were captured by a force plate (KISTLER type: 9287BA, Winterthur, Switzerland) with a 1,500 Hz sampling rate and the software myoForce (Noraxon, USA, version MR3 3.10.30). The bases were placed directly next to the plate with their toes pointing towards the plate but not touching it. The flyers had to plan their landing onto the plate, whereas the bases were instructed not to step on the plate at all. A spotter

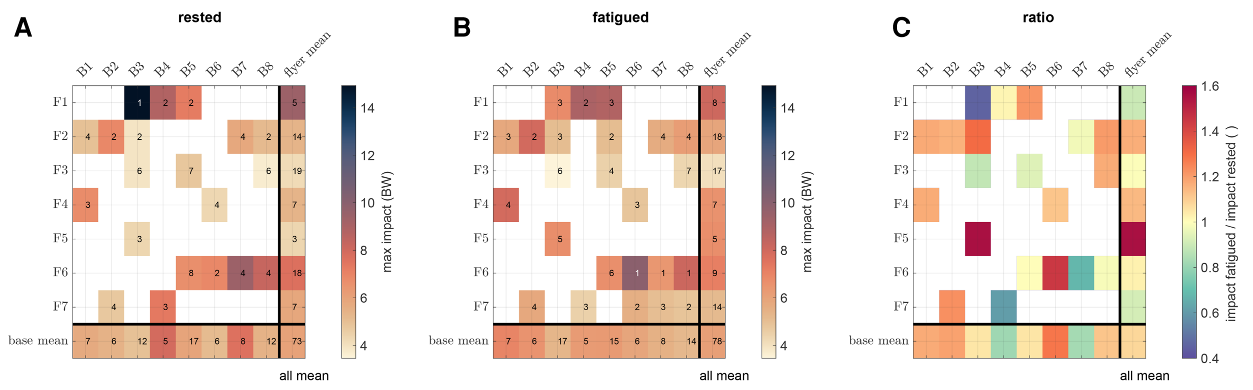

FIGURE 4
Effect of fatigue on maximum VGRF in individual flyer-base combinations. (A) Matrix plot of mean maximum VGRF in rested flyer-base pairs. Colors indicate the magnitude of VGRF. Numbers within the fields represent the corresponding quantity of stunts performed by each pair. (B) Matrix plot of mean maximum VGRF in fatigued flyer-base pairs. (C) Matrix plot of the ratio between rested and fatigued impact with a divergent colormap indicating an increase (red) or a decrease (blue) in mean maximum VGRF.

supported the base during the mounting of the flyer, directing the bases towards the plate, and observing the landing. If the flyer did not land on the plate with both feet or if the base additionally stepped on the plate, the pop-off was labelled "not successful" and left out of the analysis. Out of 197 pop-offs performed in total, 151 were successful (see Table 1).

After the first period of measurements, a 25 min high-intensity workout was performed. The workout comprised two rounds of 18 different exercises, each with 20 repetitions and 10 s pause in between – for example, squats, push-ups, lunges, sit-ups, mountain climbers, or jumping jacks. Athletes thereafter were labeled as "fatigued". A second set of measurements was conducted, not necessarily in the same order as before. In between the measurements, after approximately 40 min, there was a brief intermission, in which the participants were asked to fill out Borg's CR10-scale [category-ratio scale from 0 at minimum exertion to 10 at maximum exertion (30), Table 2] as well as a Short Recovery and Stress Scale (SRSS) questionnaire (28, 29). In the SRSS questionnaire, each four adjectives for the eight ARSS items (R1–R4 and S1–S4) are condensed into a single adjective – resulting in a less time-intensive yet well-validated form of the ARSS . The intermission was also used to performed another set of three CMJ and two sit-and-reach tests. For athletes that participated in more than one testing day (see Table 1), the average of all obtained pre-post values were considered in Tables A1 and A2. Pop-off measurements were continued after the intermission, with athletes still labeled as "fatigued". Note that while bases were active during CMJ, they were passive (catching) during pop-off stunts. From the 151 successful pop-offs, 73 were conducted by rested athletes compared to 78 by fatigued athletes (see Figure 4).

2.4 Data analysis and statistics

Post-processing of the data was conducted in MatLab (MathWorks, USA, version R2023b). No filtering procedure was applied to the force-plate data. To ensure comparability, all VGRF-time curves of both pop-off and CMJ were divided by the body weight (BW) of the flyer, shifted to $t = 0$ s at the instant of maximum (peak) impact, and cropped to 100 ms before and 250 ms afterwards, respectively. To test our first hypothesis that fatigued athletes would land (or catch) differently than rested ones, statistical parametric mapping (SPM, i.e. time-dependent, two-sided, paired t-test) was performed using the SPM MatLab package, available at https://spm1d.org (31). Contrary to t-tests for maximum VGRF alone, SPM offers the possibility to detect significant variations along the whole force-time courses. Normality of data was ensured by performing an upstream Kolmogorov–Smirnov goodness-of-fit test. To test our second hypothesis and also undergird the first, a three-way analysis of variance (ANOVA) was carried out, investigating the influence of the factors "base" (levels: B1,…,B8), "flyer" (levels: F1,…,F7), and "fatigue" (levels: 0 and 1) on the set of peak VGRF values. To test our third hypothesis that landing performance in CMJ and pop-off were related, we calculated the correlation coefficient r for both flyers and bases in both rested and fatigued state. A best-fit line was calculated, whose slope was tested for being significantly different from zero (32) using the test statistic

$$T = \frac{r \cdot \sqrt{n-2}}{\sqrt{1-r^2}}, \qquad (1)$$

where n denotes the number of flyers or bases, respectively. The corresponding p-value was calculated as $p = 2 \cdot (1 - F_{t_n}(T))$, where F_{t_n} denotes the cumulative distribution function of the t-distribution with n degrees of freedom. Further, an additional ANOVA was carried out to investigate the influence of the aforementioned factors on the quotient between pop-off and CMJ peak VGRF values. To test whether the fatiguing workout had any effect on the sit-and-reach or CMJ performance, as well as on the SRSS, a pre-post paired t-test on the individuals' mean values was performed. The null hypothesis always assumed that pre- and post-performance were equal with the alternative claiming poorer performances in fatigued athletes – yielding corresponding p-values and Cohen's d values for measuring effect sizes. As common, the p-value is interpreted as the conditional probability of an absolute pre-post deviation at least as large as the observed one, under the condition that the null hypothesis is true. Regarding the interpretation of Cohen's d, we follow the "rules of thumb" of Sawilowsky (33), i.e. distinguish between small ($d < 0.2$), medium ($0.2 \leq d < 0.8$), large ($0.8 \leq d < 1.2$), very large ($1.2 \leq d < 2$), and huge ($d \geq 2$) effect sizes. Finally, VGRF measurements were additionally equipped with their corresponding time stamp relative to the end of the intense workout. Doing this, we aimed for resolving the individual temporal progress of maximum impact forces.

3 Results

We begin with results on the effectiveness of the fatiguing workout. Detailed results of the workout-induced indices are summarized in Appendix A for both, the effects on the athletes' performances including their CR10 (Borg scale) scores (Table A1) and the result of the ARSS/SRSS questionnaires (Table A2). In brief, the subjective exertion during the workout was rated with a CR10 value of 6.8 ± 1.1 for the flyers and 6.3 ± 1.0 for the bases, i.e. was considered to be "very strong" but not exhaustive throughout. The physical effects of this workout were, on average, the following: (i) a significant decrease in sit-and-reach performance (for all athletes from 11.2 ± 11.5 cm to 9.7 ± 11.5 cm), (ii) a significant decrease in CMJ height (all athletes: from 32.3 ± 7.8 cm to 30.8 ± 7.2 cm), (iii) a slight – but not significant – decrease in CMJ impact force (all athletes: from 4.1 ± 1.3 BW to 3.9 ± 1.0 BW), and (iv) a slight increase in pop-off-impact force (all athletes: from 6.0 ± 1.5 BW to 6.1 ± 1.0 BW). Nevertheless, individual athletes showed opposite trends in certain metrics, see Table A1 for details. The effect sizes of all tests were small ($d < 0.2$) to medium ($d < 0.5$). Contrary, the effect sizes for the stress-recovery-item scores were medium to huge ($d > 2$). As expected, the recovery-item scores (R1–R4) went down, while the stress-item scores (S1–S4) increased. Particularly general stress level (S4), muscular strain (S1), general recovery status (R4), and physical performance (R1) changed (highly) significantly due to the workout. Only non-significant changes occurred for emotional balance (R3) and dysbalance (S3). For detailed values, see Table A2.

The effect of the fatiguing workout on the flyers' landing performances is shown in Figure 3. Contrary to our first hypothesis, the average VGRF-time characteristics are close, except for slightly increased landing forces 30–40 ms before and after the maximum impact. This closeness was also observed at a more detailed resolution on the level of individual flyers and bases before and after the workout (see Figures B1, B2 in Appendix B). Accordingly, a subsequent SPM (see Appendix C) revealed no significant differences at any time instance, neither for the entirety of flyers nor for each flyer individually (diagonal panels in Figure C1). The same held true for the catching performance of the bases (diagonal panels in Figure C2). Consistently, the ANOVA yielded a non-significant ($p = 0.46$) effect of fatigue on peak VGRF values.

To resolve our measurements on an individual performance level, Figure 4 shows the average maximum VGRF values for each flyer-base pair. Note that not every base was paired with every flyer due to the three-day experimental setup and time limitations. Yet, individual pairings seem to have substantial influence on the maximum landing impact. For example, the rested flyers F1 and F6 in Figure 4A showed overall high maximum impact, which however differed by several BWs depending on the catching base. Particularly the flyer-base combination F1-B3 produced a maximum impact of 14.9 BW, despite B3 being the base with the lowest average impact of 4.9 BW of the flyers caught. The smallest single achieved maximum impact was 2.1 BW by the pair F3-B8, who also held the smallest average maximum impact of 3.7 BW.

VGRFs for the fatigued pairs likewise showed a highly individual-dependent profile (Figure 4B). To better assess the changes from before to after the workout, the ratio between rested and fatigued mean maximum VGRF values is shown in Figure 4C. Again contrary to our hypothesis that fatigue would cause higher maximum impact forces (see e.g. pairs F5-B3 and F6-B6), some flyer-base pairs even reduced their impacts by up to 50% (particularly pairs F1-B3, F7-B4, and F6-B7). Across flyers or bases – on average – no significant increase could be discerned. However, an interesting result arose from SPM of inter-flyer and inter-base comparison before and after workout (see lower and upper triangular panels in Figures C1, C2, respectively). Here, the landing characteristics of flyers partly differed significantly around the time instance of maximum impact, particularly for flyer F3. On the other side, the catching characteristics of bases did not differ significantly at any time instance. This was again underpinned by the ANOVA analysis, reporting a highly significant influence of the flyer ($p < 10^{-16}$), but only a weak influence of the base ($p \approx 0.086$).

To compare landing impacts with and without partners, maximum VGRF during CMJ and during pop-off measured were juxtaposed in Figure 5. In accordance with our hypothesis that higher landing impacts during CMJ positively relate to higher impact forces during pop-offs, rested flyers showed a high correlation coefficient of $r = 0.71$, which highly significantly differed from zero ($p \approx 0.01$), according to Equation (1). However, correlation and thus significance vanished for fatigued flyers ($r = 0.13$, $p > 0.1$). For rested and fatigued bases, both the CMJ and pop-off impacts were expectedly not significantly correlated ($|r| < 0.4$, $p > 0.1$), as their landing mechanics during CMJ have nothing to do with their catching mechanics during pop-offs. When the ANOVA was performed for the quotient between pop-off and CMJ peak impact force, the influence of all factors decreased but did not change the aforementioned significances (flyers: $p < 10^{-12}$, bases: $p \approx 0.17$, fatigue: $p \approx 0.98$).

As a last observation, the time-resolved VGRF evolution for each flyer and each base are shown in Figure 6. The experiments for rested pairs were hereby lumped into the time instance $t = 0$ s – assumed to serve as a reference – while the time stamps of the pairs after the workout were divided into intervals of

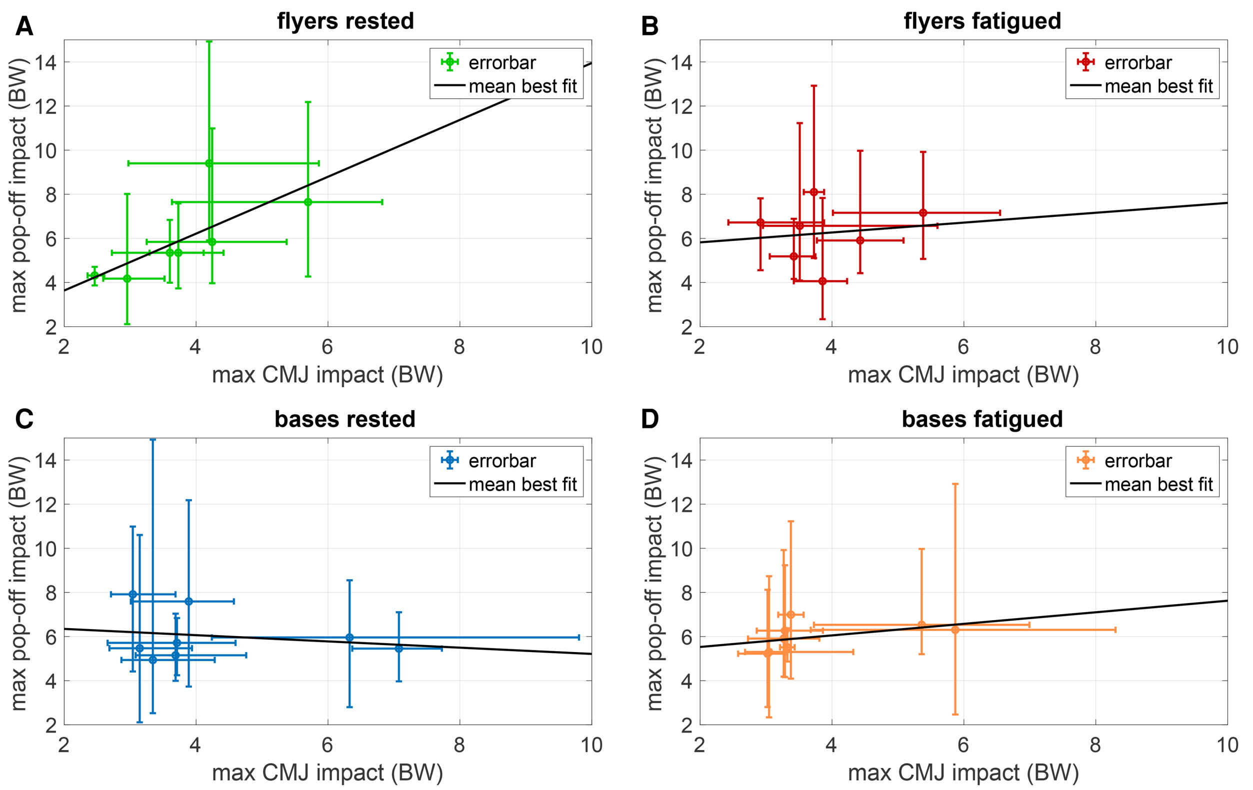

FIGURE 5
CMJ vs. pop-off impacts in rested and fatigued athletes. Colored dots indicate mean maximum pop-off impact vs. mean max CMJ impact (Table A1) with colors corresponding to VGRF-time curves in Figures B1 and B2. Errorbars indicate the range of the measurements. Best-fitting lines through the mean values are shown in black lines with slopes 1.29 for rested flyers (A), 0.22 for fatigued flyers (B), −0.14 for rested bases (C), and 0.26 for fatigued bases (D).

15 min. Within these intervals, the mean time and VGRF for each flyer and base was determined and displayed along with errorbars for the absolute range (Figure 6A,C). To better estimate the changes in performance of each individual, all VGRF values were scaled (additionally to being already normalized to the body weight) to their corresponding rested state value in Figure 6B,D. These plots again suggest a highly individualized response to the fatiguing workout: While some flyers (e.g. F2, F3, F4, and F5) and bases (e.g. B1, B2, B6, and B8) showed an initial increase and a subsequent decrease in VGRF after the workout, some other flyers (e.g. F1 and F7) and bases (e.g. B4 and B7) showed decreased VGRF right after the workout.

4 Discussion and implications

4.1 Measured impact forces put in context

In this study, we found that maximum VGRF during pop-off landing reached values between 2.1 and 14.9 BW (6.0 ± 1.5 BW for rested and 6.1 ± 1.0 BW for fatigued athletes). The mean to maximum VGRF values are comparable to those reported for somersaults (6.8–13.3 BW) (34) or two-foot landings in gymnastics during training and competition (5–11 BW) (15). The maximum VGRF of 14.9 BW also comes close to the theoretically predicted peak force of 15.3 BW in two-leg landing without support [(35), Equation (4), Figure 3], which we extrapolated by assuming a drop height of 220 cm. On the other hand, the minimum VGRF of 2.1 BW is significantly less than these reported values, which can be explained by the supporting role of the base, see Section 6. It can only be assumed that our measured VGRF values are reliable estimates for typical training environments, as the flyer-base pairs were experienced, but aware of the measurements, and thus keen to perform flawless stunts. Future investigations should also consider real-life training situations, with inexperienced or unwary pairs as well as during unplanned drops.

As to our first hypothesis, our results showed no significant effect of fatiguing on the peak impact forces during pop-offs, which is in line with prior findings on single-leg landing (36, 37). Regarding the second hypothesis, both SPM and ANOVA unambiguously show that the flyer significantly influences the peak impact force, while the base does not. There is, to date, no biomechanical study resolving the issue of flyer-base interaction, see Section 6. The third hypothesis, addressing a possible connection between CMJ and pop-off peak impact forces, could partly be answered by showing a significant correlation in the rested state, while the correlation was not significantly different from zero in the fatigued state. Finally, with regard to monitoring

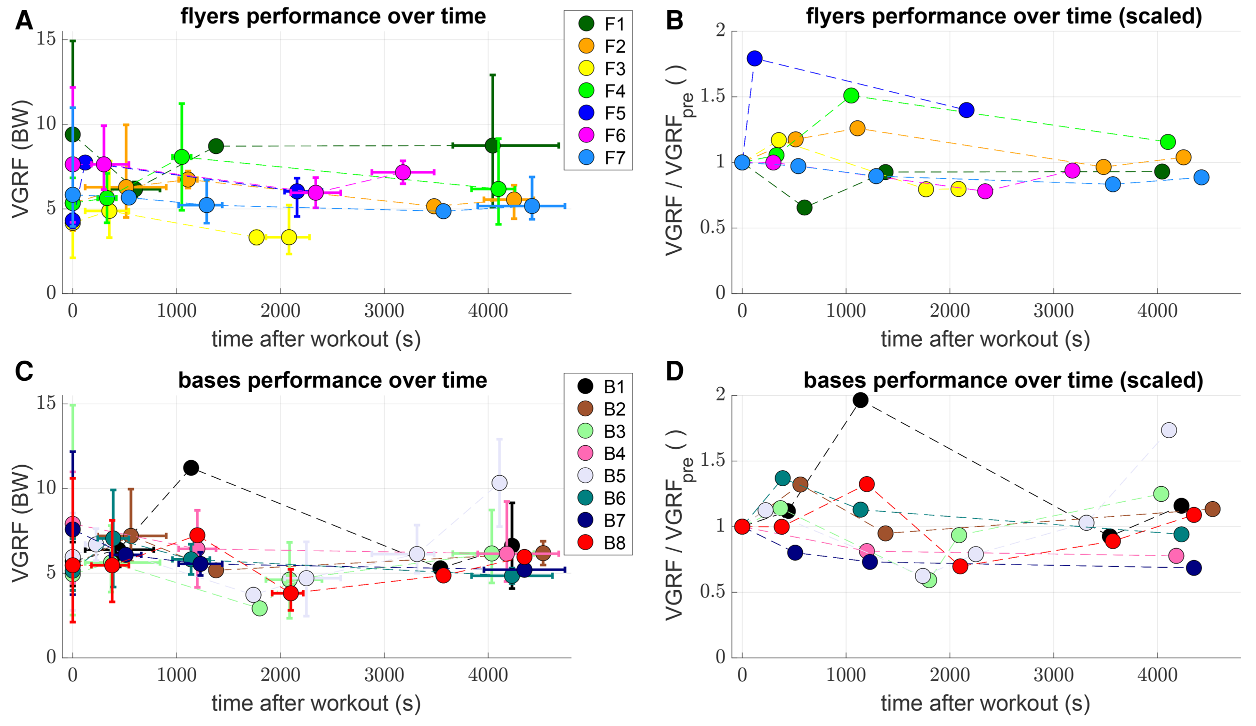

FIGURE 6
Consider individual changes of impacts over time. Plots of mean maximum VGRF after pop-off vs. mean time after the fatiguing workout at $t = 0$ s (colored dots) in intervals of 15 min (900 s) for both jumping flyers (A) and catching bases (C). Correspondingly colored errorbars indicate the range, i.e. minimum and maximum value within each interval. (C) and (D) show the values of (A) and (C) normalized to the mean VGRF of each individual athlete in the rested state, i.e. the $t = 0$ s value.

FIGURE 7
Pose estimation of different flyers during maximum impact. Representative measurements of angles $\phi_{flyer,joint}$ for different flyer-base pairs (left: F1-B3, mid: F6-B5, right: F2-B7) and different joints (toe, ankle, knee, and hip) at the time instant of maximum VGRF.

the VGRF profiles over time, we found highly individual patterns with no systematic regularities.

4.2 Injuries related to high impacts

Besides injuries caused directly by the measured high impacts (3, 6–9), degenerative changes can occur as a consequence of repetitive overloading (2). To obtain a rough estimate on the stresses acting in the ankle joint, let us consider a mean cartilage area of about $484\,mm^2$ [(38), Table 2] in the flyer's ankles. The mean maximum VGRF (≈ 6 BW) times the body mean weight of the flyers (Table 1) yields $6.0\,BW \cdot 53.0\,kg/BW \cdot 9.81N/kg \approx 3{,}120\,N$. This force, divided by two feet and the ankle area results in a peak cartilage stress of $3{,}120\,N/(2 \cdot 484 \cdot 10^{-6}\,m^2) \approx 3.2\,MPa$ in each ankle. For comparison, maximum stress for flyer F1 (max VGRF

14.9 BW, mass 54.1 kg) lay around 8.2 MPa. Although these values are far below the 15–20 MPa reported as a critical value for causing permanent cell death of the cartilage in the knee (39), the latter lies above the threshold of 4.5 MPa reported as the start of chondrocyte apoptosis (40). Consequently, it could be possible that repetitive stresses after pop-off dismounts lead to long-term degenerative changes of the cartilage, if a 53 kg flyer showed a repetitive maximum impact of more than $\approx$ 8 BW. Note here that pop-offs constitute rather simple stunts. Consequently, mean VGRF – and thus injury risk – may increase with or depend on the difficulty of more complex routines.

4.3 Landing techniques and training requirements

Based on our rough estimate on ankle stresses during cheerleading stunts and the corresponding injury risk during both cheerleading training and championships, precautions against high impact forces should be taken. Two known precautions include proper landing techniques (41) and suitable surfaces (42).

The former precaution calls for experienced trainers and detailed biomechanical analyses (see also Section 6.). Impact forces occurring during landing cause a considerable increase in external bending moments, particularly in the knee, which requires a proportional increase in muscle forces to counteract these moments (41). Hence, a well-controlled landing phase is crucial – encompassing the management of the center of mass trajectory, body momentum, and angular rotation (15). The posture of the trunk likewise plays an important role in determining landing forces and quadriceps activation. A more flexed upper trunk causes flexed knees and hips, thereby reducing landing forces and thus the associated risk of injury (41, 43). As our results suggest that CMJ peak forces are correlated with pop-off peak forces, and that flyers predominantly influence the latter, we conjecture that improving the CMJ landing in flyers could already have a positive effect on their stunt landing. In this regard, proprioception and strength training may be beneficial for athletes (44). Alternatively, McNair et al. (45) showed that already few verbal instructions, or auditory feedback in general, could help to improve landing techniques, indicated by obtaining significantly lower peak VGRF. Whether these results are transferable to cheerleading yet remains an open question.

The mentioned precautions are subject to local availability. The International Cheer Union (ICU) argues in favor of accessibility, costs, and the grassroot growth of cheerleading to advocate standard foam mat floors instead of spring floors for their championship (46). The European Cheer Union (ECU) follows this recommendation (47), while the CCVD requires spring floors (48) – at least for championships. Aside from these championships, most stunts are being practiced during training sessions at the local clubs. To the best of our knowledge, no reports exist on either prevailing training conditions or injury prevalence in Europe (and thus Germany). Therefore, we are of the opinion that further biomechanical studies on the performance and safety of stunt landings ought to be carried out, e.g. regarding acute or overuse injuries (15, 44) or flooring (42). As a consequence, both ICU and CCVD could establish joint, science-backed guidelines on training conditions within their purview. This holds for planned dismounts, but particularly for accidental drops, which happen frequently during training.

5 Limitations

This study has several limitations concerning the quantity and validity of the measurements. For this project, we only evaluated VGRFs of a single stunt (pop-off) in a controlled environment. To the best of our knowledge, we are the first group to report VGRFs during Cheerleading stunts. Hence, no validation of our results with respect to comparable datasets was possible. This holds in particular for the effects of fatiguing training. In this study, we found no significant effect of a high-intensity workout on the athletes' average VGRF-time performance. However, if the absence of such an effect was caused by insufficient fatigue, extended pauses, poor choice of exercises, or systematic bias in the questionnaire could not be resolved. Future studies will thus have to include a broader spectrum of workouts, stunt techniques, landing surfaces (mats), training methods, and footwear (see Section 4.1) to quantify their corresponding influences reliably (42). Further, kinematic tracking of the flyer (and the base) are necessary to assess differences in dismounting, e.g. variations in dipping, foot placement, landing technique (see Section 6.), or deceleration measures (49). Such kinematic information would also enable to inform inverse dynamic models (26) in order to estimate the force propagation along the flyer's body. Last, aside from compressive VGRFs, shear forces such as medio-lateral and anterior-posterior GRFs will have to be compared, as these are considered a key factor in landing injuries (50).

6 Perspective: the biomechanical role of the base

Contrary to usual reports of VGRF in jumping, running, or tumbling, a distinguishing aspect of cheerleading is the existence of a supporting base, see Figures 1 and 7. Depending on the flyer-base interaction, we measured a total range of 12.8 BW ($= 14.9\,\text{BW} - 2.1\,\text{BW}$ in VGRF during landing from approximately the same height, constituting a vast variability. To our knowledge, no biomechanical study has yet thoroughly investigated the role of supported landing. In this section, we motivate this investigation to be conducted in further studies.

As mentioned in Section 4.3, a variety of heterogeneities already ought to be considered in the flyer's landing alone. The coupling of the landing with a base adds even more. Here, we have investigated the impacts of rested and fatigued flyer-base partners, but their individual contribution on maximum VGRF could not be resolved. Further, our flyer-base teams were well-attuned to each other, but it can be assumed that the same flyer's VGRF would differ significantly with a completely unfamiliar base. To what extent, however, has yet to be quantified.

Apart from these individual factors, bases cause a more fundamental change in landing biomechanics. In Figure 7, the differences in body geometry of the flyer at the time instance of maximum impact are shown for three exemplary (rested) flyer-base pairs. For this, screenshots of the videos were manually marked with six points of interest, namely (i) reference point on the floor, (ii) different point on the floor at which the toe joint touched the ground, (iii) estimated mid point of the ankle joint, (iv) estimated mid point of the fibula head at the knee, (v) estimated mid point of the Trochanter major at the hip, (vi) estimated mid point of the shoulder joint. From these markers, we obtained five point-to-point segments (floor, foot, lower leg, upper leg, torso) and thus four joint angles between adjacent segments (toe, ankle, knee, hip). We denoted these angles $\phi_{\text{flyer, joint}}$ to distinguish flyers and joints. Note that the placement of the markers has not been validated, might be prone to errors, and serves for purely qualitative, descriptive purpose here.

The three exemplary pairs were F1-B3 (Figure 7, left), F6-B5 (mid), and F2-B7 (right) with decreasing maximum VGRFs of 14.9 BW, 7.5 BW, and 3.7 BW, respectively. Whether the effects stated hereinafter were statistically significant, or how the geometric changes propagated through the entire landing phase, was not further investigated due to low image quality and lack of clearly visible body landmarks. Solely based on these three samples, we note the following observations. First, the hip joint marker in all three athletes is placed more dorsally than the ankle joint marker. In gymnasts' landing, this would certainly result in toppling down backwards, as the center of mass is not supported by the feet. Second, the knee joint markers were positioned further forward the lower the maximum VGRF. For flyer F2, the knee joint even protruded over the toes. Third, in accordance with Blackburn and Padua (41), a more backwards extended trunk seemed to correspond to higher VGRF. Fourth, flyer F2 was able to distinctly reduce the knee angle ($\phi_{\text{F2,knee}} = 113.4^\circ$) in comparison to flyer F6 ($\phi_{\text{F6,knee}} = 125.7^\circ$), by not landing on the heel, but on the toes only, thereby increasing the toe joint angle.

In summary, further biomechanical studies on cheerleader's landing ought to consider these geometric alterations of the flyers in order to provide insight on how to reduce the risk of injuries.

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 University of Koblenz. 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

AM: Conceptualization, Data curation, Methodology, Project administration, Visualization, Writing – original draft; RR: Conceptualization, Data curation, Formal Analysis, Project administration, Visualization, Writing – original draft; AKA: 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.

Publisher's note

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Appendix

A. Stress-recovery data

TABLE A1 Effects of the fatiguing workout on athletes.

Identifier	CR10 score	Sit and reach		CMJ height		CMJ impact		pop-off impact	
	( )	(cm)		(cm)		(BW)		(BW)	
		Pre	Post	Pre	Post	Pre	Post	Pre	Post
F1	6.0	16.2	13.0	29.5	26.4	4.2	3.7	9.4	8.1
F2	5.0	20.6	19.7	25.9	21.4	3.7	4.4	5.3	5.9
F3	7.0	17.0	15.6	29.4	31.5	3.0	3.9	4.2	4.1
F4	8.3	19.2	18.5	25.9	26.7	3.6	3.5	5.3	6.6
F5	8.0	19.0	16.6	25.2	25.0	2.5	2.9	4.3	6.7
F6	6.5	19.0	18.7	31.3	31.2	5.7	5.4	7.6	7.2
F7	7.0	24.3	23.7	28.5	25.2	4.2	3.5	5.8	5.2
All flyers	6.8	19.3	18.0	28.0	26.8	3.8	3.9	6.0	6.2
	± 1.1	± 2.6	± 3.9	± 2.3	± 3.6	± 1.0	± 0.8	± 1.9	± 1.3
		$p = 0.02$		$p = 0.25$		$p = 0.84$		$p = 0.64$	
		$d = 0.45$		$d = 0.39$		$d = 0.05$		$d = 0.14$	
B1	8.0	2.7	1.1	27.1	26.0	3.7	3.4	5.7	7.0
B2	7.0	18.7	14.9	46.3	43.8	7.1	5.4	5.5	6.5
B3	6.7	-3.8	-3.8	42.3	41.4	3.3	3.0	4.9	5.3
B4	6.0	19.1	15.2	39.0	37.3	3.0	3.3	7.9	6.3
B5	6.7	12.0	14.1	46.7	42.6	6.3	5.9	6.0	6.3
B6	5.0	-5.4	-11.4	33.7	29.2	3.7	3.3	5.2	5.9
B7	5.0	-12.8	-11.9	21.4	23.5	3.9	3.3	7.6	5.5
B8	6.0	2.6	1.7	32.5	31.1	3.1	3.0	5.5	5.2
All bases	6.3	4.1	2.5	36.1	34.4	4.28	3.8	6.0	6.0
	± 1.0	± 11.6	± 11.3	± 9.1	± 7.9	± 1.53	± 1.1	± 1.1	± 0.6
		$p = 0.13$		$p = 0.05$		$p = 0.05$		$p = 0.97$	
		$d = 0.14$		$d = 0.21$		$d = 0.34$		$d = 0.02$	
All athletes	6.5	11.2	9.7	32.3	30.8	4.1	3.9	6.0	6.1
	± 1.1	± 11.5	± 11.5	± 7.8	± 7.2	± 1.3	± 1.0	± 1.5	± 1.0
		$p = 0.01$		$p = 0.02$		$p = 0.20$		$p = 0.76$	
		$d = 0.13$		$d = 0.19$		$d = 0.20$		$d = 0.08$	

Different measures before and after the intense workout are summarized. The CR10 score of Borg's psychophysical exertion scale (0: minimum, 10: maximum), the sit-and-reach range, CMJ height and impact, as well as pop-off impact are thought to indicate the strenuousness of the workout. Statistical measures such as mean, standard deviation (± sign), as well as p-values and Cohen's d effect sizes of the paired t-tests are given for all flyers, all bases, and all athletes, respectively.

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TABLE A2 Results from recovery-stress questionnaires.

	R1		R2		R3		R4		S1		S2		S3		S4	
Identifier	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
F1	2.5	2	4	2	4.25	2	2	0	2.25	4	0.25	2	1.5	0	3.75	5
F2	4.5	4	4.5	4	5.25	5	4.5	2	0.25	4	0.5	1	0.5	0	0.75	4
F3	5.25	3	5.25	3	5.75	5	5	2	0.25	4	0	1	0.25	2	0.5	4
F4	3.75	3	3.75	3.33	4.1	3.66	3.75	3	1.7	4.7	1.6	2.3	2	2	1.8	4.7
F5	2.5	2	3.5	4	3.25	3	2	3	5.5	3	2	3	3.25	2	4	5
F6	4.75	3.5	4.5	4.5	4.9	5	3.25	2.5	3.6	4	0.6	2.5	1.5	1	2.9	3
F7	3.25	3	5	5	4.5	6	2.5	2	3	4	1.75	1	1.25	2	3.5	4
All flyers	3.79	2.93	4.36	3.69	4.57	4.24	3.29	2.07	2.36	3.96	0.96	1.83	1.46	1.29	2.46	4.24
	± 1.01	± 0.68	± 0.6	± 0.93	± 0.76	± 1.29	± 1.11	± 0.94	± 1.74	± 0.46	± 0.74	± 0.77	± 0.92	± 0.88	± 1.34	± 0.66
	$p = 0.02$		$p = 0.14$		$p = 0.46$		$p = 0.06$		$p = 0.11$		$p = 0.04$		$p = 0.69$		$p = 0.01$	
	$d = 0.92$		$d = 0.79$		$d = 0.29$		$d = 1.10$		$d = 1.16$		$d = 1.07$		$d = 0.18$		$d = 1.57$	
B1	4.25	0	5.25	1	5.5	0	4.25	1	1.25	6	0.75	2	2.25	4	3	5
B2	4.25	2	5.5	4	5.25	4	4	1	1.5	3	0.5	1	0.25	1	1	4
B3	5.1	1.7	5.3	4.3	5.3	4	5	2.3	2.7	3.7	0	1.7	0	1.3	0.75	4.3
B4	4	2	5	2	3.5	4	4.5	2	0.75	4	1.75	1	1	1	1	5
B5	3.2	1.7	4.5	3	4.1	4	3.1	1.7	0.9	3.7	1.1	2.7	1.75	1	2.9	4.3
B6	5	4	6	5	5.25	6	5.25	4	2.25	4	0	0	0.25	0	0.25	2
B7	5	3	4.5	5	5	5	3.25	2	2.5	4	0.25	1	1	0	1.25	4
B8	4.25	2	4.6	3	4.6	4.5	3.6	2	2.6	3.5	2.1	2	2.4	1.5	1.9	4
All bases	4.38	2.05	5.08	3.41	4.81	3.94	4.12	2.0	1.81	3.99	1.37	1.43	1.11	1.23	1.51	4.08
	± 0.6	± 1.07	± 0.5	± 1.34	± 0.65	± 1.63	± 0.73	± 0.88	± 0.75	± 0.82	± 1.55	± 0.79	± 0.87	± 1.17	± 0.94	± 0.88
	$p \ll 0.01$		$p = 0.01$		$p = 0.26$		$p \ll 0.01$		$p \ll 0.01$		$p = 0.09$		$p = 0.77$		$p \ll 0.01$	
	$d = 2.51$		$d = 1.54$		$d = 0.66$		$d = 2.45$		$d = 2.60$		$d = 0.76$		$d = 0.10$		$d = 2.65$	
All athletes	4.1	2.46	4.74	3.54	4.7	4.08	3.73	2.03	2.07	3.97	1.18	1.61	1.28	1.25	1.95	4.15
	± 0.87	± 1.01	± 0.66	± 1.17	± 0.71	± 1.49	± 1.01	± 0.91	± 1.34	± 0.68	± 1.26	± 0.8	± 0.91	± 1.04	± 1.24	± 0.79
	$p \ll 0.01$		$p < 0.01$		$p = 0.16$		$p \ll 0.01$		$p \ll 0.01$		$p < 0.01$		$p = 0.93$		$p \ll 0.01$	
	$d = 1.69$		$d = 1.22$		$d = 0.52$		$d = 1.70$		$d = 1.74$		$d = 0.92$		$d = 0.02$		$d = 2.05$	

Juxtaposing the four recovery items (R1: physical performance, R2: mental performance, R3: emotional balance, and R4: general recovery status) and the four stress items (S1: muscular strain, S2: lack of activation, S3: emotional dysbalance, and S4: general stress level) before (pre) and after (post) the fatiguing workout. Statistical measures such as mean, standard deviation (± sign), as well as *p*-values and Cohen's *d* effect sizes of the paired *t*-tests are given for all flyers, all bases, and all athletes, respectively. If $0.001 < p < 0.01$ it is indicated by $p < 0.01$, if $p \leq 0.001$ we write $p \ll 0.01$.

B. Individual VGRF-time courses before and after workout

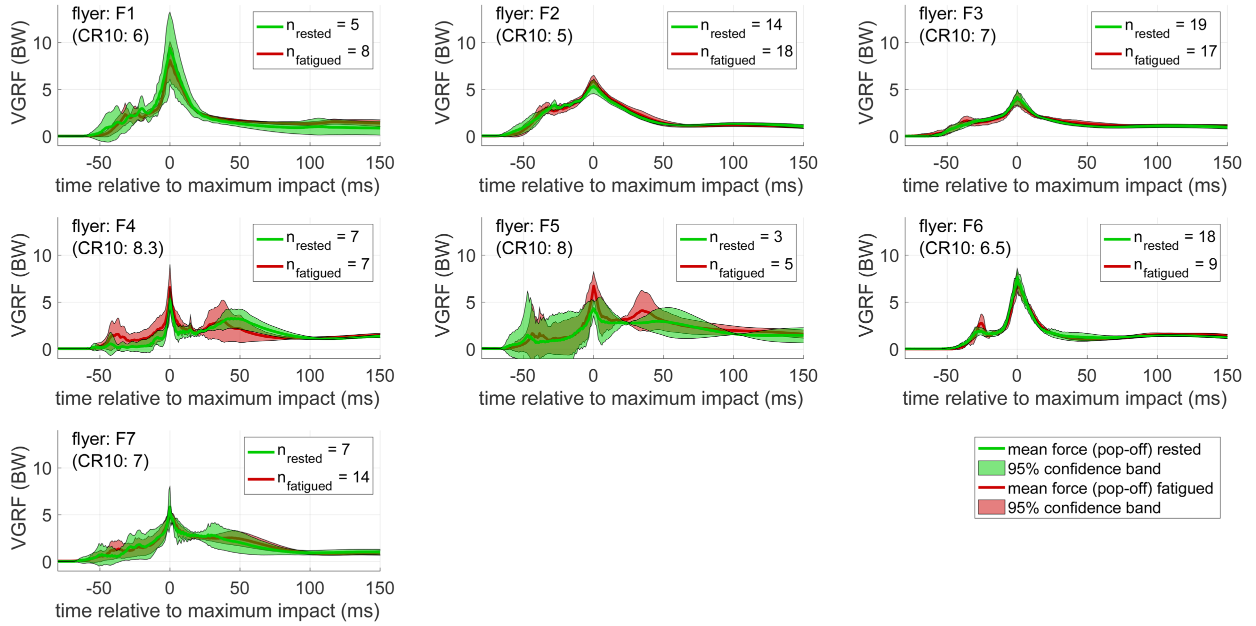

FIGURE B1
Mean VGRF-time courses of individual flyers (jumping). Pop-off impact forces before (green) and after (red) the workout are juxtaposed. Lines show the mean force-time courses and correspondingly shaded areas the 95% confidence bands. The extent of exhaustion is indicated by alongside CR10 scores (in parentheses) according to Borg's scale. The quantity of measured pop-offs are given in the legends.

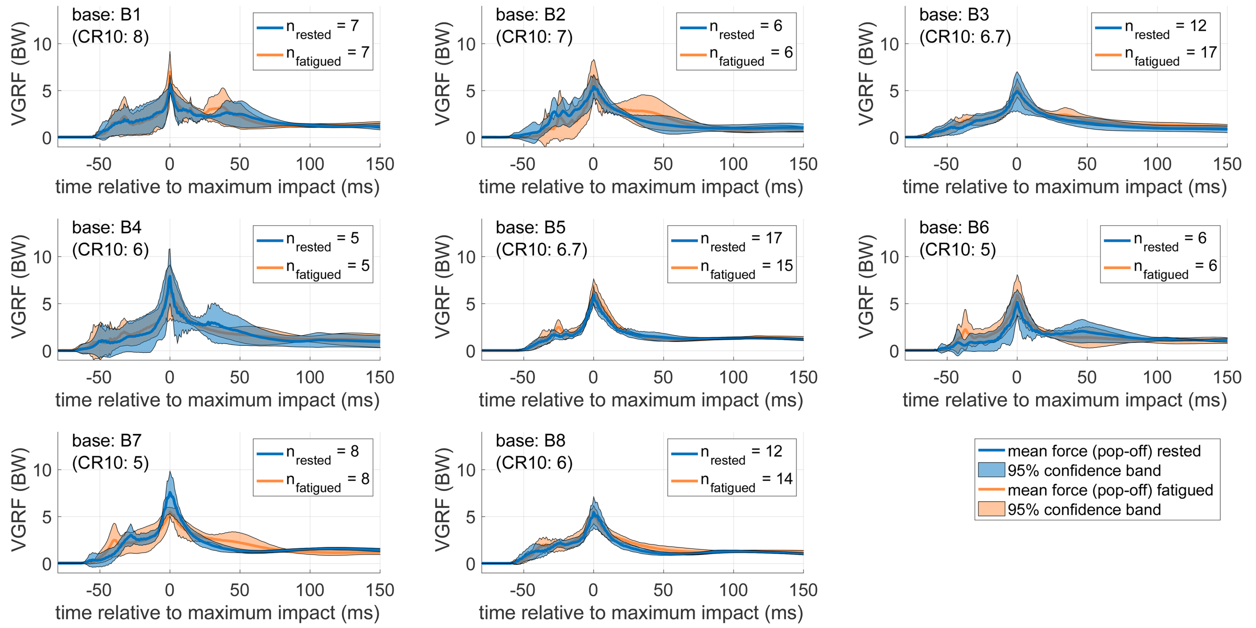

FIGURE B2
Mean VGRF-time courses of individual bases (catching). Pop-off impact forces before (blue) and after (orange) the workout are juxtaposed. Lines show the mean force-time courses and correspondingly shaded areas the 95% confidence bands. The extent of exhaustion is indicated by alongside CR10 scores (in parentheses) according to Borg's scale. The quantity of measured pop-offs are given in the legends.

C. Statistical parametric mapping results

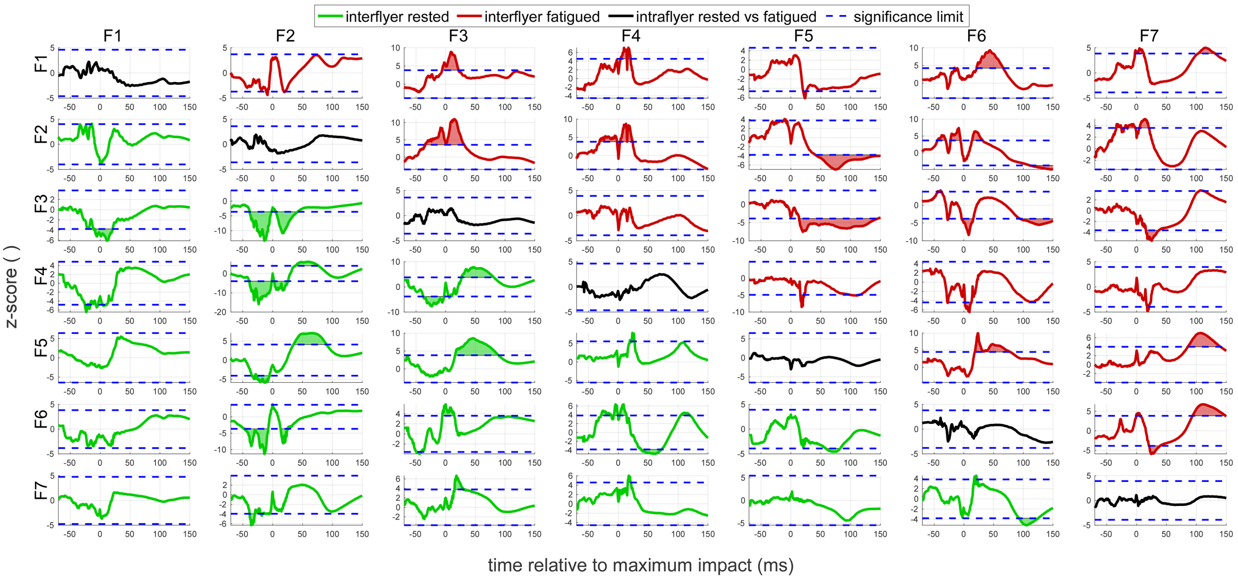

FIGURE C1
SPM of rested versus fatigued flyers. The subplot in the *N*th row and the *M*th column shows the result of a statistical parametric mapping of VGRF-time courses from flyer F*N* versus flyer F*M*, see Figure B1. If $N > M$ (green curves), the "rested" measurements of flyer F*N* are tested against those of flyer F*M*. If $N < M$ (red curves) the "fatigued" measurements are taken instead. If $N = M$ (black curves) the same flyer's "rested" measurements are tested against the "fatigued" ones. Correspondingly colored shaded areas indicate instances of significant deviation above the significance limit (blue dashed lines).

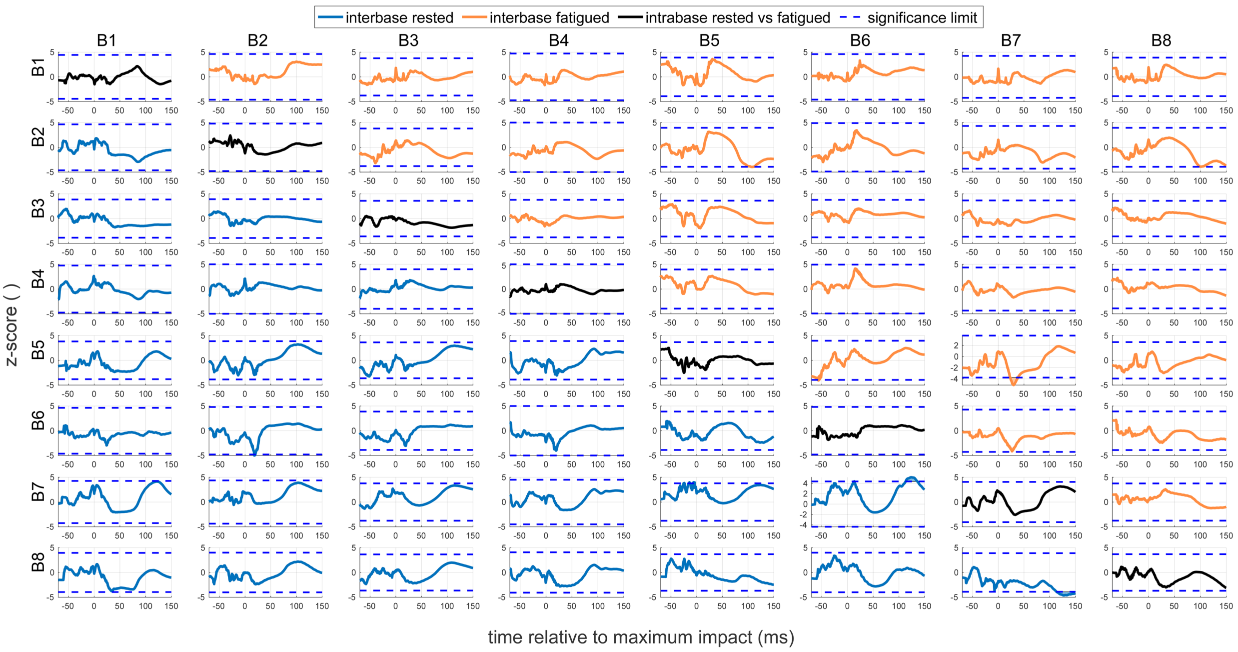

FIGURE C2
SPM of rested versus fatigued bases. The subplot in the *N*th row and the *M*th column shows the result of a statistical parametric mapping of VGRF-time courses from bases B*N* versus flyer B*M*, see Figure B2. If $N > M$ (blue curves), the "rested" measurements of base B*N* are tested against those of base B*M*. If $N < M$ (orange curves) the "fatigued" measurements are taken instead. If $N = M$ (black curves) the same base's "rested" measurements are tested against the "fatigued" ones. Correspondingly colored shaded areas indicate instances of significant deviation above the significance limit (blue dashed lines).

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Assessment of trunk and shoulder muscle asymmetries during two-armed kettlebell swings: implications for training optimization and injury prevention

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Introduction: Greater side-to-side asymmetry can indicate impaired skill, reduced power production, and an increased risk of injury. Bilateral differences highlight the presence of asymmetries that should be assessed to understand their impact on both injury risk and performance enhancement.
Objective: This study aimed to assessment muscle activation and bilateral asymmetry in major trunk and shoulder muscles during a two-armed kettlebell swing exercise.
Methods: Twenty-seven participants (age: 24.2 ± 2.6 years; body mass: 82.9 ± 7.7 kg; height: 176.9 ± 7.0 cm) were included in the study. Electromyographic (EMG) data were collected bilaterally from twelve muscles (six muscles per side: anterior deltoid [AD], posterior deltoid [PD], erector spinae longissimus [ESL], erector spinae iliocostalis [ESI], external oblique [EO], and rectus abdominis [RA]).
Results: Results indicated that asymmetry indices for the AD, ESL, ESI, and RA muscles during the upward propulsion phase fell within the determined threshold of 15%. However, the asymmetry indices for the PD and EO muscles exceeded this threshold by 3.36% and 2.62%, respectively. The findings suggest that trunk muscle asymmetries during the kettlebell swing are generally less pronounced than those of the shoulder muscles, particularly during the float phase.
Conclusion: These results provide valuable insights into bilateral muscle asymmetry during a two-armed kettlebell swing, which can inform the development of targeted training programs. The methods and findings of this study may further contribute to understanding the effects of muscle balance, symmetry, and injury mechanisms in dynamic movements.

KEYWORDS
physical activity, strength training, wearable sensors, EMG, sports exercise

1 Introduction

Over the last decade, resistance training has gained popularity as a form of exercise due to its ability to enhance athletic performance in various ways (1). Among these methods, kettlebell training has garnered increasing interest and popularity among both professional and amateur athletes since its introduction in 2009 (2).

Kettlebell training is a versatile resistance-training technique that serves multiple purposes, including improving muscular strength (3), endurance (1), explosive power (4), weight management and flexibility (2), general fitness (5), and injury rehabilitation (6). Kettlebells have been incorporated into strength and conditioning programs across various sports, such as handball (7), shot put (8), sprinting (9), and soccer (10). Previous research has demonstrated that kettlebells can enhance 1-RM in back squats (3), increase power output in vertical jumps and power (11), and improve aerobic capacity in female soccer players (6, 12). Additionally, kettlebells have been considered for military task performance (4, 13) and as part of the Royal Air Force's aircrew training program (14). They are also used in clinical settings for osteoporosis management, fall and fracture prevention (15), and fitness enhancement among healthcare workers (16), as well as in initiatives aimed at improving health-related physical fitness (4, 17).

Traditionally, kettlebells are made of cast iron and increase in size with weight. Currently, they are available in various materials and weights, ranging from 2 kg to 92 kg (4). The six fundamental hardstyle techniques include the Turkish get-up, clean, swing, squat, press, and snatch and the two-handed hardstyle swing was identified as the most frequently used kettlebell exercise (4). This movement involves propelling the kettlebell forward and upward with a swinging motion driven by hip extension, transferring force to the trunk and arms (6).

Several studies have examined surface electromyography-based muscle activation during the kettlebell swing exercise (5, 6, 18). Research has focused on muscles most affected by the exercise, including the anterior deltoid, erector spinae, rectus abdominis, and external oblique (18). Van Gelder, Hoogenboom (19) demonstrated that both one-handed and two-handed kettlebell swings effectively recruit muscles for strengthening. Andersen, Fimland (20) specifically investigated trunk muscle activation during one-handed vs. two-handed Russian kettlebell swings. Assessing muscle activity across various kettlebell swing variations is crucial for understanding the exercise's potential applications in injury prevention, performance enhancement, and rehabilitation (5).

Previous research has shown that unilateral and bilateral resistance training exercises have distinct effects on trunk muscle activation (21, 22). The kettlebell swing can be performed either unilaterally or bilaterally (6). Bilateral asymmetry, defined as differences in function or performance between the dominant and non-dominant limb or side, is an important factor in assessing injury risk and performance enhancement (23). The asymmetry index (AI) is used to measure imbalances be-tween the dominant and non-dominant limbs or sides during performance (24). Prolonged engagement in the same sport can lead to the development of bilateral asymmetry (25, 26), which is increasingly recognized as a concern due to its impact on the likelihood of sports injuries (27).

Current literature suggests that multiple evaluations of asymmetry in a given activity may re-veal varying degrees of imbalance, often without consistently favoring the same side or direction (28). Madruga-Parera, Bishop (29) examined whether asymmetry remained consistent across three unilateral jump-based assessments among team sport participants. For advanced lifters, who are accustomed to lifting loads closer to their 1RM, it is beneficial to analyze whether weight distribution asymmetries persist in individuals with high technical proficiency (30).

Greater side-to-side asymmetry may indicate impaired skill and power production, along with a heightened risk of injury (31). A symmetry score of zero indicates perfect weight distribution, while scores above zero suggest varying degrees of asymmetry, with higher AI scores representing greater imbalance (30). To minimize injury risk and achieve optimal performance, it is crucial to reduce performance imbalances (32, 33). Bilateral asymmetry in functional performance above a specific threshold has been associated with increased sports-related injury risk (34). Thus, measuring bilateral asymmetry in physical, biomechanical, and electromyographical variables can be critical in athlete evaluation (35), and provide a valuable monitoring tool (36). Consistency across these measures, in addition to assessing bilateral asymmetry, could offer insights for targeted exercise interventions tailored to each individual's dominant and non-dominant sides (37, 38).

Therefore, studying the factors influencing muscle activation and bilateral asymmetry during the two-armed kettlebell swing can provide valuable insights into its effectiveness, potentially enhancing our understanding of performance improvement and injury mechanisms. The current study aimed to identify differences in muscle activation and bilateral asymmetry of major trunk and shoulder muscles on both sides during the two-armed kettlebell swing exercise. We hypothesized that bilateral asymmetry would score low, indicating near-perfect symmetry in weight distribution according to the established threshold.

2 Materials and methods

2.1 Subjects and study design

A priori power analysis was calculated using G-Power software version 3.1.9.7 (Universität Kiel, Germany). Assuming 6 repetitions per subject, a power of 0.80, an alpha level of 0.05, and a medium effect size of 0.25, indicated that an average of 19 participants would be needed for statistical tests. Based on this estimate, 27 participants were included in the study (age: 24.2 ± 2.6 years; body mass: 82.9 ± 7.7 kg; height: 176.9 ± 7.0 cm). The inclusion criteria required participants to be over 18 years old and have at least five years of experience in kettlebell training. Participants were excluded if they had significant gaps in their training history (longer than six months) or if they were currently injured or recovering from injuries that could affect their performance. All participants provided written informed consent, and the study was approved by the institution's ethics committee.

2.2 Experiment protocol

Participants performed a kettlebell-specific warm-up that included five minutes of submaximal kettlebell swings. Following the warm-up, they completed one set of two-armed Russian kettlebell swings, with each set consisting of five repetitions using a 16-kg kettlebell. The sequence of the exercises remained consistent between the warm-up and the experimental tests. The participants' self-selected foot stance was recorded during the initial exercise and maintained throughout all tests and the participants were asked which limb they would prefer to use for the exercises in order to identify which limb was dominant (39). Using a Simi Motion Capture System (Simi Reality Motion Analysis V. 9.0.6) that was synchronized with the EMG at 100 frames per second, video analysis was used to determine the phases; swing phases and timing were measured upon the participant's signal, with the swing divided into four distinct phases: upward propulsion, float, drop, and deceleration (Figure 1).

Participants initiated the swing by flexing their hips during the downward movement and ex-tending them rapidly and forcefully to lift the kettlebell to chest height in a "Russian swing" motion (4). Each participant completed two trials of the two-armed kettlebell swings, performing at least five repetitions per trial with the 16 kg kettlebell (40). To avoid fatigue, a one-minute rest period was provided between trials. The first and last repetitions were excluded from analysis. Results from the successful trials (two trials with three repetitions each) were averaged to generate a single variable for each participant, which was then used in the asymmetry index calculation and statistical analyses (Figure 2) (41).

2.3 sEMG activity recording and analysis

In accordance with SENIAM guidelines, the participants' skin was shaved, abraded, and cleaned with alcohol prior to electrode application (42). Gel-coated, self-adhesive electrodes (bipolar, 10 mm diameter silver chloride surface electrodes; SKINTACT FS-RG1/10, Leonhard Lang GmbH, Innsbruck, Austria) were used, with a 2 cm center-to-center spacing. Electrodes were placed according to SENIAM guidelines (www.seniam.org) on

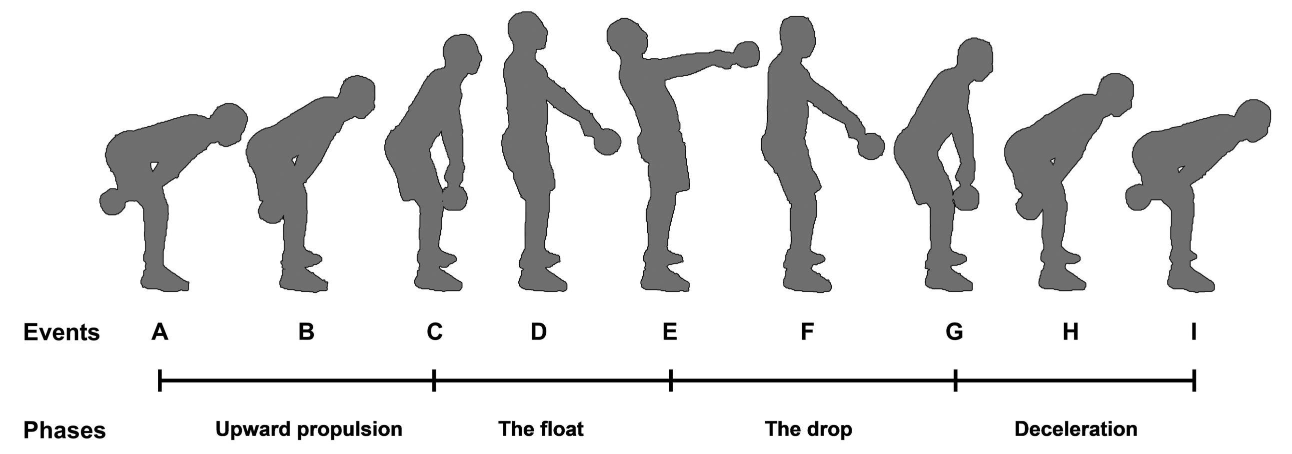

FIGURE 1
A single cycle of two-armed kettlebell swing phases: **(A–C)** phase 1 (upward propulsion of the kettlebell), **(C–E)** phase 2 (the float: passive shoulder flexion with hips and knees in terminal extension), **(E)** Mid-swing (top of the swing), (E-G) phase 3 (the drop: passive extension of the shoulders with hips and knees in terminal extension), **(G–I)** phase 4 [deceleration of the kettlebell to the end of the cycle (bottom of the swing)].

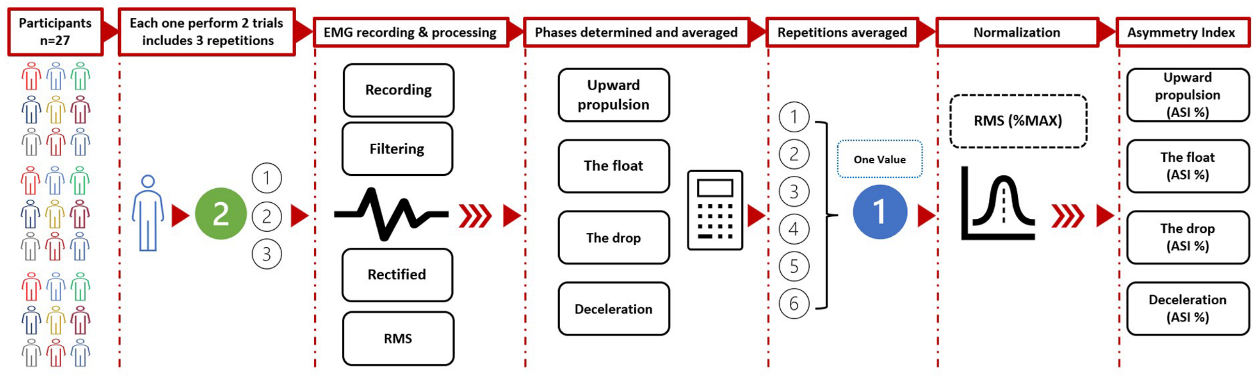

FIGURE 2
Flow diagram of the test and processing procedures.

selected trunk and upper limb muscles: rectus abdominis (RA), external oblique (EO), erector spinae longissimus (ESL), erector spinae iliocostalis (ESI), anterior deltoid (AD), and posterior deltoid (PD) on both dominant and non-dominant sides. A surface EMG device (Myon m320RX; Myon, Switzerland) recorded the raw EMG signals, which were sampled using a 16-bit A/D converter at 1,000 Hz. EMG data were processed using Visual 3D software (C-Motion, Germantown, MD, USA). To reduce movement artifacts, a high-pass Butterworth filter with a cut-off frequency of 25 Hz and a low-pass filter at 15 Hz were applied. The signals were preprocessed using a full-wave rectifier and a linear envelope obtained using the root mean square (RMS) approach with a window size of 100 ms (43). EMG signal amplitudes were normalized to the maximum signal observed across the two trials, including all three repetitions for each participant.

2.4 Asymmetry index

The asymmetry Index was calculated following the methodology of Sheikhi, Letafatkar (44), measures the degree of bilateral distribution symmetry across the upper limbs and trunk muscles (Equation 1).

$$\text{Asymmetry Index (\%)} = \frac{2(\text{dominant} - \text{non dominant})}{(\text{dominant} + \text{non dominant})} * 100 \quad (1)$$

An index value of zero represents perfect symmetry, while values greater than zero indicate varying degrees of asymmetry, with larger values signifying more pronounced asymmetry (30). The Asymmetry Index was calculated for each muscle on both sides based on muscle activity during the two-armed kettlebell swing. Figures 3, 4 display the raw, rectified, and RMS values of muscle activation from a representative subject.

2.5 Statistical analysis

Descriptive statistics were reported as means and 95% confidence intervals (mean ± CI). Data distribution was assessed using Shapiro-Wilk tests, confirming the suitability for

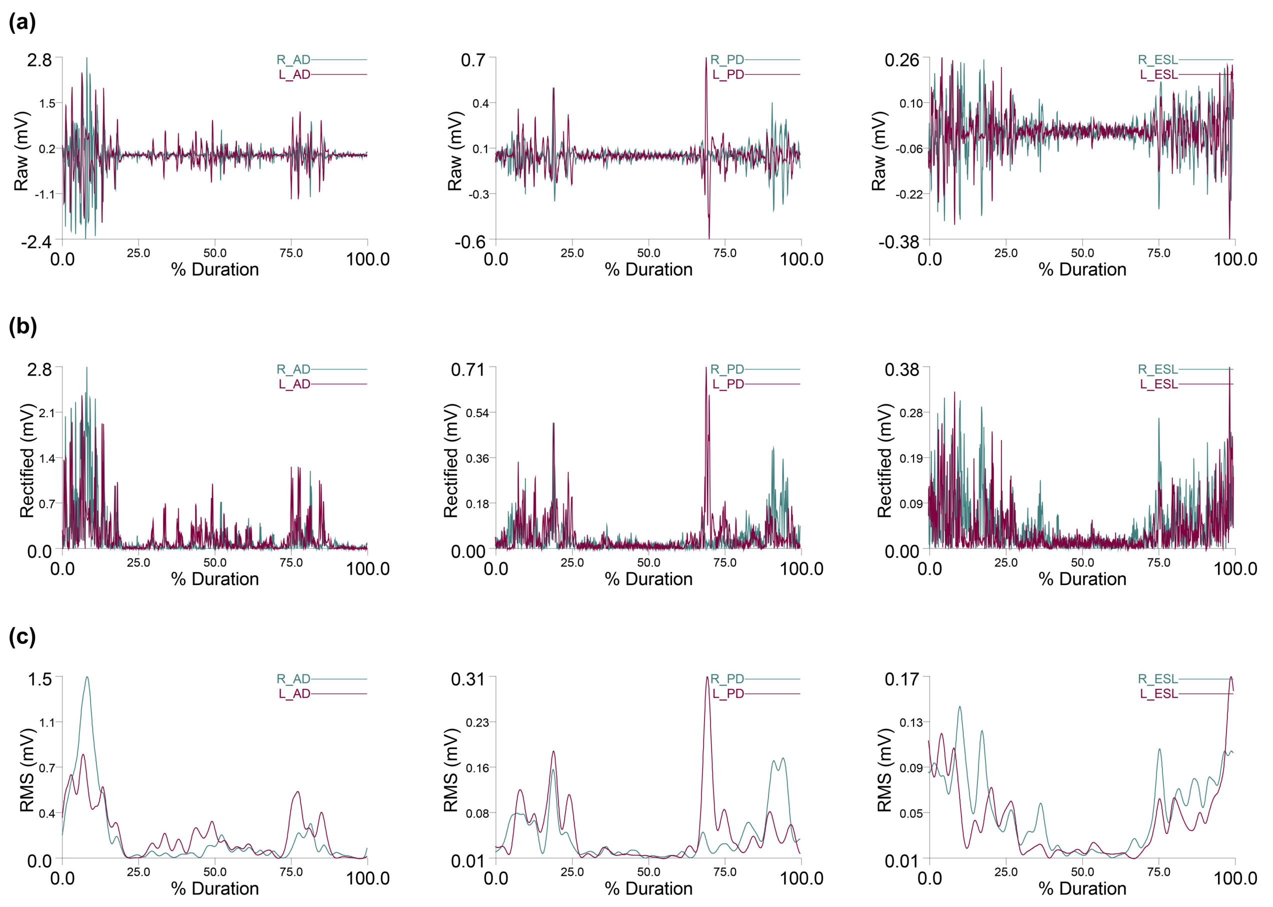

FIGURE 3
Anterior deltoid (AD), posterior deltoid (PD), and erector spinae longissimus (ESL) muscle activity. (a) Raw EMG data, (b) Rectified EMG data, and (c) data from a representative subject.

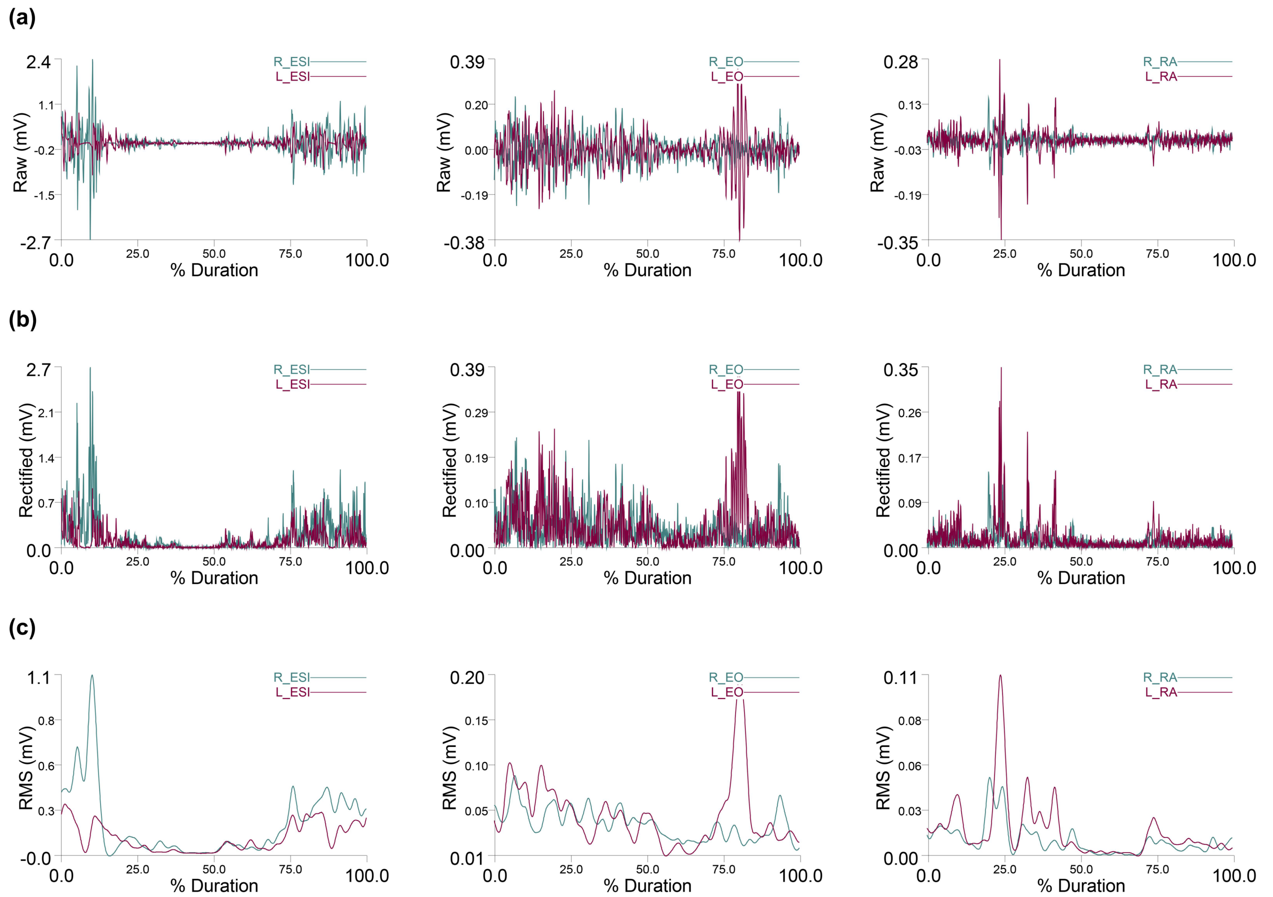

FIGURE 4
Erector spinae iliocostalis (ESI), external oblique (EO), and rectus abdominis (RA) muscle activity. **(a)** Raw EMG data, **(b)** Rectified EMG data, and **(c)** data from a representative subject.

parametric analysis. Within-group differences between phases were evaluated using repeated measures one-way analysis of variance (RM ANOVA), with Sidak *post hoc* tests comparing the means of each variable during the four phases (upward propulsion, float, drop, and deceleration). Effect size was assessed using partial eta squared (η^2_p), where $\eta^2_p \geq 0.01$ is a small effect, $\eta^2_p \geq 0.06$ is a medium effect, and $\eta^2_p \geq 0.14$ is a large effect (45). All statistical analyses were conducted using IBM SPSS Statistics v27 (IBM® Corp., NY, USA).

3 Results

Figure 5 displays the average values and confidence intervals for the duration of the two-armed kettlebell swing phases. The RM-ANOVA showed significant main effects across the exercise phases ($\eta^2_p = 0.97$). *post hoc* comparisons indicated significant differences among the phases ($p < 0.001$), with the longest duration observed during the drop phase, followed by a decrease in the deceleration phase.

Figure 6 presents the average values and confidence intervals for the normalized RMS (%max) of the right and left limbs during the phases of the two-armed kettlebell swing. Muscle activities of the right and left anterior deltoid (AD), posterior deltoid (PD), erector spinae longissimus (ESL), erector spinae iliocostalis (ESI), external oblique (EO), and rectus abdominis (RA) were recorded during the upward propulsion, float, drop, and deceleration phases, respectively (Figure 6). The peak activities of the right and left AD, PD, ESL, and ESI muscles occurred during the upward propulsion phase, while the peak activities of the right and left EO and RA muscles occurred during the float phase.

Figure 7 provides the asymmetry indices for individual muscles during each phase. During upward propulsion, asymmetry indices were AD (−2.74%), PD (18.36%), ESL (7.66%), ESI (1.15%), EO (−17.62%), and RA (3.88%) (Figure 7a). During the float phase, asymmetry indices were AD (−40.67%), PD (25.49%), ESL (6.29%), ESI (15.79%), EO (−0.96%), and RA (2.27%) (Figure 7b). During the drop phase, asymmetry indices were AD (−9.44%), PD (−0.60%), ESL (0.41%), ESI (−4.05%), EO (−11.90%), and RA (2.31%) (Figure 7c). During deceleration, asymmetry indices were AD (3.77%), PD (30.23%), ESL (−6.38%), ESI (−5.53%), EO (−23.68%), and RA (−3.30%) (Figure 7d).

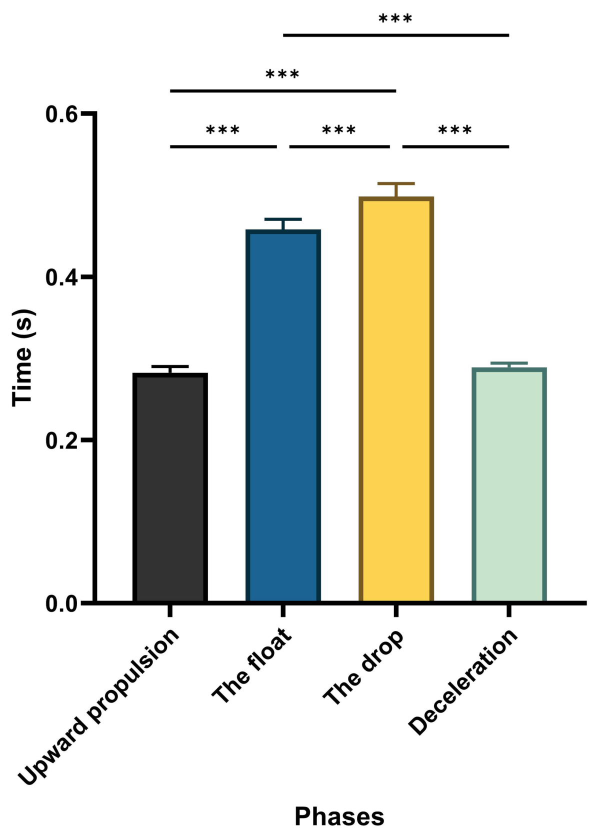

FIGURE 5
Average values and CI for the duration for the two-armed kettlebell phases. Significant differences for the *post hoc* tests between phases: Partial eta squared ($\eta^2_p = 0.97$) and asterisk signs represent significant differences between speeds: (***) indicates $p < 0.001$.

The RM-ANOVA revealed significant main effects for bilateral asymmetries in AD ($F = 12.71$, $\eta^2_p = 0.33$) (Figure 8a), PD ($F = 4.52$, $\eta^2_p = 0.15$) (Figure 8b, ESL ($F = 1.70$, $\eta^2_p = 0.06$) (Figure 8c), ESI ($F = 5.45$, $\eta^2_p = 0.17$) (Figure 8d), EO ($F = 4.30$, $\eta^2_p = 0.14$) (Figure 8e), and RA ($F = 0.79$, $\eta^2_p = 0.03$) (Figure 8f). Significant differences in asymmetries were found between upward propulsion and float phases for AD ($p < 0.001$) and EO ($p < 0.05$), but not for PD, ESL, ESI, or RA. Additional significant differences were observed between the float and drop phases for AD ($p < 0.001$), PD ($p < 0.05$), ESI ($p < 0.05$), and EO ($p < 0.01$). For the drop and deceleration phases, significant variations were found only for PD ($p < 0.05$). Lastly, significant differences were identified between the float and deceleration phases for AD ($p < 0.001$) and ESI ($p < 0.05$).

4 Discussion

The aim of this study was to identify differences in muscle activation and examine bilateral asymmetry in the major trunk and shoulder muscles during the two-armed kettlebell swing exercise. To our knowledge, this is the first study to investigate muscle activity asymmetry during the two-armed kettlebell swing using electromyographic analysis. This approach provides insights into the effective-ness of this technique, contributing to the understanding of performance enhancement and potential injury mechanisms.

Based on the bilateral performance of the two-armed kettlebell swing, we hypothesized that muscle activity would be symmetrical between sides. However, the results revealed that the AD muscle on the left side exhibited greater activation compared to the right, particularly during the float phase. The discrepancy between the sides diminished during the drop and deceleration phases. This finding suggests that the AD muscle plays a key role in accelerating the kettlebell specifically during the initial upward movement, which is in agreement with Salem, Hassan (18). During the two-armed kettlebell swing phases, the PD muscles on both sides exhibited a high level of asymmetry (>15%), resulting in notable differences between the dominant and non-dominant sides during the upward propulsion, float, and deceleration phases. In contrast, the PD muscle's primary role is to engage in braking movement during the drop phase, leading to an asymmetry level of less than 15% in this phase.

Simultaneous activity of the trunk muscles (ESL, ESI, EO, and RA) on both sides, especially during the upward propulsion, float, and drop phases, underscores the importance of stability in the two-armed kettlebell swing. In general, and particularly in sports, greater joint coordination instability increases the risk of injury, while smaller side-to-side asymmetry helps reduce this risk and enhances training effectiveness (36, 46). Several studies have shown that higher functional asymmetries are associated with an increased risk of injury and are considered a known risk factor (30, 47). Thus, reducing asymmetry in these muscles can enhance performance and lower the risk of injury (48, 49).

To evaluate bilateral muscle activity differences, we employed the asymmetry index (AI) method to calculate the asymmetry between the right and left sides for each muscle. Our findings, along with previous studies, suggest a 15% threshold of inter-limb or side asymmetry as normal physiological variability, serving as a reference value for injury risk (dotted lines in Figure 7) (50–52). This study is the first to quantify and compare muscle activity asymmetry during and between phases of the two-armed kettlebell swing exercise. Regarding muscle asymmetry, our findings indicate that the asymmetry indexes for AD, ESL, ESI, and RA muscles during the upward propulsion phase were within the acceptable range of 15%. These results suggest that the observed asymmetries are within normal limits during performance. However, the PD and EO muscles exhibited asymmetries exceeding the targeted threshold, possibly due to unilateral activation or compensatory responses aimed at enhancing stability. The ESL, ESI, and RA muscles consistently remained within the AI threshold across all four phases, likely due to the RA's role in core stability, facilitating force transfer from the hip extensors to the arms and kettlebell. Additionally, trunk muscles like the ESL are crucial for extending the trunk during the upward phase and providing stability to prevent spinal twisting under load (20). Extensor core muscles are activated in response to flexion moments, further supporting their stabilizing role (53).

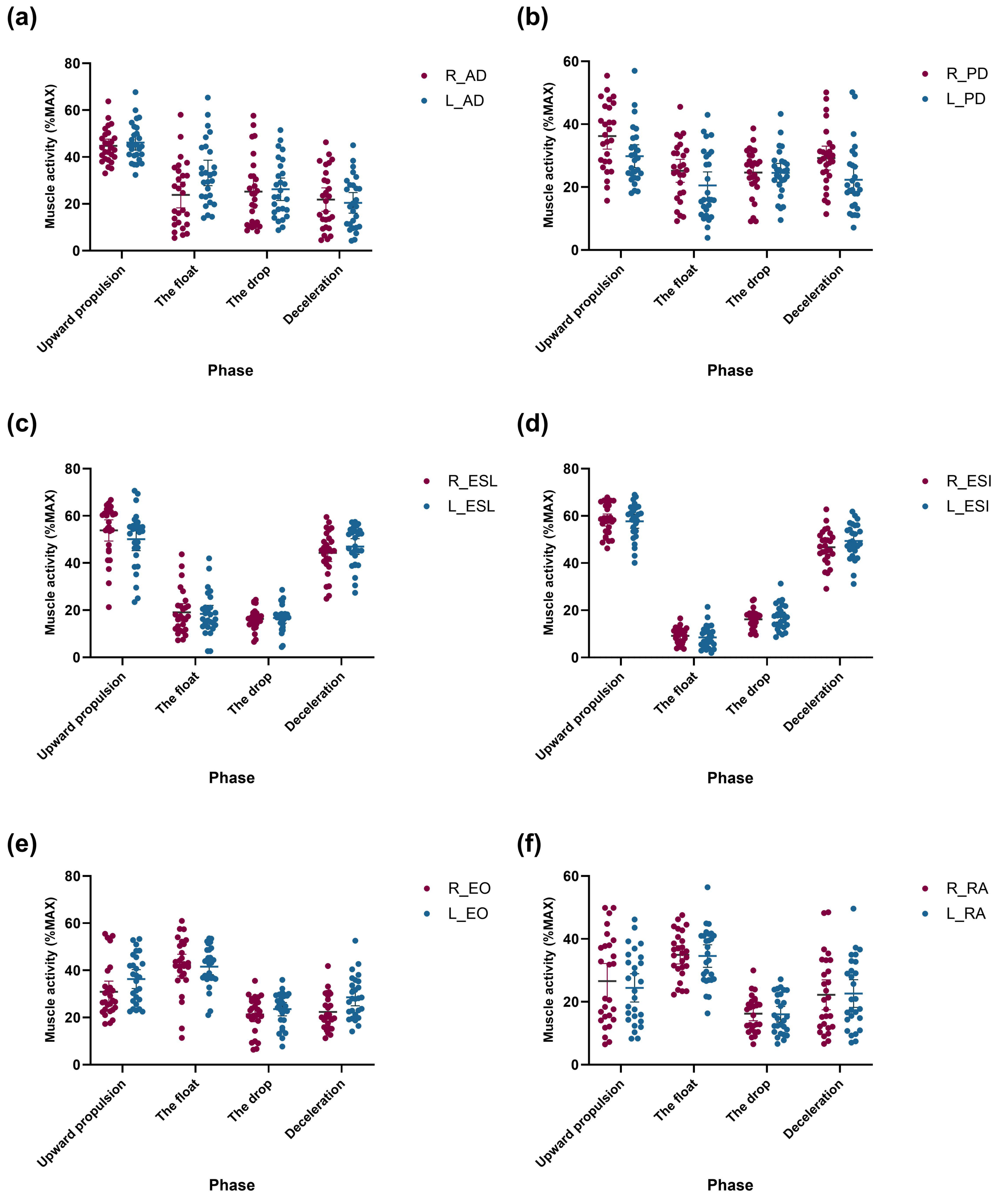

FIGURE 6
Average values and CI for the normalized RMS muscles activation (%MAX) per phase of the two-armed kettlebell exercise: **(a)** right and left AD muscles, **(b)** right and left PD muscles, **(c)** right and left ESL, **(d)** right and left ESI muscles, **(e)** right and left EO muscles, and **(f)** right and left RA muscles.

Our results support the hypothesis that bilateral asymmetry would be minimal, indicating near-optimal weight distribution symmetry based on the established threshold. However, the PD muscle demonstrated high asymmetry during the upward propulsion, float, and deceleration phases, while the AD muscle showed significant asymmetry during the float phase. Additionally, the EO muscle exhibited slightly greater asymmetry than the threshold during the upward propulsion and

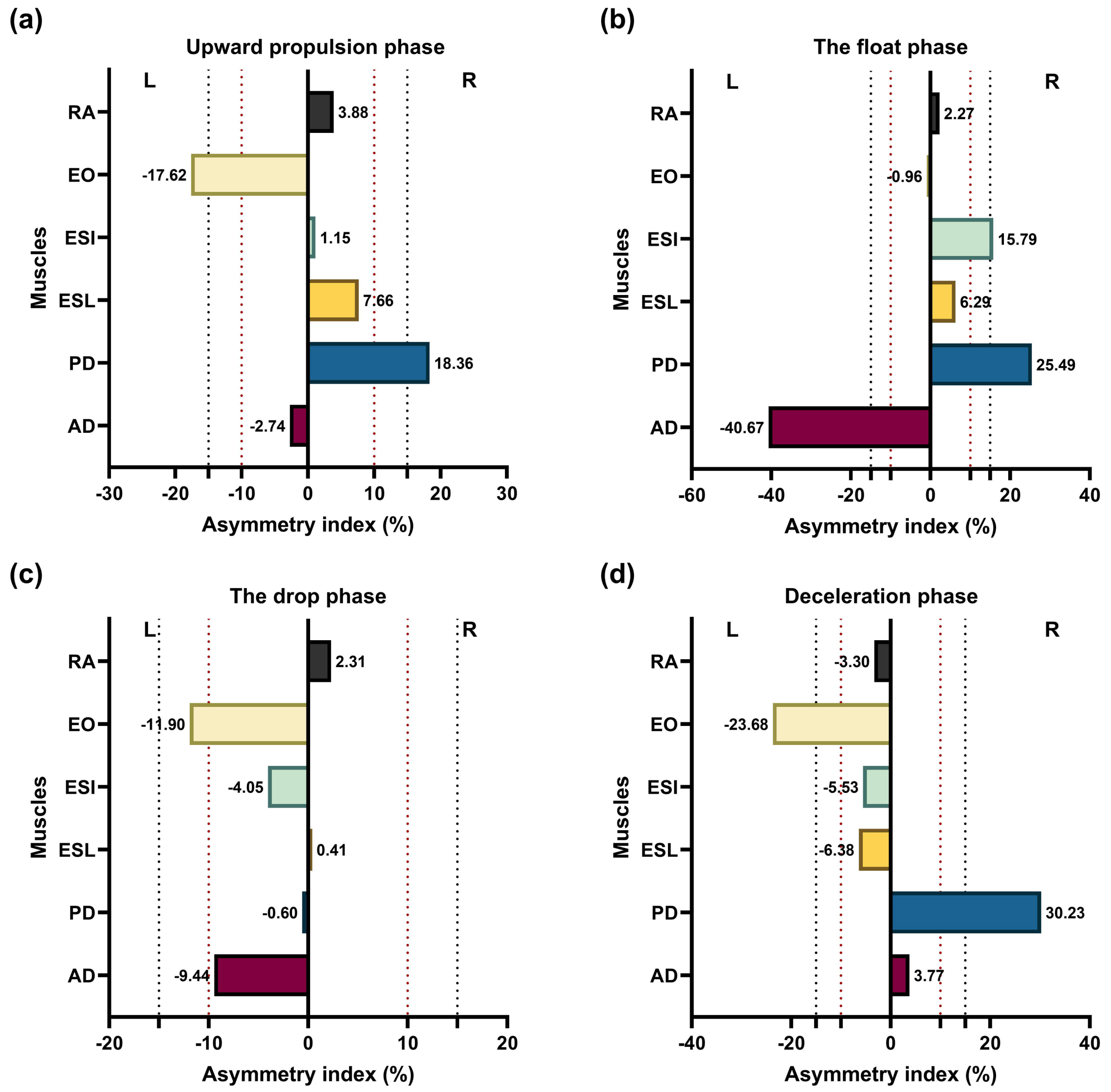

FIGURE 7
Muscles asymmetry data (%) for two-armed kettlebell exercise during the four phases: **(a)** upward propulsion, **(b)** the float, **(c)** the drop, and **(d)** deceleration. The asymmetry favoring the right side was indicated by bars oriented towards the right, while the asymmetry favoring the left side was indicated by bars oriented towards the left. Dot lines indicate; red 10% and black 15% of asymmetry threshold for right and left (L) side.

deceleration phases. This highlights the critical roles of these muscles in kettlebell training. The AD muscle generally shows greater activation than the PD during kettlebell exercises, with both muscles being essential for controlling the swing, especially during the float phase (18). These asymmetry index results are valuable for physiotherapists and strength and conditioning coaches in identifying athletes at risk of injury, enabling the development of targeted neuromuscular prevention programs. Corrective strategies focused on reducing asymmetry may help lower the risk of injury (50).

Analyzing inter-phase asymmetry revealed significant differences in the AD muscle between phases, with notable asymmetry during the float phase, likely due to the increased load of resisting the kettlebell's weight and gravity. Additionally, differences in bilateral asymmetry were observed between the float and drop, and float and deceleration phases for the PD, ESI, and EO muscles. Our findings suggest that trunk muscle asymmetries during the two-armed kettlebell swing are generally lower than those observed in shoulder muscles (AD and PD), particularly during the float phase, which plays a key role in generating muscle activity and force during the ballistic lift of the kettlebell.

5 Practical applications

The study's findings have practical implications for coaches and practitioners aiming to optimize kettlebell training. By identifying phases with higher asymmetry, targeted corrective exercises can be incorporated into training routines to enhance symmetry and

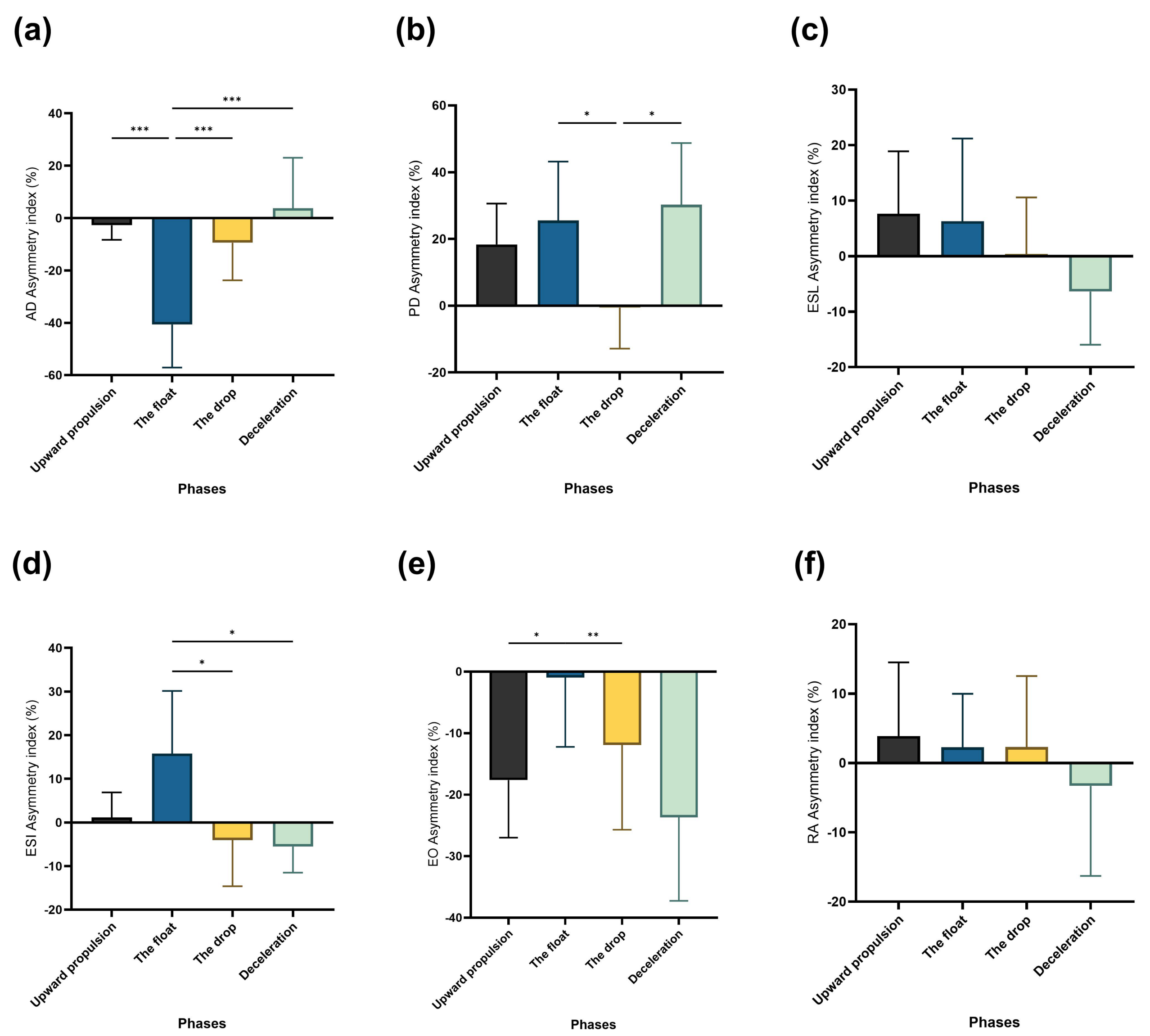

FIGURE 8
Pairwise comparisons associated with the significant main effects from the RM-ANOVA with mean and confidence intervals for the asymmetry index (%) per phase: **(a)** AD bilateral asymmetry, **(b)** PD bilateral asymmetry, **(c)** ESL bilateral asymmetry, **(d)** ESI bilateral asymmetry, **(e)** EO bilateral, and **(f)** RA bilateral asymmetry. Asterisk signs represent significant differences between speeds: (***) indicates $p < 0.001$, (**) indicates $p < 0.01$, (*) indicates $p < 0.05$.

reduce injury risk. Moreover, the use of sEMG to monitor muscle activation and asymmetry provides a valuable tool for assessing training progress and individualizing exercise prescriptions.

6 Limitations and future work

Despite the robust findings, this study has some limitations. The relatively small sample size may limit the generalizability of the results. Future studies should include a larger cohort to confirm these findings. Additionally, while this study focused on trunk and upper limb muscles, lower limb muscle activity, which also plays a crucial role in kettlebell swings, was not assessed. Incorporating lower limb muscles into the analysis could provide a more comprehensive understanding of the exercise's demands. Lastly, exploring the impact of different kettlebell weights and swing variations could further elucidate the relationship between load, phase duration, and muscle asymmetry.

7 Conclusions

This study concluded that asymmetry indices for the anterior deltoid (AD), erector spinae longissimus (ESL), erector spinae iliocostalis (ESI), and rectus abdominis (RA) muscles during the upward propulsion phase were within the determined threshold of 15%. However, the asymmetries of the posterior deltoid (PD) and external oblique (EO) muscles exceeded this threshold by 3.36%–2.62%, respectively. The results suggest that trunk muscle asymmetries during the two-armed kettlebell swing are generally smaller than those of the shoulder muscles (AD and PD), particularly during the float phase. These findings highlight the importance of monitoring bilateral muscle activity and addressing asymmetries when performing the two-armed kettlebell swing exercise. Trainers and professionals should consider these asymmetries to reduce imbalances between both sides, potentially enhancing performance and reducing injury risk. This study provides valuable insights into muscle bilateral asymmetry during kettlebell swings, which can inform the development of targeted training programs. The techniques and findings presented may further our understanding of muscle balance, symmetry, and injury mechanisms in dynamic exercises. Ultimately, the application of these insights will need to be tailored to each individual, requiring personalized assessment by coaches and medical professionals to effectively address muscle asymmetries and optimize training outcomes.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the ethics committee of the Faculty of Sports Education, Alexandria 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.

Author contributions

KA: Conceptualization, Funding acquisition, Methodology, Visualization, Writing – original draft, Writing – review & editing. A-RA: Conceptualization, Data curation, Formal Analysis, Methodology, Project administration, Software, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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Evaluation of the impact of a 3-week specific-sport rehabilitation program on neuromotor control during single-leg countermovement-jump tests in professional soccer players with lower-limb injuries

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Purpose: This study investigated the evolution of neuromotor control during a typical short sport-specific rehabilitation program (SSR) in professional soccer players who had incurred a major lower-limb injury ($n = 15$, chondral and muscle injuries, ACL-reconstruction).

Methods: All injured participants ($n = 15$) were in the on-field rehabilitation phase of their specific sport rehabilitation process, prior to return to play. An experimental group (EG, chondral and muscle injuries, ACL-reconstruction) followed a 3-week SSR-program composed of muscular and core strengthening (weightlifting, functional stability, explosivity and mobility exercises), running and cycling, neuromotor reprogramming, cognitive development and specific soccer on-field rehabilitation (acceleration, braking, cutting, dual-contact, high-speed-running, sprint, jump, drills with ball). Neuromotor control via analysis of movement kinematics, muscle activation and kinetic parameters was evaluated using a single-leg Countermovement-Jump, pre- and post- rehabilitation program. A control group ($n = 22$) of healthy soccer players of similar standards performed the same single-leg Countermovement-Jump to provide reference values regarding the level to be attained by the injured players for return to play.

Results: In the experimental group, almost all kinetic analyses values progressed during the program and significantly for concentric Rate-of-Force-Development ($p < 0.05$), height jump ($p < 0.001$) and Reactive-Strength-Index Modified ($p < 0.001$) but remained lower than control group values for RSI-Mod ($p < 0.05$) and RFDconcentricLate ($p < 0.001$). Activation changed ($p < 0.05$) for all muscles except for rectus femoris and medial gastrocnemius in the pushing phase and rectus femoris during landing in the EG. Activation of all muscles decreased for EG, except for semitendinous which increased. Regarding kinematic analyses during the landing phase, there were a significant decrease in peak trunk flexion ($p < 0.001$) and lateroflexion ($p < 0.001$) and an increase in peak knee flexion ($p < 0.001$) for both legs. Trunk flexion ($p < 0.001$) and lateroflexion ($p < 0.001$) values were again higher for EG while knee flexion remained significantly lower than the CG ($p < 0.001$).

Conclusion: The SSR generally improved neuromotor control suggesting that the present specific sport rehabilitation program, albeit of only three weeks duration, was effective in aiding elite footballers recover their neuromotor qualities although this was potentially insufficient to return to the values observed in healthy players.

KEYWORDS

neuromotor control, rehabilitation, elite soccer, CMJ, lower-limb injuries, LSI, norm values

Level of evidence: Therapeutic studies of level II.

Introduction

Contemporary elite soccer is imposing ever-increasing levels of stress on players notably due to increases in the frequency of matches and competitive physical demands (1). While over the last 20-years the incidence of joint and ligament injuries has decreased, hamstring and ligament injury severity has concomitantly increased (2, 3). Injury recurrence rates are high, attaining values of 36% for knee chondral injuries (CH), 17.5% for lower-limb muscle injuries (MI) and 6.6%–10% for anterior cruciate ligament ruptures (4) (ACL). These injuries generate various alterations including arthrogenic muscular inhibition (AMI) (5), pain interference (6), detraining or sensorimotor impairments (7). These can have a strong impact on lower-limb functioning. Indeed, RFD deficits ranging from 10% to 57% have been reported up to 24 months after ACL reconstruction in the injured and non-injured leg (8, 9). For thigh muscle strains, a weakness in eccentric force production has been observed, notably in external muscle range of motion post hamstring injury (10). Moreover, a chondral injury generates inappropriate activation and muscle imbalances leading to impaired dynamic coordination (11).

As such, sport-specific rehabilitation programs (SSR) (12–15) aim to ensure complete restoration of any affected functions and safe and efficient return-to-play phases (RTP) (16). SSR generally include neuromotor training and reprogramming (17–19) (strengthening, postural-work, core-training, mobility, motor-learning, locomotor exercises), physiological energy system conditioning, cognitive work (17) and specific on-field rehabilitation exercises. Buckthorpe et al. (17) suggest that on-field rehabilitation is constructed around 4 pillars: fitness, movement quality, sport-specific skills, and training load. The sport-specific rehabilitation phase can be organized in 5 distinct phases where the intensity, volume, complexity and specificity of the exercises and sessions on the field are progressively increased. One example is the “control-chaos continuum” (CCC) proposed by Taberner (14). The athlete must be able to perform all the movements occurring in their sport (cutting, shifting, jumping, landing, shooting, contact, sprinting, braking, acceleration, processing information and decision-making), all at maximum intensity, repeatedly over time, and with quality movement (18, 20).

To support decision-making during RTP, medical and reconditioning staff frequently utilize information derived from motor evaluations (17, 21, 22) (e.g., hop, landing, isokinetic, agility tests) commonly performed in clinical settings. However, these tests might not be considered discriminating enough to specifically assess any motor deficits that might persist in injured athletes (23) during RTP. As such, RTP assessment batteries frequently including multiple tests have been proposed (22). However, it is not always practically or logistically easy to perform several tests. One test, the Countermovement-Jump (CMJ) is useful as a performance measure (24), a means to evaluate neuromotor control deficits, and also a readiness to play measure (24, 25) while limiting core and limb compensations.

During RTP processes, the between-leg (a)symmetry derived from analyses of neuromotor control is commonly investigated using a “leg symmetry index” (LSI, percentage difference in values for a selected variable between both legs) when performing a locomotor task (20, 26). The LSI-method is used to evaluate neuromotor control impairment and recovery (21, 27) in injured athletes performing lower-limb tests. Recovery is generally considered “complete” if LSI = 100% (20, 26). However, it has been suggested that the LSI overestimates players’ progress in returning to play (28, 29). The utilization of “normative” values is relevant where comparisons of the athlete’s current post-injury state can be made with reference values that are both reliable and level-appropriate in cohorts of healthy players (14, 30, 31).

The purpose of this study was to assess the effects of a typical 3-week SSR-program on neuromotor control recovery in the injured and non-injured legs of elite soccer players. Analyses of kinematic, kinetic and EMG (electromyography) variables derived from a single-leg CMJ (SLCMJ) *before* and *after* the SSR-program would help determine the variables most impacted during the players’ rehabilitation over the 3-week period. The hypothesis forwarded is that the SSR would have a positive impact on all variables, thanks to its comprehensive, functional, and systematic approach whilst bringing the results in both legs of injured players closer to reference values observed in a control group of healthy players.

Materials and methods

Experimental approach to the problem

The effect of a 3-week SSR-program (13–15) on neuromotor control was investigated in injured male professional soccer players. Two groups were formed: an experimental (EG, $n = 15$) comprised of players with a unilateral lower-limb injury and a control group (CG, $n = 22$) comprised of uninjured (healthy) players of the same playing standard. All players performed 3-unilateral CMJ using each leg; before and after the SSR-program for the EG and during a single-session for the CG. Metrics included whole-body kinematics, kinetics, and lower-limb muscle activation.

Participants

The cohort included an EG composed of players having sustained a lower-limb injury (Chondropathy $n = 4$, Muscle Injury $n = 4$, Anterior Cruciate Ligament-rupture $n = 7$) and receiving treatment at the Clairefontaine FIFA Medical Center of the French Football Federation, and a CG. The CG ($n = 22$) included players who had not incurred any significant injury (absence longer than one week) during the six months before the study. All injured participants were in the advanced part of their rehabilitation, the final "on-field rehabilitation" phase, the aim of which, irrespective of the injury, is to regain the ability to meet the demands of competitive practice in all areas. The groups presented similar anthropometric characteristics (Table 1). This study complied with the Declaration of Helsinki (1964) and permission was obtained from French national ethics committee for sports science research (CERSTAPS n°IRB00012476-2020-24-03-48).

Experimental task and protocol

The experiments were performed between 2:00 and 3:30 PM in a training-room, at 20°C. The protocol began with a 10-min warm-up on an ergocycle followed by a progressive increase in power from 100W to 200W. Two maximal isometric voluntary contractions (MVIC) of the leg muscles were then performed for EMG normalization, followed by series of unmeasured SLCMJ trials (three per leg) on a force-plate. These blank trials were performed to ensure familiarization with the experimental task, apparatus, and instructions. Following a one-minute rest period, the two series of SLCMJ were repeated and recorded.

Participants performed barefoot with their hands fixed on their hips. They started in a static position with their stance leg stretched and the contralateral leg slightly flexed with the foot a few centimeters above the force-plate. Participants returned to the same posture following SLCMJ. They were instructed to "jump as high and as quickly as possible and stabilize themselves three-seconds in the final posture".

Following this first series of tests (pre-SSR), EG participants followed the SSR-program over a 3-week period, which corresponds to a micro-cycle work unit duration within a typical rehabilitation program (13, 14). It also corresponds to the average duration of an injured player's stay at the present Football Medical Center. Post-program, the EG repeated the testing protocol (post-SSR). CG only performed a single test as conducting the same tests twice in healthy top-level footballers is difficult notably due to logistics regarding their training and competition schedules in addition to the effect of the associated loading. In addition, some of the players were no longer able to perform the test battery as they no longer met the inclusion criteria on being injury free. A pilot study in the twenty-two CG subjects showed that the raw experimental variables did not differ significantly when SLCMJ was performed on their dominant or non-dominant leg ($p > 0.05$). As such, only the dominant leg was tested in the CG.

SSR-program

The SSR-program (13, 14, 32) was composed of muscular strengthening (weightlifting and functional exercises), physiological energy system conditioning running and cycling, neuromotor reprogramming and specific soccer on-field rehabilitation (acceleration, braking, cutting, dual-contact, high-speed-running, sprint, jump, drills with ball) on the pitch, core-training, mobility and cognitive development (2, 20, 32–36). EG players performed the program approximately 5-h per day, 5-days a week, during 3-weeks consecutively. On each day of the on pitch SSR-program, players performed mobility, specific lower-limb activation, neuromotor control and specific soccer rehabilitation in the morning and lower-limb strengthening, core-training and specific care in the afternoon. The soccer-specific rehabilitation part included general and specific drills and soccer movement (accelerations, decelerations, cutting, jump, landing, dribble, shift), high-speed-running and sprinting, short and long passes, duels and physical contact work, and cognitive work (information analysis and decision making). A progressive augmentation in the volume, intensity and complexity of the content of the pitch sessions was implemented over the 3weeks following previous recommendations for on-field rehabilitation (12, 20, 32–34, 36, 37). The external and internal workloads and intensities were monitored and adapted in relation to

TABLE 1 Comparison of anthropometric characteristics between EG and CG.

	Size			Mass			Age		
	CG	Pre-SSR	Post-SSR	CG	Pre-SSR	Post-SSR	CG	Pre-SSR	Post-SSR
Subjects	22	15	15	22	15	15	22	15	15
Mean	181.8	180.7	180.7	75.1	76.6	76.8	24.8	26.6	26.6
Std. deviation	7.1	4.9	4.9	7.2	8.8	8.8	3.6	4.4	4.4
Minimum	168.0	173.0	173.0	60.0	61.5	63.0	20.0	19.0	19.0
Maximum	192.0	189.0	189.0	87.0	89.0	89.0	32.0	33.0	33.0

progression, according to the characteristics of the injury and the individual's response to the programme. This was done to respond as effectively as possible to the inter-individual differences in adaptation and recovery times. The exercises were ceased if the player deemed the pain was greater than 3/10 using a numerical rating scale (38). The decision criteria for changing training focus depended upon the progress made during strength training assessments and GPS tracking data. The program was monitored by a certified physical trainer specialized in rehabilitation and a team of sport physiotherapists working under the responsibility of three medical doctors specialized in sport rehabilitation. A weekly planning of the SSR program is available in the appendixes.

Data recordings

SLCMJ movement was analyzed though kinetic, kinematic and EMG data recording (Figure 1). Kinetic data was obtained using a force-plate (9260AA6 Kistler Instruments, Hampshire, UK) that provided ground reaction force (GRF_Z), and moments applied at its surface. Kinematic data for knee flexion (KF), trunk flexion (TF) and

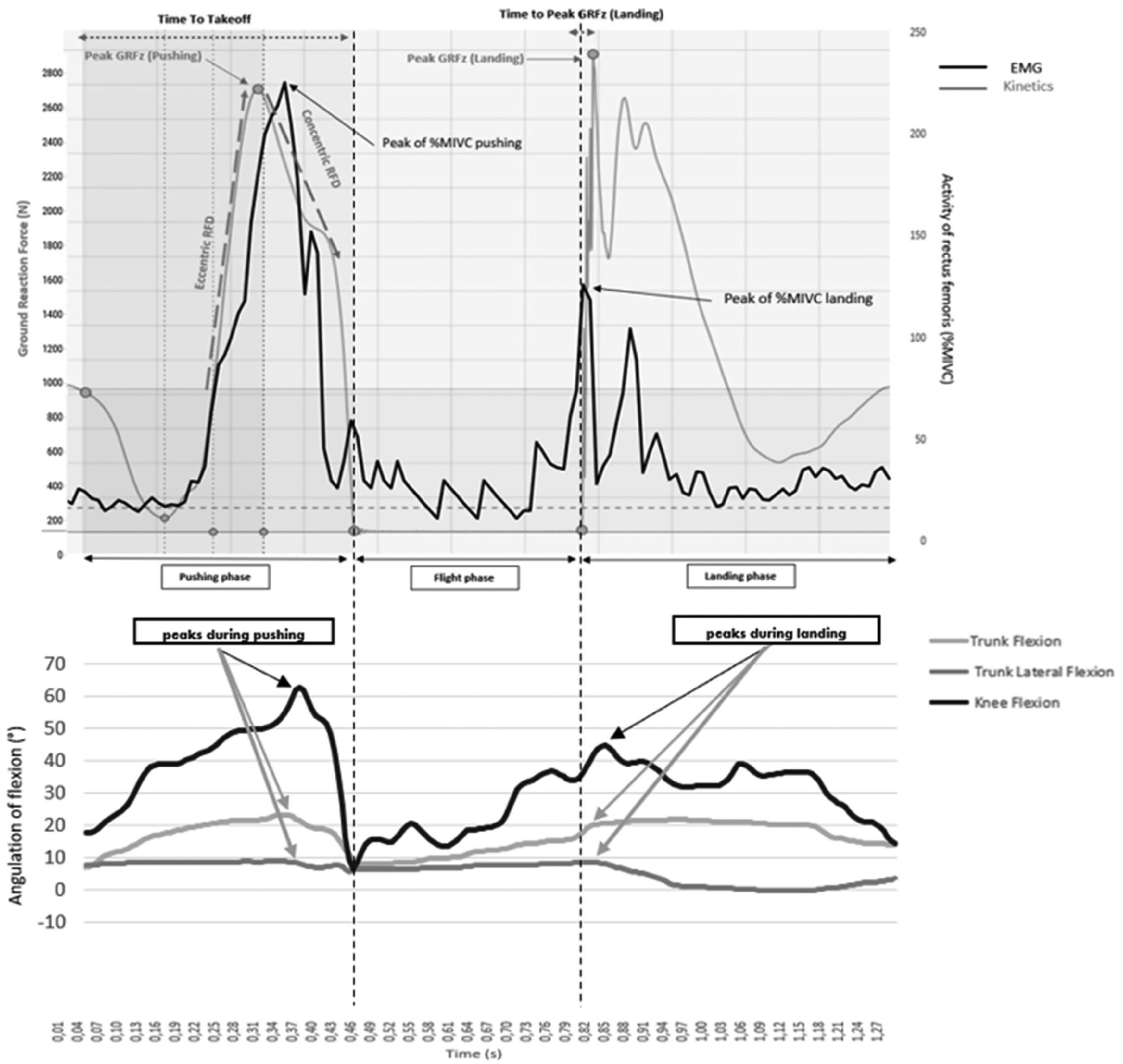

FIGURE 1
Example of electromyogram, kinematics and kinetics curve of a control group athlete during a single-leg countermovement jump on a strength platform. For the EMG and kinetic curves, a drop occurs in the curve corresponding to the countermovement (the unloading of athlete's weight), then the curves rise during the athlete's reloading phase (end of the eccentric) to the top of the curves. The curves then drop again (concentric thrust phase), then there is a slight plateau (with zero values for the kinetic) corresponding to the flight time, then finally the curves rise again during the jump landing phase before plateauing again.

lateroflexion (TLF) of the stance leg was obtained using the Humantrak system (Vald Performance, Brisbane, Australia) with a Kinect-v2 camera (Microsoft Corp., Redmond, WA, USA). Kinematic positional data was processed through a dual Butterworth filter to remove residual noise. Electrical activity of lower-limb muscles was recorded with 12-channel Delsys Trigno (39) wireless surface Ag/AgCl sensors (27 mm × 35 mm, Trinoma, Lyon, France): vastus medialis (VM), rectus femoris (RF), biceps femoris (BF), semitendinous (ST), gluteus medius (GM) and medial gastrocnemius (MG). SENIAM (40) recommendations were applied for sensors location. EMG signals were filtered by a 10-Hz bandpass filter (41) and by a Butterworth filter in EMGworks 4.4 software (Delsys, Inc.) via Root Mean Square. All recordings were sampled at 1,000 Hz.

EMG normalization

The electrical activity of each muscle obtained during propulsion and landing phases of SLCMJ series was normalized with respect to maximal voluntary isometric contraction (MVIC) (41). EMG activity during MVIC was evaluated by two successive MVIC for 5-s separated by a 30-s rest interval for each muscle studied in both legs, before each test session. The highest maximal averaged value obtained on the sliding 0.5-s periods (the highest average recorded over a period of 0.5 during the 5-s isometric contraction) was considered MVIC (41). This was assessed during specific analytical exercises carried out on a guide machine, with the targeted muscle contracting against an over-maximal resistance. MVIC was evaluated with the leg extended at 45° knee flexion for the vastus medialis and rectus femoris and for the leg curl at 45° knee flexion for the biceps femoris and semitendinous using a fixed pulley at 25° of abduction for the gluteus medius and on the calf press with the leg extended and neutral ankle position for the medial gastrocnemius (40).

Raw experimental variables

The following spatio-temporal and kinetics variables were obtained from the force-plate (Figure 1):

- Peaks of upward vertical ground reaction force (peak vGRF, in *Newton*) produced during the pushing phase and during the landing phase of the single-leg-CMJ (24). The landing phase corresponds to the dynamic phase after the flight phase.
- Jump height (in cm) represents the maximal altitude attained by the athlete during the single-leg-CMJ, estimated by the force-plate software through flight duration. Values are a functional measure of the athlete's neuromotor performance (24).
- The Reactive Strength Index Modified (RSI-mod, in m/s) is the ratio of jump height to time to take-off (countermovement duration). This metric reflects lower-limb explosiveness (24).
- Rate-of-Force Development (RFD, in N/s) during both the eccentric (RFDeccentric) and concentric (RFDconcentric) phases of the pushing motion (see Figure 1). RFDeccentric is determined by the slope of the line between the return to the athlete's body weight while ascending the ground reaction force (GRF) and the first upward peak of the vertical GRF trace. RFDconcentric is defined as the slope of the line from this first upward peak to take-off time (23). These parameters reflect lower-limb explosiveness.
- The vertical ground reaction force value at $t = 50$ ms after foot landing (vGRF at 50 ms landing, in Newtons). This moment is known to coincide with the peak risk of knee injury (42, 43).
- Time to peak vertical ground reaction force during the landing phase (in ms), indicating the duration between foot landing and the peak of the vertical ground reaction force.

The EMG parameters encompassed both the peak and mean values of electrical activity in the leg muscles, expressed as a percentage of the activity observed during maximal isometric voluntary contraction, throughout both phases of the single-leg-CMJ (see Figure 1).

Kinematic variables included peak knee flexion, peak trunk flexion, and peak trunk lateroflexion angles (in degrees) recorded during both phases of the single-leg-CMJ (see Figure 1) (7, 44).

Statistics

Group means and standard deviations were computed for VAR_{IL}, VAR_{NIL} and VAR_{CT} raw variables in pre- and post-SSR. The Shapiro-Wilk test was used to check the normality of the data distribution. To assess the neuromotor capacity of IL and NIL, repeated measures (RM) ANOVAs included the method (3-levels: VAR_{IL}, VAR_{NIL} vs. VAR_{CT}) and SSR (2 levels: pre-SSR vs. post-SSR) as within subject factors were used on each VAR_{IL}, VAR_{NIL} and VAR_{CT}. A significant outcome was followed by the Tukey *post hoc* test to assess pairwise statistical differences between methods and both SSR conditions. A student *T*-test was used to compare anthropometric data between the two experimental groups. Kinematic values remain expressed in degrees (°) as values can be positive or negative, so percentage methods were not relevant in this context. The significance threshold was set at $p < 0.05$. Cohen's d was used to determine the effect sizes for differences in mean values (classified as trivial: <0.2, small: 0.2–0.49, medium: 0.5–0.79, and large: ≥0.8).

Results

Comparison of anthropometric characteristics between groups

No significant differences were observed in inter-group characteristics ($p > 0.05$).

Impact of the SSR-program on IL and NIL according to the estimation method chosen

Kinetic analysis

Results reported no differences for all $RFD_{eccentric}$ and peak vGRF pushing phase values ($p > 0.05$) for both legs.

In contrast, a significant impact of the SSR was observed for $RFD_{concentric}$ ($F = 7.8$, $p < 0.01$), $RFD_{concentricEarly}$ ($F = 4.4$, $p < 0.05$), $RFD_{concentricLate}$ ($F = 5.9$, $p < 0.05$), RSI-Mod ($F = 12.4$, $p < 0.001$), jump height ($F = 13.6$, $p < 0.001$), time to peak of vGRF landing ($F = 4.0$, $p < 0.05$) and vGRF at 50 ms of landing ($F = 8.7$, $p < 0.01$). *Post hoc* tests revealed that the SSR-program increased RSI-Mod in IL ($p < 0.01$, $d = 1.1$), jump height in IL ($p < 0.001$, $d = 0.8$) and vGRF at 50 ms during landing in NIL ($p < 0.05$, $d = 0.6$).

There were a significant group*SSR interaction between IL, NIL and CT for jump height ($F = 5.4$, $p < 0.01$) and RSI-Mod ($F = 4.4$, $p < 0.05$). *Post hoc* tests revealed that post-SSR, there was no significant difference between IL, NIL and CT, except for the RSI-Mod and $RFD_{concentricLate}$ where IL was lower than CT ($p < 0.05$, $d = 0.6$ and $p < 0.001$, $d = 0.8$), underlining progression in both legs towards the values observed in the healthy players (see Figure 2).

EMG analysis

Results showed that the SSR-program led to significant differences for%MIVC mean of semitendinous ($F = 15.9$, $p < 0.001$), %MIVC max of vastus medialis ($F = 6.0$, $p < 0.05$), rectus femoris ($F = 5.7$, $p < 0.05$) and gluteus medius ($F = 7.6$, $p < 0.01$) muscles during pushing. Some significant differences were observed for%MIVC mean of biceps femoris ($F = 6.3$, $p < 0.05$), medial gastrocnemius ($F = 7.6$, $p < 0.01$) and for%MIVC max of vastus medialis ($F = 6.6$, $p < 0.05$), biceps femoris ($F = 5.8$, $p < 0.05$), semitendinous ($F = 23.6$, $p < 0.001$), gluteus medius ($F = 11.2$, $p < 0.001$) and medial gastrocnemius ($F = 9.5$, $p < 0.01$) muscles during landing. *Post hoc* tests revealed that the SSR-program led to an increase in pushing phase mean%MIVC for the semitendinous in the IL ($p < 0.05$, $d = 0.5$) and NIL ($p < 0.01$, $d = 0.6$), in%MIVC max for the semitendinous in the IL ($p < 0.01$, $d = 0.7$) during landing. Decreased max%MIVC of the gluteus medius for the NIL ($p < 0.01$, $d = 0.6$) and of medial gastrocnemius for NIL ($p < 0.001$, $d = 0.7$) were observed during landing.

There was a significant group*SSR interaction for%MIVC mean of semitendinous during pushing ($F = 4.5$, $p < 0.01$), for% MIVC max of gluteus medius ($F = 4.4$, $p < 0.05$) and medial gastrocnemius ($F = 5.5$, $p < 0.05$) during landing (see Figure 3).

Kinematic analysis

Results showed that SSR-program led to significant differences in active knee flexion at push ($F = 5,4$, $p < 0.05$,), at landing ($F = 26,4$, $p < 0.001$); and in trunk flexion ($F = 50,7$, $p < 0.001$) and trunk lateroflexion ($F = 405,9$, $p < 0.001$) during the landing phase. *Post hoc* tests revealed that the SSR-program led to a decrease in knee flexion of NIL at push ($p < 0.001$, $d = 0.5$), a knee flexion of NIL increase at landing ($p < 0.001$, $d = 1.0$) and a decrease in IL and NIL values, respectively for trunk flexion ($p < 0.001$, $d = 3.2$ and $p < 0.001$, $d = 2.5$) and trunk lateroflexion of IL ($p < 0.001$, $d = 1.1$) during the landing phase.

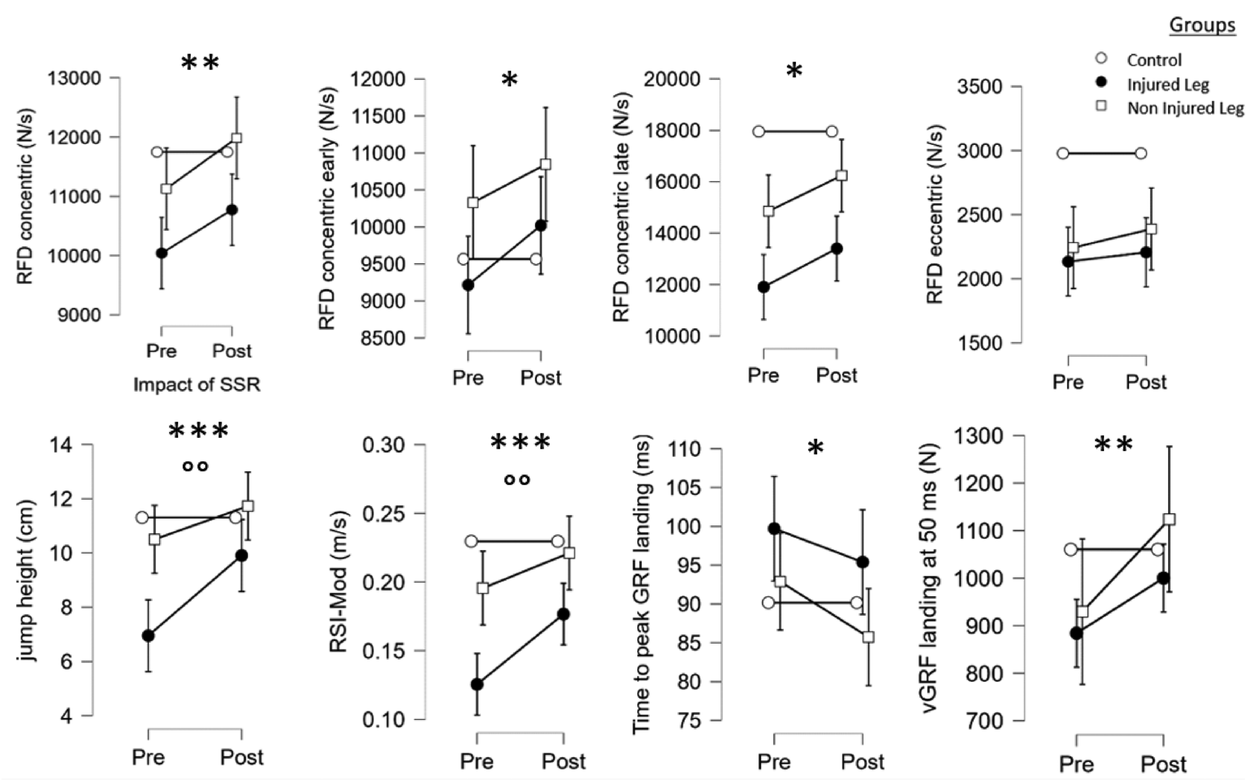

FIGURE 2
Main effects of the SSR program and the group on the kinetics variables of the single-leg-CMJ. *, **, ***: significant effect of the SSR program (pre vs. post-SSR) with $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively. °, °°,°°°: significant effect of the group with $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

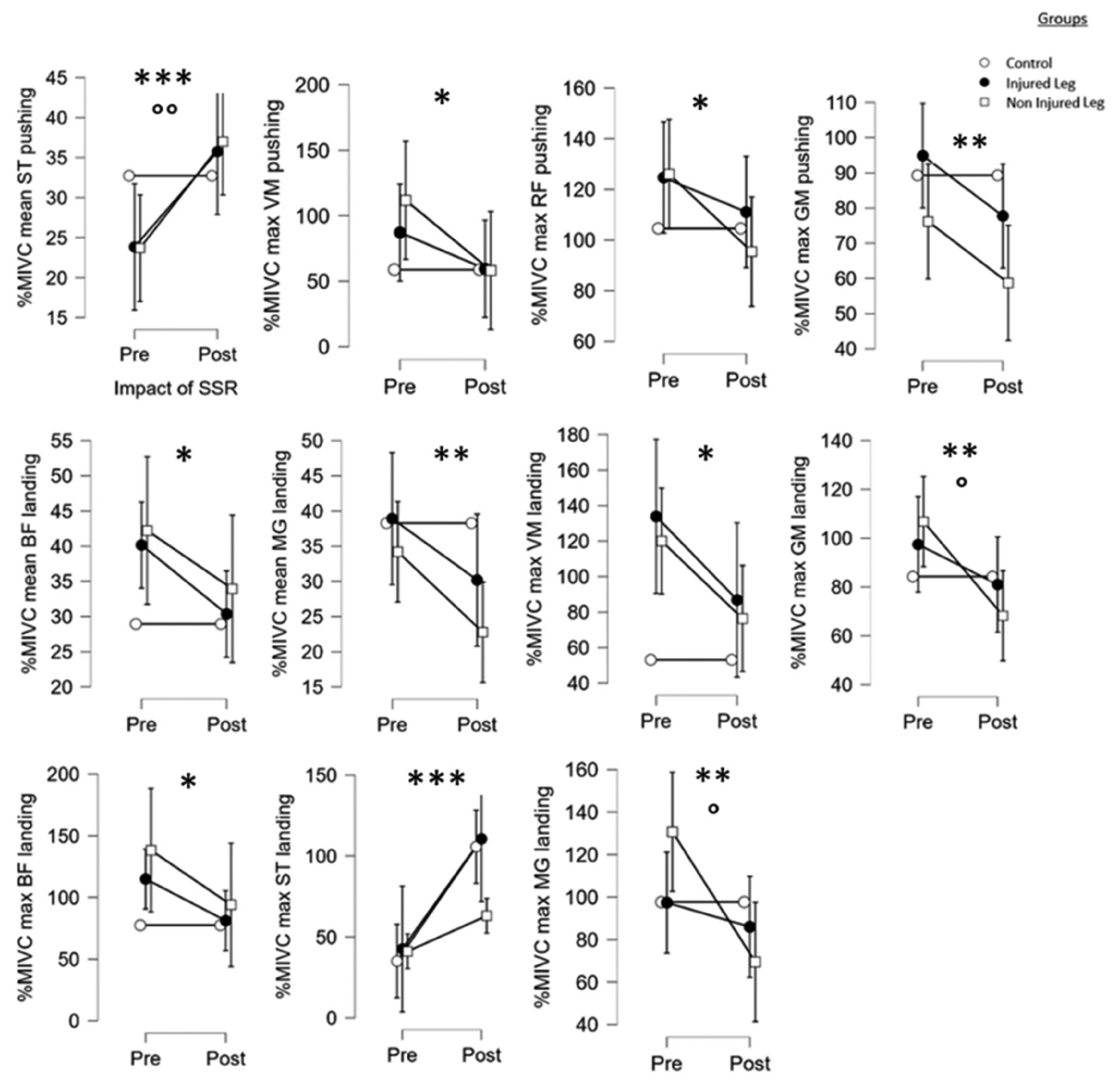

FIGURE 3
Main effects of the SSR program and the group on the EMG variables of the single-leg-CMJ. *, **, ***: significant effect of the SSR program (pre vs. post-SSR) with $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively. °, °°, °°°: significant effect of the group with $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

Finally, there were a significant group*SSR interaction between IL, NIL and CT for knee flexion ($F = 9.5$, $p < 0.001$), trunk flexion ($F = 16.3$, $p < 0.001$) and trunk lateral flexion ($F = 123.3$, $p < 0.001$) during landing (see Figure 4).

Discussion

Impact of the SSR-program

The present study firstly assessed the effectiveness of a typical 3-week SSR-program on neuromotor control for the injured leg (IL) in a group of professional soccer players. The SSR-program positively impacted several neuromotor parameters for both the IL and non-injured leg (NIL). Similar results have previously been observed related to the impact of neuromuscular training but with an eccentric dominance during muscle-strengthening program (35). Here, strength conditioning and neuromotor control work coupled with high-intensity and soccer-specific movements generated significant gains in RFD, despite the program's short duration (3-weeks). Improvement in neural aspects in the RFD_{Early} phase including muscle activation, reduction of recruitment threshold and increase in the rate of motor-unit discharge or a facilitation of spinal and supraspinal

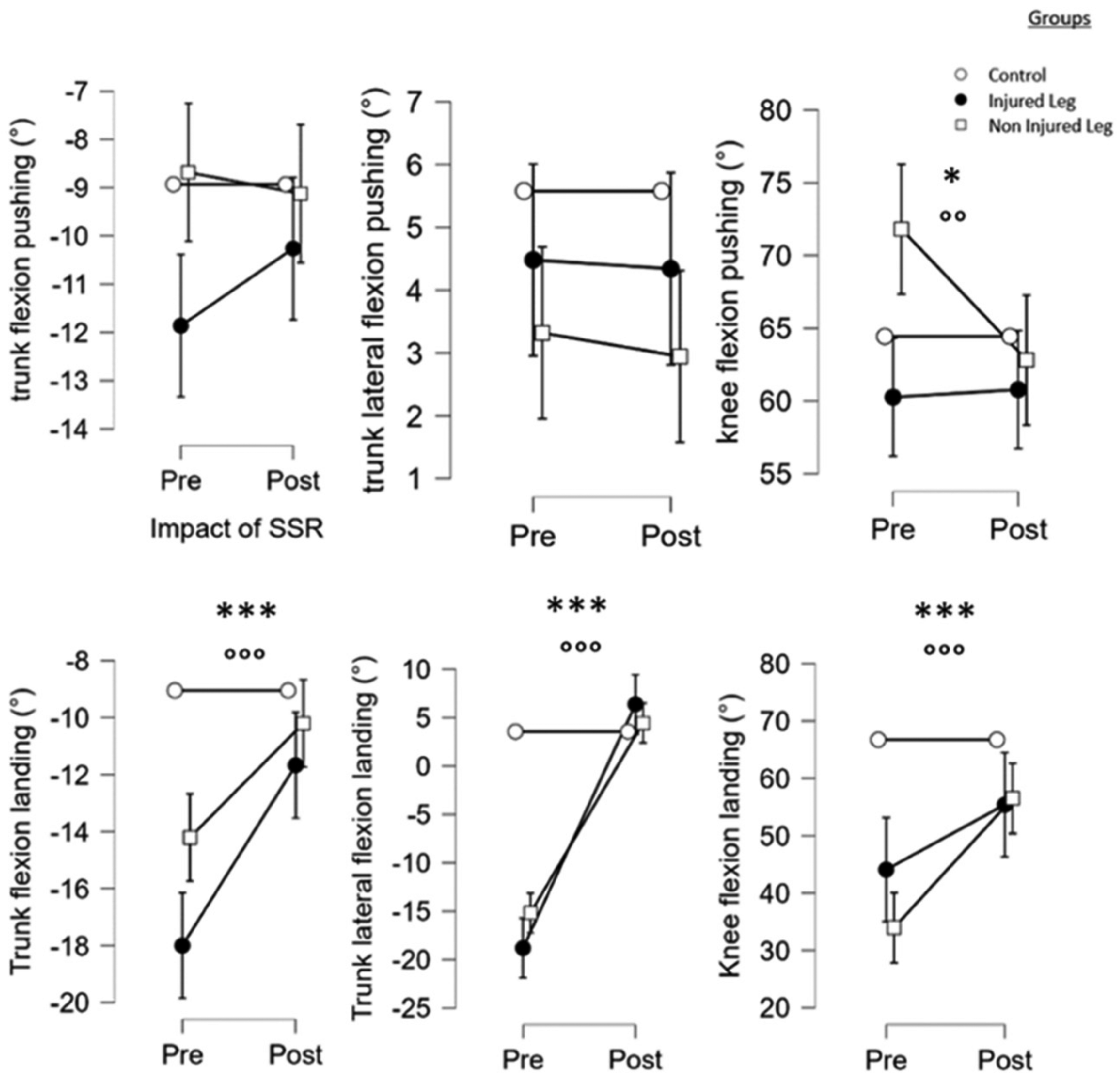

FIGURE 4
Main effects of the SSR program and the group on the kinematics variables of the single-leg-CMJ. *, **, ***: significant effect of the SSR program (pre vs. post-SSR) with $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively. °, °°, °°°: significant effect of the group with $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

outputs can potentially explain this gain (8, 9, 45–47). Structural contractile factors are preponderant for the RFD_{Late} phase (8, 9, 45–47). These include muscle fiber architecture, composition, and strength level. Concentric gains are achieved more quickly because the coordination, muscle recruitment and neural adaptations specific to this contraction regime are less complex (35). In contrast, no progress was observed in the injured players for $RFD_{EccentricLate}$. To our knowledge, this variable has not yet received any attention in the literature. Nevertheless, we can hypothesize that a 3-week period is potentially insufficient to establish nerve force adaptations unlike structural ones (21, 35). Other possible explanations include a lack of quality eccentric explosiveness based on muscular pre-activation and pre-synaptic facilitation (48, 49); or self-confidence to descend quickly during a post-injury ballistic movement. As such, players must continue neuromotor training to improve inter and intramuscular coordination and optimize this eccentric-concentric transition period (48–50).

Regarding muscle activation, the semitendinous was the muscle most positively impacted by the SSR, with a significant increase observed. In relation to the associated literature, one would expect a significant increase in muscle activation following neuromotor training (45, 51, 52). This is linked to improvements in corticomotor excitability, motor-unit synchronization and a reduction in inhibitory processes, and even after only 1-week of targeted work (52). To generate the same force, an eccentric contraction requires less muscle activation than a concentric one (53). An increase in discharge frequency and recruitment of slow motor-units to distribute the mechanical stress applied to the muscle can be responsible for stimulating EMG activity (53). These observations were observed only for the semitendinous and rectus femoris (not significatively) in IL and may partly be explained by the general rehabilitation program performed pre-SSR (11–13, 19). Indeed, this enabled the players to resume running and perform one-leg jumps without pain as nerve adaptations related to activation had certainly already been stimulated. Hamstrings and quadriceps are preferential targets of central and peripheral inhibitions (AMI) (5) and pain adaptation (6) potentially explaining this evolution. Research has previously discussed the compensation capacity of the BF when ST is inhibited (54). Here, SSR enabled a higher activation of the semitendinous avoiding overactivation of the BF and can therefore be partly responsible for any stagnation. RF and MG did not change with this result possibly explained by the quadriceps being targeted at an early stage during rehabilitation in order to eliminate any possible inhibition (5), and the athletes use better coordination reducing the compensations by the ankle and therefore the MG. Research, albeit limited (55), has also shown a lack of change in muscle activation after a neuromotor program and no correlation between jump height and muscle activity (20).

Regarding kinematic data, analysis of SLCMJ demonstrated noteworthy results. IL and NIL exhibited higher trunk flexion during pushing and landing probably to compensate for a lack of knee flexion, but these were less important post-SSR. When excessive trunk lateroflexion is observed, a deficit in pelvic control with a gluteus medius deficit in functionality is highlighted (56). These improvements show that the SSR-program had a positive impact on kinematic compensations linked to the injuries and particularly improved the neuromotor function of both the IL and NIL. This is possibly due to progress in activation qualities, muscle strength and confidence in one's leg movement. Indeed, poor neuromotor control of the trunk impacts dynamic knee stability, resulting in increased abduction and tension on the ligaments and joint (16, 56). The present SSR-program increased knee flexion at landing to dampen the movement, and knee flexion at push were very similar for IL, NIL and CG after SSR, demonstrating the effectiveness of the SSR-program effects on knee functionality. Knee flexion, knee valgus and hip abduction have previously been studied (41, 48) and reported the same observations as here (16, 56). The reduction in TLF may be due to a better utilization of knee flexion (linked to activation, strength and RFD), limiting distal instability and therefore compensation with the trunk. This improvement in trunk control is essential as postural stabilization deficit of the trunk is a key risk factor for joint and muscle injury (16, 56). Increasing knee flexion and trunk flexion during jump and landing actions would reduce GRF_Z levels and therefore the stress on body structures to limit injury risk (56, 57). Dynamic postural deficits have been observed up to 9–12 months following ACL-reconstruction highlighting that there are still postural compensations that have not yet been normalized during rehabilitation, as reported in our results (8, 9). As such, the SSR-program seems to be efficient for ensuring intrinsic functionality recovery of the knee. The kinematic analyses underline compensations, orientate rehabilitation and prophylactic work, and evaluate players' capacity to return to play using qualitative control of movements (14, 56–58). Different characteristics related to neuromotor control were observed depending on the injuries studied. These are currently under investigation in a sister paper (entitled, Modeling the neuromotor capacities of professional soccer player with a lower-limb injury during a Countermovement Jump, submitted).

A recent review on return-to-play deplores that this process is too often based on subjective data and lacks objectivity, normalization, standardization and scientific consensus (59). To validate any RTP process, specialized literature including the Italian Consensus Conference recommend either no LSI deficit or values less than 10% and return-to-performance levels prior to injury (9, 14, 60–62). Our pre-SSR result of deficits in $RFD_{concentric}$ (32%), jump height (8%) and RSI-Mod (17%) highlights that the NIL is also impacted (9) by injury to the contralateral leg and therefore also requires specific care and reconditioning during rehabilitation. This deconditioning of the NIL is consistent with the rate of reinjury reported in the contralateral leg over the two years following an initial ACLR injury (63). Moreover, if the NIL has not undergone specific conditioning training, RFD deficits of LSI (10%–57%) have been reported up to 24 months after surgery (8, 9) in the IL and NIL, which is outside the acceptability threshold for any RTP process. Once again comparison with healthy players seems to be of prime importance in guiding the rehabilitation staff on the program to be implemented for injured players. However, when this NIL training is performed, NIL values are closer to healthy players' performance, as our results showed with a reduction observed for deficits in $RFD_{concentric}$, jump height and RSI-Mod respectively of 24%, 0% and 4% also underlining the efficacity of the SSR-program on NIL.

This study has two main limitations. First, the cohort size which can be explained by limited access to elite standard participants. Secondly, the GE was made up of players with different types of injury (ACLR, muscle strain and chondral injury) who have different rehabilitation durations and severities of neuromuscular alteration, which may complicate analysis of the impact of the present SSR. Three weeks is a "normal" duration for the SSR of muscle strains, whereas according to the literature, ACL and CH require a longer period of SSR.

Conclusion

The main objective of any RTP process is to monitor and aid the athlete's return from injury and ultimately help them respond to the specific demands of competition (14, 55). SLCMJ tests during the RTP process are pertinent, useful and discriminating in the evaluation of neuromotor control (14). A SSR-program, even of 3-weeks duration, was effective in recovering neuromotor qualities in a group of high-level footballers although progress in their return to play programme seemed insufficient to attain the same level as healthy players. Moreover, results also showed a positive impact of the SSR-program on the players' NIL, underlying that it is essential to develop the capacities of the both the IL and NIL, to help avoid deficits on return to play with the NIL. Monitoring the progress of athletes during a SSR is important to refine the program and RTP strategies to minimize the risk of injury recurrence (20, 22, 64). Despite this, pending a scientific and clinical consensus on the objectification of SRR and the RTP processes, the impact of sport-specific rehabilitation program arguably depends mainly on the quality of the physical trainer in charge (59).

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 national Ethics Committee for sports science research (CERSTAPS n° IRB00012476-2020-24-03-48. 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

GM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. CC: Formal Analysis, Methodology, Supervision, Validation, Visualization, Writing – review & editing. JB: Conceptualization, Investigation, Methodology, Resources, Validation, Writing – original draft. PM: Investigation, Project administration, Resources, Supervision, Visualization, Writing – review & editing. BT: Conceptualization, Methodology, Validation, Writing – review & editing. PF: Conceptualization, Data curation, Methodology, Writing – review & editing. EY: Conceptualization, Data curation, Formal Analysis, Methodology, Validation, 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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Intramuscular stiffness distribution in anterior and posterior upper trapezius muscles in healthy young males

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Introduction: Increased muscle stiffness in the upper trapezius has been suggested to be associated with cervical myofascial pain and myofascial trigger points (MTrP). Recently, efforts have been made to objectively detect MTrP using ultrasound shear wave elastography (SWE). However, there is no consensus on the relationship between muscle stiffness assessed by SWE and MTrP. This may be due to the possibility that muscle stiffness is not uniform even in the asymptomatic trapezius. The present study aimed to characterize passive muscle stiffness at the proximal, central, and distal sites of the anterior and posterior parts of the upper trapezius.
Methods: Seventeen healthy young males without neck pain participated in the study. The upper trapezius was divided into anterior and posterior parts based on anatomical landmarks: the line between C6 and the lateral end of the clavicle was defined as the anterior part, while the line between C7 and the acromion angle was defined as the posterior part. Shear wave speed (SWS; an index of stiffness) was measured using ultrasound SWE at six sites in the anterior and posterior parts of the upper trapezius, at 25% (proximal), 50% (central), and 75% (distal) of the muscle belly length.
Results: SWS in the anterior part was significantly higher at the proximal ($p < 0.001$) and distal ($p < 0.001$) sites than at the central site. In the posterior part, there was no significant difference in SWS between the proximal, central, and distal sites. Comparisons between the anterior and posterior parts showed no significant differences in SWS at the proximal ($p = 0.147$), central ($p = 0.339$), and distal sites ($p = 0.051$).
Conclusions: The characteristics of passive stiffness distribution in the anterior and posterior parts of the upper trapezius have important implications with respect to the optimal location of the control point during MTrP detection. In particular, it may be preferable to set the control point for detecting MTrP in the transverse direction rather than in the fascicle direction, that is, to compare passive muscle stiffness at the same levels between the anterior and posterior parts.

KEYWORDS
myofascial pain syndromes, trigger point, shear wave speed, elastography, ultrasound

1 Introduction

Myofascial pain syndrome (MPS) is a type of musculoskeletal pain syndrome caused by myofascial trigger points (MTrP) in skeletal muscles and occurs most frequently in the upper trapezius (1). MTrP are hypersensitive spots within taut bands of a skeletal muscle that cause pain on compression and referred pain. MTrP can be classified into active and latent MTrP (2); the former causes spontaneous pain, while the latter does not cause spontaneous pain but elicits pain upon palpation. Latent MTrP are clinically asymptomatic; however, repetitive muscle overuse, acute muscle overload, or repetitive minor muscle trauma can transform them into active MTrP that cause musculoskeletal pain (3). In addition, the presence of latent MTrP in the upper trapezius can result in altered shoulder girdle dynamics, leading to musculoskeletal disorders such as impingement syndrome and rotator cuff lesions (4, 5). Therefore, early detection of the MTrP in the upper trapezius is important for the management of musculoskeletal pain and disorders. Clinically, MTrP are diagnosed by palpation of the taut band; however, palpation is considered to lack consistent reproducibility (6). Moreover, due to the lack of established objective and reliable diagnostic criteria, they are often overlooked.

Recently, efforts have been made to detect MTrP objectively. Ultrasound shear wave elastography (SWE), which can noninvasively quantify local tissue stiffness (7), has received particular attention for the diagnosis of MTrP in the upper trapezius. The previous studies (8) passive muscle stiffness at the central point of the upper trapezius was measured using ultrasound SWE in healthy individuals and those with taut bands and MTrP. The study found that individuals with MTrP had significantly higher passive muscle stiffness compared to healthy individuals. Furthermore, one of the previous studies (9) found a positive correlation between passive muscle stiffness and pain scores in patients with cervical MPS. The previous findings suggest that increased passive muscle stiffness is associated with MPS. In contrast, another study (10) compared passive muscle stiffness at the latent or active MTrP detected by palpation with that at a control point (3 cm lateral to the MTrP) in the upper trapezius. They failed to find significant differences in passive muscle stiffness at the latent or active MTrP compared to the control point. However, based on the previous findings, it is difficult to conclude that ultrasound SWE cannot detect MTrP from asymptomatic sites within a muscle. In this context, a recent review indicated that there is still no consensus regarding the association between passive muscle stiffness and pain symptoms (including MTrP) in the upper trapezius (11). Additionally, passive muscle stiffness in the upper trapezius has been reported to be non-uniform along the fascicle direction (12). Collectively, it may be preferable to set a control point for detecting MTrP in the transverse direction rather than in the fascicle direction in the upper trapezius.

The upper trapezius is transversely divided into two compartments (13, 14): anterior (between the sixth cervical spinous process and the lateral end of the clavicle) and posterior (between the seventh cervical spinous process and the acromion). The origins, insertions, and actions of the fascicles differ between the anterior and posterior parts of the upper trapezius. However, most of the available information on the upper trapezius passive stiffness is limited to the posterior part (8, 12), and detailed information on the anterior part is lacking. Understanding the stiffness distribution within the anterior and posterior parts of the upper trapezius in healthy individuals can be useful in determining the optimal control point location. Therefore, the purpose of the present study was to characterize passive muscle stiffness at the proximal, central, and distal sites of the anterior and posterior parts of the upper trapezius. Based on previous findings of non-uniform stiffness distribution along the fascicle direction in the upper trapezius, we formulated the following hypotheses: the passive stiffness of both the anterior and posterior parts of the upper trapezius is not uniformly distributed along the fascial direction. Furthermore, we proposed that there is no difference in passive stiffness between the anterior and posterior (transverse) parts, allowing them to serve as control points when comparing with MTrP. Based on this assumption, we established an additional hypothesis: the passive stiffness of the proximal, central, and distal sites does not differ between the anterior and posterior parts.

2 Materials and methods

2.1 Subjects

Seventeen healthy young males (171 ± 5 cm, 66 ± 8 kg, 22 ± 3 years old) participated in the present study. The exclusion criteria were as follows: (1) taking pain medications, muscle relaxants, or steroids; (2) currently undergoing physical therapy; (3) having a history of diagnosis of orthopedic disorders (cervical osteoarthritis, cervical disc herniation, cervical spondylosis nerve root disease, cervical spondylosis myelopathy, scoliosis); (4) having a history of neck or shoulder injuries (whiplash); (5) having a history of surgery on the spine, chest, shoulder joint, or upper arm; (6) having a history of diagnosis of a medical disorder (diabetes, Ehlers-Danlos syndrome, autoimmune disease, cancer, infectious disease, or cerebrovascular disease); and (7) having skin lesions that interfere with ultrasound measurements of the upper trapezius. The Japanese version of the FLANDERS handedness Questionnaire (15) was used to assess the dominant hand. Subjects were asked to avoid strenuous exercises within 48 h prior to the experiment.

2.2 Experimental setup and procedure

All measurements were performed on the right side of each subject. The subjects lay prone on an examination bed with a face hole, with their arms resting alongside their trunk and forearms in a pronated position. The subject's face was placed on the face hole, and they were instructed to relax their muscles as much as possible. The lumbar and lower legs were firmly secured to the bed with nonelastic straps. In order to determine the measurement sites for ultrasound SWE and electromyography (EMG) prior to data acquisition, the spinous processes of the C6 and C7 vertebrae, the lateral end of the clavicle, and the acromion angle were first identified by palpation. In the present study, the lines between the C6 and the lateral end of the clavicle and between the C7 and the acromion angle were defined as the anterior and posterior parts of the trapezius, respectively. Ultrasound SWE and EMG measurements were performed at 25% (proximal), 50% (central), and 75% (distal) of the muscle belly length (determined by identifying the proximal and distal muscle-tendon junctions using B-mode ultrasonography) at each part. The measurement sites were marked on the skin with a waterproof pen. It is very difficult to perform ultrasound SWE and EMG measurements simultaneously because of insufficient surface area. Therefore, ultrasound SWE and EMG measurements were performed separately; ultrasound SWE measurement was followed by EMG measurement. Then, the presence of latent MTrP was investigated.

2.3 Ultrasound SWE measurement and analysis

An Ultrasound SWE system (Aixplorer Ver.12, Supersonic Imagine, France) with a 2–10 MHz linear probe (SL10-2, Supersonic Imagine, France) was used to assess muscle shear wave speed (SWS) (preset: “MSK”, persistence: high, smoothing: 5). The ultrasound probe was placed at the marked sites mentioned above, and the probe orientation was adjusted to identify several fascicles within the B-mode image (Figure 1). Care was taken not to press and deform the muscles while scanning. Ultrasound SWE images were acquired after confirming that the color map was stable for a few seconds. At each measurement site, three measurements were performed (i.e., three images were acquired). The Ultrasound SWE data were analyzed using software in the ultrasound SWE system. A circular area as large as possible, with the exclusion of fascia and subcutaneous fat tissue, was selected as the region of interest (Figure 2). The diameters of the regions of interest for each site are shown in Table 1. The mean SWS over the region of interest was calculated for each image. The values of three measurements at each site were averaged and used for statistical analyses.

To evaluate the inter-trial (intra-day, intra-rater) reliability of ultrasound SWE measurements, a pilot study ($n = 5$) was performed prior to the main experiment mentioned above. The inter-trial reliability tests were performed three times with at least 5-min intervals by the same examiner who conducted the main experiment. In the reliability tests, the marks for the measurement sites were completely erased after each trial.

2.4 EMG measurement and analysis

Muscle activities of the upper trapezius were assessed at six measurement sites using a wireless surface EMG system (Trigno, Delsys, USA). Skin preparation that included shaving and

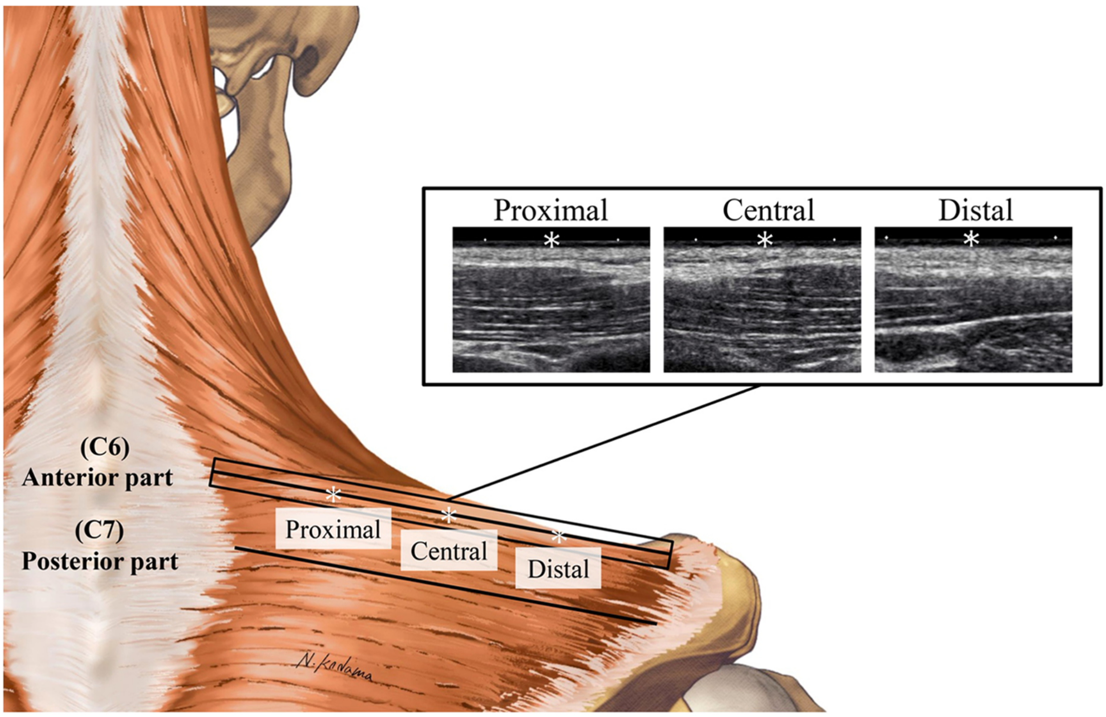

FIGURE 1
Examples of B-mode images at the proximal, central, and distal sites of the anterior part of the upper trapezius. * Denotes 25% (proximal), 50% (central), and 75% (distal) points of the muscle belly length.

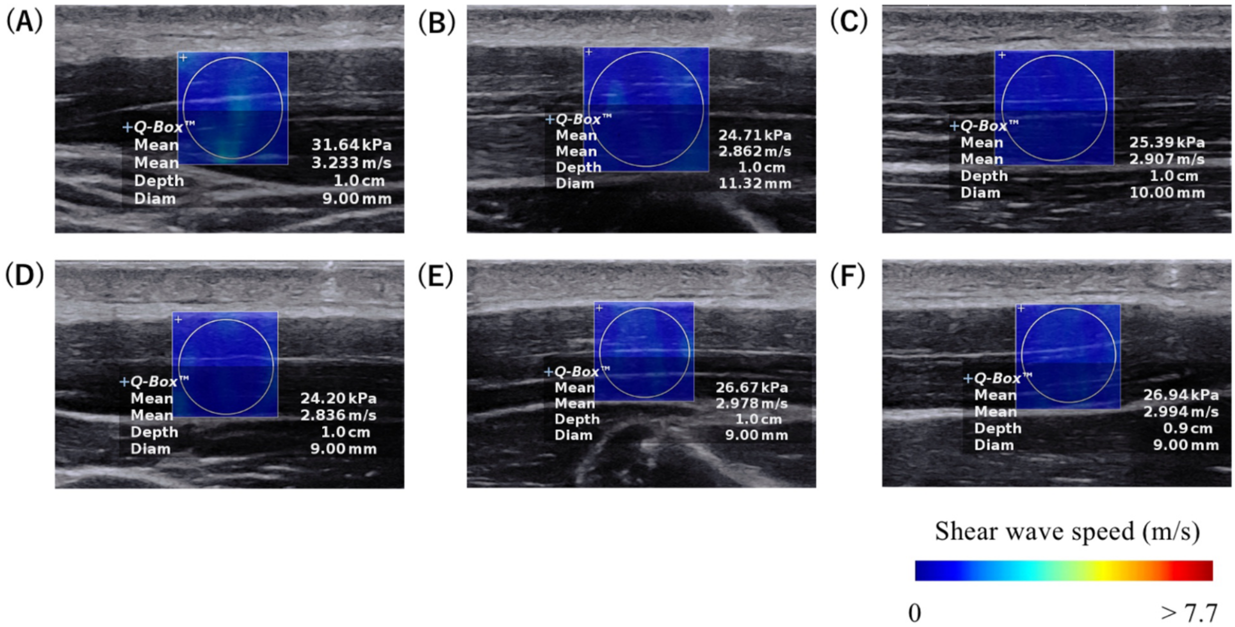

FIGURE 2
Typical examples of ultrasound SWE images at the **(A)** proximal, **(B)** central, and **(C)** distal sites of the anterior part, and at the **(D)** proximal, **(E)** central, and **(F)** distal sites of the posterior part of the upper trapezius. The colored region represents the shear wave speed map, with the scale shown at the bottom of the images.

TABLE 1 Diameter of region of interest in elastography measurement.

Upper trapezius	Proximal	Central	Distal
Anterior part (mm)	11.7 ± 1.6	9.6 ± 1.7	5.9 ± 1.5
Posterior part (mm)	7.9 ± 1.4	7.0 ± 1.8	5.7 ± 1.6

cleaning with alcohol was performed before fixing the surface electrodes with adhesive tape at the marked sites. After the surface electrodes were fixed, EMG signals were recorded at 1 kHz using a 16-bit analog-to-digital converter (PowerLab/16SP, ADInstruments, Australia). Additionally, to normalize EMG data at rest, each subject performed one maximal voluntary isometric contraction (MVC) of shoulder abduction with the shoulder abducted at 90° against manual resistance in the prone position on the bed. During MVC, subjects were verbally encouraged. EMG data were processed using commercially available software (LabChart 8, ADInstruments, Australia). For each measurement site, the root-mean-square value of the EMG signal (EMG-RMS) for 5 s at rest was calculated and normalized to the maximal value of EMG-RMS during MVC.

2.5 Latent MTrP identification

The presence of the latent MTrP was tested in the prone position. A single examiner with more than 10 years of experience in the assessment and treatment of MTrP determined the presence or absence of latent MTrP, according to the diagnostic criteria by Fernández-de-las-Peñas et al. (16). The criteria for latent MTrP were as follows: (1) presence of a palpable taut band in the muscle; (2) presence of a hypersensitive tender spot in the taut band; and (3) local twitch response provoked by snapping palpation of the taut band. Among the measurement sites that met all three criteria, those where palpatory stimuli did not reproduce symptoms previously experienced by the subject, or where the evoked symptoms were not recognized by the subject as those previously felt, were considered latent MTrP (16). No latent MTrP was detected at any of the ultrasound SWE and EMG measurement sites.

2.6 Statistical analysis

The sample size was calculated using G*Power software (Kiel University, Germany). Since there were no previous data on the intramuscular difference in the upper trapezius stiffness to estimate the sample size, the minimum sample size was estimated with a "moderate" effect size for differences between measurement sites ($f^2 = 0.25$), an α level of 0.05, and a power (1-β) of 0.8. According to our calculation, 14 subjects were required for an analysis of variance (ANOVA) with repeated measures. Thus, the 17 subjects in the present study satisfied the minimum sample size.

To evaluate the reliability of the ultrasound SWE measurements, intraclass correlation coefficient (ICC) (ICC1,3) and coefficient of variation (CV) were calculated using the pilot study data. The normality of the data distribution of SWS and EMG-RMS at each measurement site in the main experiment was assessed by the Shapiro-Wilk test. The SWS at the central site in the posterior part and EMG-RMS at the distal site in the anterior part and at the central and distal sites in the posterior part were not normally distributed. Therefore, the Friedman test was used to compare the variables between the proximal, central, and distal sites. When a significant main effect was detected, *post-hoc* Bonferroni-adjusted Wilcoxon signed-rank tests were performed. For comparisons between the anterior and posterior parts at the proximal, central, and distal sites, the Bonferroni-adjusted Wilcoxon signed-rank test was used. For all statistical tests, $p < 0.05$ was considered significant. The statistical analyses were performed with statistical software (SPSS statistics Ver. 29, IBM, USA).

3 Results

3.1 Subjects′ characteristics

Among the 17 subjects, 16 were right-handed. Subjects had the following previous athletic experience (soccer [2], soft tennis [1], volleyball [1], powerlifting [1], cycling [1], baseball (outfielder) [3], and track and field [8]). The breakdown of the track and field events were sprint (2), mid-distance (1), long-distance (2), jump (2), and throw (1).

3.2 Reliability of measurement

For the SWS of the anterior part, ICC1,3 ranged from 0.79 to 0.91, with CV of 8.1% to 12.3%. For the SWS of the posterior part, ICC1,3 ranged from 0.82 to 0.83, with CV of 9.2% to 11.1%. ICC1,3 greater than 0.75 indicates good reliability.

3.3 SWS

Figure 3 shows the upper trapezius SWS at the proximal, central, and distal sites of the anterior and posterior parts. For the anterior part, the Friedman test showed a significant main effect ($p < 0.001$, observed power = 0.99). Follow-up *post-hoc* tests revealed that the SWS was significantly higher at the proximal ($p < 0.001$, observed power = 0.99) and distal sites ($p < 0.001$, observed power = 0.99) than at the central site. For the posterior part, the Friedman test did not show a significant main effect ($p = 0.113$, observed power = 0.76). For comparisons between the anterior and posterior parts, the Bonferroni-adjusted Wilcoxon signed-rank tests showed no significant difference at the proximal ($p = 0.147$, observed power = 0.95), central ($p = 0.339$, observed power = 0.81), and distal sites ($p = 0.051$, observed power = 0.99).

3.4 EMG-RMS

Figure 4 shows the EMG-RMS of the upper trapezius at the proximal, central, and distal sites of the anterior and posterior parts. For both the anterior and posterior parts, the Friedman test showed significant main effects (anterior: $p < 0.001$; posterior: $p = 0.019$). Follow-up *post-hoc* tests revealed that the EMG-RMS of the anterior part was significantly greater at the proximal ($p = 0.049$) and distal sites ($p < 0.001$) than at the central site and greater at the distal site than at the proximal site ($p = 0.049$). The EMG-RMS of the posterior part was significantly greater at the central site than at the proximal site ($p = 0.018$). The

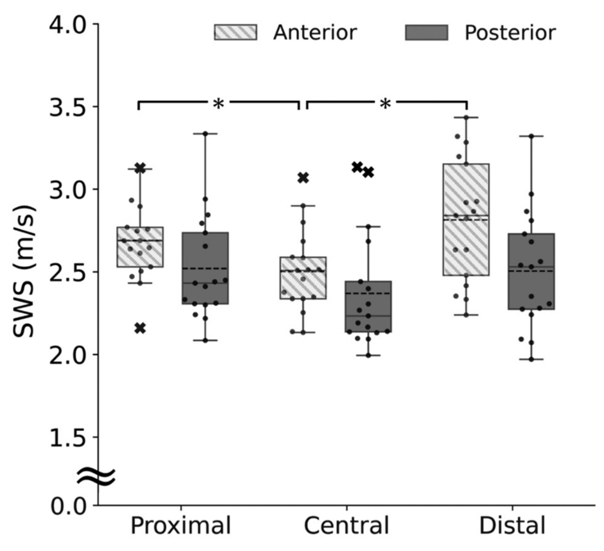

FIGURE 3
Upper trapezius shear wave speed (SWS) at the proximal, central, and distal sites of the anterior (box plot with shading) and posterior parts (gray). *Significant difference at $p < 0.05$.

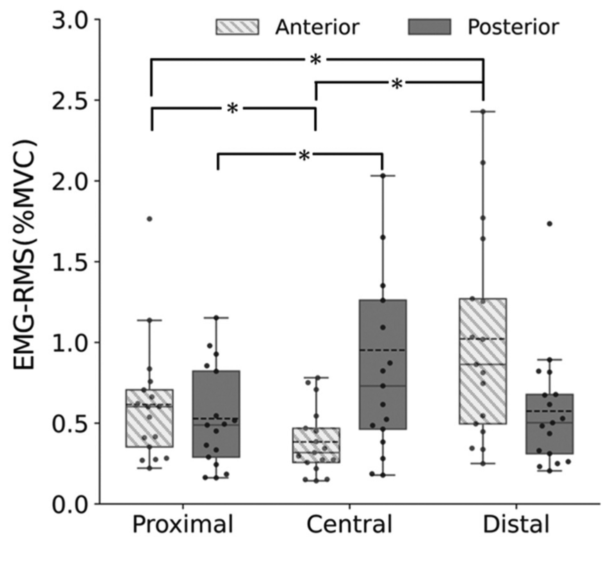

FIGURE 4
Upper trapezius muscle activities (EMG-RMS) at the proximal, central, and distal sites of the anterior (box plot with shading) and posterior parts (gray). *Significant difference at $p < 0.05$.

Bonferroni-adjusted Wilcoxon signed-rank test revealed that the EMG-RMS was significantly greater in the posterior part than in the anterior part at the central site ($p < 0.001$).

4 Discussion

The present study focused on the intramuscular distribution of passive stiffness in healthy subjects without latent MTrP. Multiple proximo-distal site SWS were measured using ultrasound SWE for the anterior and posterior parts of the upper trapezius. To our knowledge, this study is the first to demonstrate non-uniform intramuscular stiffness distribution in the anterior part of the upper trapezius.

In the present study, passive muscle stiffness in the anterior part of the upper trapezius was non-uniformly distributed, with stiffness at the proximal and distal sites being higher than at the central site. This result supports our hypothesis.

Previous studies have examined the intramuscular stiffness distribution in the hamstring (17) and gastrocnemius (18). In both muscles, passive muscle stiffness was in the order of the distal >central >proximal sites when measured in stretched positions, whereas passive muscle stiffness was uniform when measured in shortened (not stretched) positions. Our findings on the anterior part were not consistent with the previous findings, regardless of whether the measurement position in the present study was stretched or shortened. This discrepancy between the present and previous studies may be due, at least in part, to the difference in the muscles investigated, but it may also be due to the difference in the influence of muscle activity. The previous study investigating intramuscular stiffness distribution within the hamstring (17) showed that muscle activity at the distal site, where passive muscle stiffness was higher, was lower than at the proximal and central sites, concluding that the non-uniform distribution of passive muscle stiffness within the hamstring was not due to muscle activity. In contrast, in the present study, muscle activities were higher at the proximal and distal sites, where passive muscle stiffness was higher than at the central site. These findings suggest that the non-uniform distribution of passive muscle stiffness distribution in the anterior part of the upper trapezius may be due, at least in part, to the regional differences in muscle activity although absolute values of muscle activities were not large at either site.

Contrary to part of our hypothesis, passive muscle stiffness in the posterior part of the upper trapezius was uniformly distributed in the present study. In a previous study examining passive muscle stiffness distribution within the posterior part of the upper trapezius in healthy adults without shoulder pain and a history of neck or shoulder disorder, passive muscle stiffness was measured at four sites: 17%, 33%, 50%, and 67% of the line from the seventh cervical spinous process to the acromion (12). The highest passive muscle stiffness was observed at the 33% site, which is close to the proximal site of the present study (note that in the present study, the measurement sites were determined based on the muscle belly length rather than the origin-insertion length). The discrepant results between the present and previous studies may be due to differences in the measurement posture (prone in the present study and seated in the previous study) and the resulting degree of muscle stretching as mentioned above. On the other hand, although there were regional differences in muscle activities in the posterior part as observed in the anterior part, there were no significant differences in passive muscle stiffness. The reason for this is unknow at this time and requires further study.

This study is the first to compare the upper trapezius muscle stiffness between the anterior and posterior parts. Consistent with our hypothesis, we did not find significant differences in passive muscle stiffness between the two parts. Specifically, although a significant difference in muscle activity was found between the anterior and posterior parts at the central site, no significant difference in passive muscle stiffness was observed between these parts. The results of the present study on passive muscle stiffness have important implications for setting a control point for objective detection of MTrP using ultrasound SWE. Although there is no agreement on whether passive muscle stiffness at MTrP is higher than at normal sites, if MTrP exhibits higher passive muscle stiffness, setting the control point for MTrP detection in the fascicle direction may make MTrP detection difficult. For example, if the MTrP is located at the central site of the anterior part of the upper trapezius (where passive muscle stiffness is low in normal individuals, as in the present study) and the control point is set proximally or distally along the fascicle direction, the MTrP may be overlooked. Given the findings of the present study, it is preferable to set the control point for MTrP detection in the transverse direction rather than in the fascicle direction, that is, to compare passive muscle stiffness at the same levels between the anterior and posterior parts.

5 Limitations

The present study has some limitations. First, the present study included only healthy subjects without latent MTrP. Thus, it remains unclear whether the present findings hold for individuals with active or latent MTrP. Second, passive muscle stiffness of the upper trapezius in the present study was measured in the prone position. Therefore, it is unclear whether similar results would be obtained in other postures such as sitting. Third, all measurements in the present study were conducted on the right side. Although a consensus has not yet been reached regarding the influence of hand dominance on passive muscle stiffness of the upper trapezius, previous studies have reported both higher (19, 20) and lower (21) passive muscle stiffness in the upper trapezius on the dominant side. Given the possibility that hand dominance may have influenced the results of muscle stiffness distribution, further investigation on this point is needed. Fourth, a preliminary power analysis using pilot data was not conducted to determine the sample size in the present study. When a power analysis was conducted using the data obtained, with an alpha level of 0.05 and a power of 0.80, the minimum sample size required to detect differences within the anterior part and between the anterior and posterior parts at the proximal, central, and distal sites, was 17, indicating that the sample size of the present study met the criterion. In contrast, the minimum sample size required to detect differences within the posterior part was found to be 21. Therefore, some of the results should be interpreted with caution.

6 Conclusions

We investigated the intramuscular distribution of passive stiffness in the anterior and posterior parts of the upper trapezius in healthy adult males without MTrP. Muscle stiffness was non-uniformly distributed in the anterior part, whereas the posterior part showed a uniform distribution. There are no significant differences in muscle stiffness between the anterior and posterior parts. These results have important implications with respect to the optimal location of the control point during MTrP detection. In particular, it may be preferable to set the control point for detecting MTrP in the transverse direction rather than in the fascicle direction.

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 Juntendo University Ethics Committee (Approval Number: 2022–85). The studies were conducted in accordance with local legislation and institutional requirements. 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

KS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. NM: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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Unilateral baseball pitching: morphological and functional adaptations in the neck muscles

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Background: Functional asymmetry and muscle imbalances are recognized as contributors to injury risk in athletes. Sports with repetitive unilateral movements such as baseball pitching can lead to adaptations in shoulder and scapular muscles. There is a lack of research on whether these movements result in neck muscle alterations. Understanding potential asymmetries in neck musculature could provide valuable insights into athletes' performance and injury prevention strategies.
Methods: A total of 14 collegiate baseball pitchers and 15 controls voluntarily participated in this study. Bilateral dorsal neck muscle thickness, stiffness, neck range of motion (ROM), neck repositioning error, and extensor strength were measured, and the asymmetry between the two groups was compared. Rehabilitative ultrasound imaging was used to assess muscle thickness and stiffness. An inclinometer and a dynamometer were utilized to evaluate neck ROM and strength, respectively.
Results: The mean age of the baseball pitchers and controls was 21.86 ± 1.6 and 25.87 ± 5.10 years, respectively. A significantly greater thickness of the splenius capitis on the non-dominant side was observed in baseball pitchers [$p = 0.029$, effect size (ES) = 0.857], whereas controls demonstrated symmetrical muscle thickness in all dorsal neck muscles. Pitchers exhibited higher neck extensor maximal voluntary contraction compared to controls ($p = 0.017$, ES = 0.926). Controls showed more bilateral differences in muscle stiffness in the splenius capitis and the semispinalis cervicis, although statistical asymmetry was not demonstrated.
Conclusion: The cervical multifidus muscles showed bilateral symmetry despite the unilateral throwing motion in baseball pitching. However, unilateral neck rotation toward the non-dominant side appears to contribute to greater thickness of the splenius capitis on the non-dominant side of pitchers.

KEYWORDS

neck muscles, baseball, muscle adaptation, functional asymmetry, strength, proprioception

1 Introduction

Functional asymmetry, muscle imbalance, and strength asymmetry have been identified as factors associated with a higher risk of injury in both the upper and lower limbs of athletes (1–4). Asymmetry can be defined as a bilateral imbalance between a homologous group of muscles or a disruption in the agonist–antagonist ratio (2). According to motor control theory, the presence of asymmetry represents potential restraints that limit an athlete's movement strategies (4, 5). Sports that often require unilateral excursion of skilled movements to be repeated frequently during games and throughout the season, such as pitching or batting in baseball, considerably increase the chances of developing a stronger dominant side (3).

Baseball fundamentally involves throwing, batting, and catching the ball. Throwing and batting are predominantly executed by the athlete's dominant hand. Notably, pitching and batting involve explosive, fast, rotational movements that can put significant strain on the dominant side, potentially leading to overloading injuries (6).

Previous research has demonstrated shoulder and scapular asymmetries in baseball players, which appear as adaptations predominantly to their dominant arm (7–10). These adaptations manifest as increased scapular anterior tilt (9) and decreased upward rotation on the dominant side (9). In addition, studies have noted asymmetries between the strength of the rotator cuff on the dominant and non-dominant sides (8) and increased strength of the lower and middle trapezius muscle on the dominant side (7). Moreover, some recent investigations revealed that adolescent baseball pitchers exhibit greater thickness and cross-sectional area of the lower trapezius muscle in their dominant arm compared to their non-dominant arm (7, 11). Although these studies have shed light on asymmetries in the upper extremities, there is a lack of evidence on neck muscle asymmetries in baseball players. This gap in knowledge is significant due to the strong activation and changes in thickness of deep dorsal neck muscles observed during isometric shoulder contraction, particularly during maximal isometric shoulder abduction (12–14).

The increased risk of injury associated with bilateral asymmetry in muscle strength has been reported in various types of overhead athletes (3, 15), including volleyball players (16, 17). For example, Hadzic et al. found that in male volleyball players, the external to internal rotation strength ratio of the dominant shoulder was lower, regardless of the playing position or skill level. In female players, however, this ratio was reduced only in those with higher skill levels. Accordingly, they suggested that female volleyball players may have a lower risk of developing shoulder-related problems compared to their male counterparts (17). In addition, Wang and Cochrane reported that an imbalance in the external to internal rotator strength on the dominant side was significantly associated with a higher risk of injury in volleyball players (18). Although asymmetric scapular dyskinesia has been observed in volleyball players, its link to injury risk remains controversial (19, 20). Furthermore, Reeser et al. found an association between shoulder pain and asymmetric pectoralis shortness in volleyball players (16). However, there is limited evidence regarding muscle asymmetry, particularly in the neck muscles of baseball players, and whether such asymmetry is associated with an increased risk of injury for these athletes.

The significance of neck muscles lies in their pivotal role in glenohumeral biomechanics, owing to their anatomical interconnection with the shoulder. Deep neck extensor muscles are responsible for upholding neck stability and regulating the segmental movements of the cervical spine, while working with the deep neck flexors (21). Consequently, any alteration or asymmetry in this region can impact the kinetic chain during complex movements such as pitching in baseball, potentially predisposing athletes to injury.

To date, no studies have examined the impact of these repetitive unilateral arm movements on the potential asymmetry of dorsal neck muscles, specifically in terms of muscle thickness or stiffness. Therefore, the primary aim of this study was to investigate the thickness and stiffness of the dorsal neck muscles in baseball pitchers and compare them with individuals who generally engage in symmetrical activities. We hypothesized that baseball pitchers would exhibit greater thickness in their dorsal neck muscles on their dominant side, accompanied by decreased stiffness compared to their non-dominant side and compared to non-baseball players.

2 Material and methods

2.1 Participants

A cohort containing 14 collegiate baseball pitchers and 15 controls voluntarily participated in this study, providing their written informed consent. The inclusion criteria were as follows: male participants; aged 18–40 years; and without any recent history (within the past 12 months) of neck pain, trauma, injury, or surgical interventions. Individuals were excluded from participation if they reported current neck or shoulder discomfort, or engaged in sports other than baseball, or any regular unilateral sport activities such as tennis. However, individuals with a regular regimen of gym exercise were considered eligible to participate in this study. Approval for the study was obtained from the Institutional Review Board (IRB) at California State University, Los Angeles (IRB No. 1991571-1).

2.2 Experimental procedure

The experimental procedure was carried out during a single visit. Participants were informed about the procedure and the equipment before data collection. Anthropometric data, including height, weight, and age, were collected via demographic information sheets. In addition, participants provided information about their exercise routines, including the duration in years and frequency per week. The outcome measures included dorsal neck muscle thickness, stiffness, and strength, neck range of motion (ROM), and cervical repositioning error as an index of neck proprioception. Ultrasound imaging for muscle thickness and stiffness was conducted by the principal investigator with over 10 years of experience in ultrasound imaging. The remaining tests and measurements were performed by a physical therapist with more than 5 years of experience.

2.2.1 Ultrasonography measurements

Rehabilitative ultrasound imaging (RUI) using a V7, 2020 (Samsung, Korea), equipped with a 4-cm LA2-14A linear probe, was used to measure muscle thickness and stiffness. Participants were seated with relaxed heads and necks, with their hands resting on their thighs (22). The cervical vertebra 4 (C4) was palpated and marked by a skilled physical therapist. Then, the probe was horizontally placed on the C4 spinous process and gradually slid to either the left or right side (randomized order). Once the vertebral lamina and separating fascia were clearly visible, the image was frozen to measure muscle thickness. In the aforementioned probe position, the screen displayed images of the trapezius, splenius capitis, semispinalis capitis, semispinalis cervices, and multifidus muscles. This process was repeated three times and the average thickness of each muscle on each side was used for further analysis. No normalization was done for muscle thickness as weight is the main factor influencing neck muscle size (23) and due to the similarity of weight across both groups.

Elastography settings were configured to the musculoskeletal neck preset, with a 10 Hz penetration rate and a shear modulus range of up to 600 kPa. For the stiffness measurement, the probe was adjusted vertically on C4 and slid to either the right or left side (randomized order) until a clear image was obtained. Image quality was assessed using the Relative Measurement Index (RMI). With the greenest possible RMI screen indicating optimal image quality, the image was saved. A region of interest (ROI) was manually set for each muscle, excluding the fascia and hypoechoic layers. Within each ROI, five distinct points were selected on each muscle, with the average stiffness across these points considered to be the muscle's stiffness.

2.2.2 Neck proprioception

Neck proprioception was assessed using the neck repositioning error test (24, 25). Participants were seated relaxed on a chair with their hands resting on their thighs. The chair was positioned at a fixed distance of 90 cm from a wall. A headband equipped with a laser pointer was affixed on the individual's head, directing the laser light onto the wall in front of them. A target was placed on the wall at eye level. Participants were instructed to maintain a natural gaze and keep their head and neck relaxed throughout the procedure (Figure 1A).

The laser point on the wall served as the initial reference. Participants were then asked to rotate their head and neck either to the right or left (randomly selected) as far as possible before returning to starting position to familiarize themselves with the procedure. Next, they repeated the same movement sequence with their eyes closed. Upon reaching what they perceived as their original head position, the new location of the laser pointer on the wall was marked. The difference between the target point and the new marked point represented the repositioning error (24, 25).

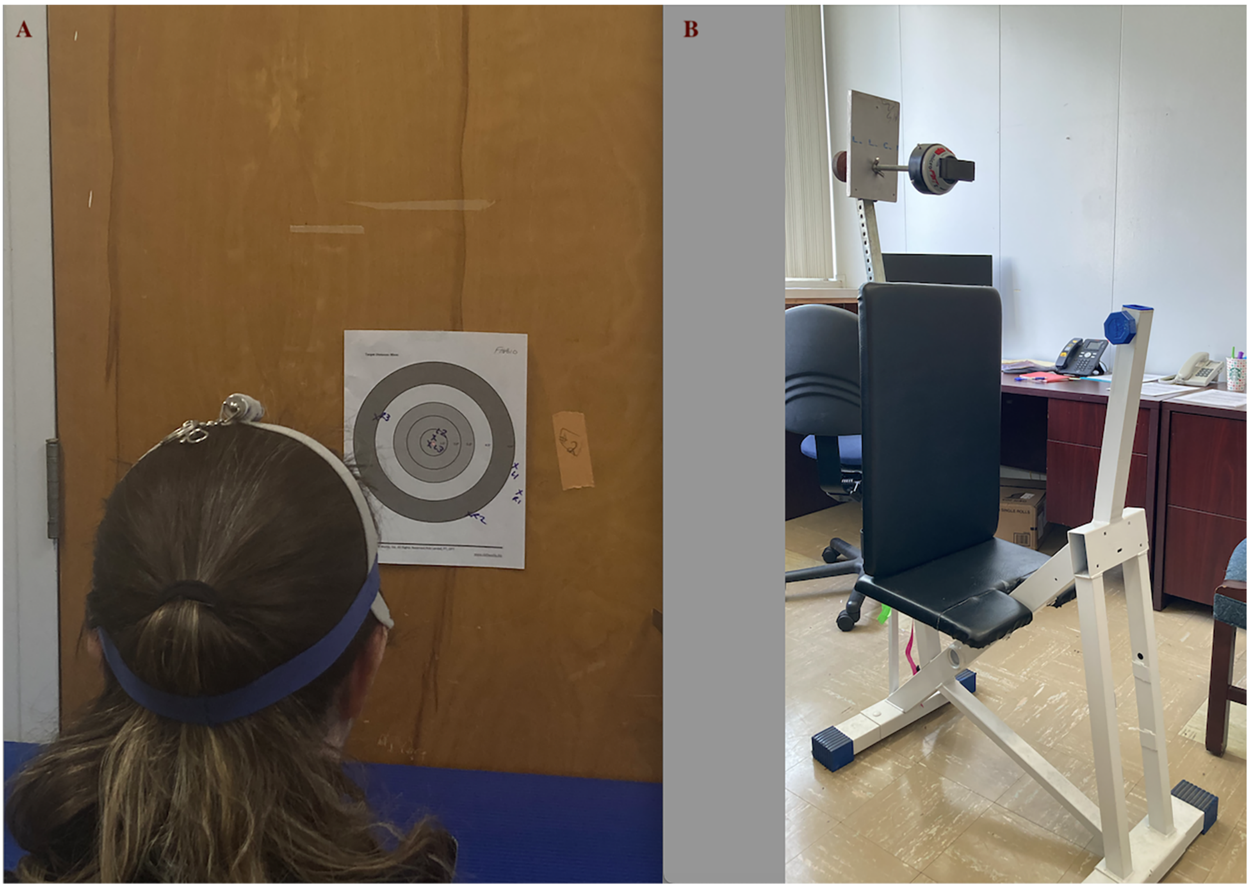

FIGURE 1
(A) Neck repositioning error test. (B) The customized chair and mounted handheld dynamometer.

Participants repeated this protocol on both sides (right and left), three times per side. The average error derived from the three trials on each side was utilized for further analysis. The distance error was computed as the arctangent of the average distance from the target point, normalized to the fixed distance of 90 cm to the wall. A distance error exceeding 4.5° is considered clinically important (26).

2.2.3 Neck range of motion

The right and left lateral flexion and rotation movements of neck ROM were assessed using a bubble inclinometer.

For lateral flexion ROM assessment, the bubble inclinometer was positioned on the participant's head apex. Participants were seated comfortably on a chair with their hands resting on their thighs. They were instructed to move their neck to the furthest point within the available range in one of the randomly assigned directions of head/neck movements. Participants were then prompted to bend their ears toward either their right or left shoulder while ensuring their shoulders remained stationary.

To evaluate the rotation ROM, participants were positioned in a supine manner, to avoid trunk rotation, and the bubble inclinometer was placed on the forehead. They were instructed to rotate their head to the maximum extent possible on either the right or left side. Each movement direction was performed three times and the average value was computed for further analysis (27, 28).

2.2.4 Neck extensor strength

Maximum voluntary contraction (MVC) of neck extension strength was assessed using a customized chair to mount a handheld dynamometer on it without it moving around (Figure 1B) (29). The handheld dynamometer (MicroFET2 Manual muscle tester; Hoggan Scientific, Salt Lake City, UT, USA) was mounted on a rod that was fitted to each participant's height. In addition, a mechanism allowed the forward and backward movement of the dynamometer to adjust its distance, ensuring the participant's neutral head position (Figure 1).

Participants were seated with relaxed heads and necks, hands resting on thighs, and a chest belt to restrict trunk and shoulder involvement. They were instructed to push the dynamometer with the back of their head for a maximum of 3 s. The procedure was repeated three times with 30-s intervals to prevent fatigue. The highest recorded force was considered as the neck extension MVC.

2.3 Statistical analysis

The asymmetry index was calculated as the difference between the values of each variable on the dominant and non-dominant sides. The bigger the asymmetry index, the larger the asymmetry observed between the two sides.

Normality was assessed using the Shapiro–Wilk test. To compare symmetry indices between the groups, an independent samples *t*-test was used for normally distributed data, while a Mann–Whitney test was utilized for non-normally distributed data. Within each group, the mean dominant and non-dominant side muscle stiffness and thickness were compared using a paired *t*-test. The level of significance was set at $\alpha = 0.05$.

3 Results

3.1 Demographic information

The participants' demographic information is outlined in Table 1. A significant age difference was observed between the two groups, with older individuals found in the control group. The mean age difference between the groups was calculated to be 4 years ($p = 0.009$). In addition, baseball players were approximately 10 cm taller than the control group ($p < 0.001$). No significant difference was observed among the two groups in terms of weight. All baseball players and 13 of the 15 controls were right-handed. All baseball players were collegiate athletes with a mean of 16.23 ± 3.03 years of experience in baseball. They were actively participating in baseball (pitching) at the time of data collection.

3.2 Muscle thickness

The independent samples *t*-test revealed that baseball players exhibited a significantly greater asymmetry in the splenius capitis muscle thickness compared to the control group [$p = 0.029$, effect size (ES) = 0.857]. Table 2 details the mean and standard deviation (SD) of muscle thickness in both groups. Within each group, a paired *t*-test highlighted that among baseball players, the non-dominant side splenius capitis is significantly thicker than that on the dominant side ($p < 0.001$, ES = 1.14, mean = 0.656 vs. 0.589 cm, respectively) while no significant asymmetry was observed in the control group for this muscle. No other significant asymmetry was observed in other muscles.

3.3 Muscle stiffness

Due to low RMI of dorsal neck muscles in one participant within the control group, the measurement of muscle stiffness was considered unreliable for them. Consequently, we excluded

TABLE 1 Demographic information of participants.

	Baseball pitchers (n = 14)	Controls (n = 15)
Age (years)	21.86 ± 1.61	25.87 ± 5.10
Height (cm)	184.53 ± 8.51	174.45 ± 5.33
Weight (kg)	86.82 ± 11.47	84.55 ± 22.49
Years of experience (years)[a]	16.23 ± 3.03	7.36 ± 7.39
Exercise history (days/week)	5.21 ± 0.89	3.78 ± 1.52

[a]"Years of experience" for the control group reflect their regular gym exercise routines, while for the baseball players, it represents their years of experience in baseball.

TABLE 2 Mean ± standard deviation of muscle thickness and stiffness in both groups.

	Side	Muscle thickness (cm)		Muscle stiffness (KPa)	
		Baseball pitchers (*n* = 14)	Controls (*n* = 15)	Baseball pitchers (*n* = 14)	Controls (*n* = 14)
Trapezius	Dominant	0.28 ± 0.08	0.24 ± 0.08	52.38 ± 31.17	60.92 ± 20.92
	Non-dominant	0.28 ± 0.07	0.33 ± 0.21	49.33 ± 24.31	78.37 ± 29.00
Splenius capitis	Dominant	**0.59 ± 0.10**	0.70 ± 0.14	31.79 ± 14.51	41.76 ± 18.74
	Non-dominant	**0.66 ± 0.12**	0.699 ± 0.11	38.37 ± 17.41	58.30 ± 20.14
Semispinalis capitis	Dominant	0.69 ± 0.09	0.64 ± 0.11	32.46 ± 33.91	36.19 ± 11.00
	Non-dominant	0.72 ± 0.10	0.62 ± 0.12	35.49 ± 24.89	60.24 ± 27.36
Semispinalis cervicis	Dominant	0.70 ± 0.10	0.70 ± 0.08	39.27 ± 32.46	37.50 ± 19.04
	Non-dominant	0.67 ± 0.15	0.71 ± 0.09	31.52 ± 22.55	48.23 ± 29.02
Multifidus	Dominant	0.94 ± 0.23	0.74 ± 0.11	37.03 ± 24.33	32.71 ± 11.66
	Non-dominant	0.92 ± 0.13	0.77 ± 0.15	37.47 ± 19.03	43.68 ± 25.58

The values in bold indicate where there is a significant difference.

this individual from the analysis. Independent samples *t*-tests demonstrated that the control group exhibited a greater degree of stiffness asymmetry in the splenius capitis muscle compared to baseball players ($p = 0.006$, ES = 1.179). In addition, a Mann–Whitney *U*-test showed a similar asymmetry difference between the two groups, with greater stiffness asymmetry for the semispinalis cervicis muscle in the controls ($p = 0.043$, mean rank: 10.46 vs. 16.54). However, the within-group comparisons did not demonstrate any significant side differences for either of the groups.

No other significant differences were observed for muscle stiffness asymmetry between the two groups.

3.4 Neck proprioception and range of motion

No significant difference in proprioception asymmetry index was found between the groups. Similarly, the neck rotation asymmetry index was found to be comparable in both groups. However, for ROM, baseball players exhibited a significantly smaller asymmetry in terms of lateral side bend with the mean difference of 6.44° ($p = 0.045$, ES = 0.8). Controls generally showed a greater lateral bend to the non-dominant side, although there was no significant difference between sides (mean difference: 1.82°). Table 3 presents the mean and SD values of neck ROM and repositioning errors.

TABLE 3 Mean ± standard deviation of neck ROM and joint repositioning error (JRE) in both groups.

		Baseball pitchers (*n* = 14)	Controls (*n* = 15)
JRE (°)	Dominant	6.00 ± 1.84	5.31 ± 2.09
	Non-dominant	5.96 ± 2.18	5.98 ± 2.77
Neck side bend ROM (°)	Dominant	53.45 ± 11.18	47.95 ± 7.91
	Non-dominant	54.36 ± 9.73	49.63 ± 7.39
Neck rotation ROM (°)	Dominant	93.68 ± 6.29	81.15 ± 10.08
	Non-dominant	95.90 ± 8.57	82.39 ± 9.67

3.5 Neck extensor strength

Baseball pitchers showed significantly stronger neck extensors compared to the controls. The independent samples *t*-test revealed a *p*-value of 0.017 and an ES of 0.926 for the differences in neck extensor MVC between the two groups. The mean neck extensor MVC values were 131.161 N vs. 96.653 N for baseball players and their controls, respectively.

4 Discussion

This study aimed to examine whether the repetitive throwing movements involved in baseball pitching induce morphological and functional changes in the dorsal neck muscles on the dominant side, which is predominantly utilized for throwing. In addition, we sought to compare the outcomes of baseball players with those of a control group.

Our results demonstrated a significantly thicker splenius capitis muscle on the non-dominant side of baseball players. The splenius capitis muscles extend the neck when contracting bilaterally and during ipsilateral side bends and when contracting unilaterally during rotation (30). In baseball, pitchers often turn their heads toward the non-dominant side to throw and to track the ball visually after releasing. Furthermore, during the cocking phase of throwing, the cervical spine extends in coordination with the trunk, maintaining neck extension to follow the ball's trajectory. Our findings can indicate that repetitive neck rotation to the non-dominant side among baseball pitchers significantly influences the thickness of the splenius capitis muscle on the non-dominant side. This suggests a potential link between splenius capitis thickness and the effects of neck rotation, rather than from the throwing motion of the dominant arm.

In addition, we observed significantly greater asymmetry in muscle stiffness for the splenius capitis and semispinalis cervicis muscles in the control group compared to the baseball pitchers. However, no significant differences between sides were found within the groups. This suggests the presence of latent trigger points without perceived pain in the controls, although the observed asymmetry was not sufficient to induce a significant asymmetry in controls. In other words, neck muscle stiffness was symmetric in both groups, although the controls showed a non-significant tendency toward asymmetry in the two abovementioned muscles.

Individuals experiencing unilateral pain typically demonstrate higher muscle stiffness on their affected side compared to the contralateral side (31, 32). Our findings show symmetrical dorsal neck muscle stiffness in both groups, suggesting that within healthy populations, neck muscle structure tends to exhibit symmetry.

We expected an asymmetry in neck ROM in baseball pitchers as they turn their heads to track the ball. However, contrary to our expectations, our study revealed symmetrical neck ROM among baseball pitchers and controls. This finding is consistent with Devaney's research, which similarly reported symmetrical ROM in baseball players (33).

This study represents the first investigation into cervical proprioception among baseball players. Previous research comparing neck repositioning errors in individuals with and without neck pain has shown reduced cervical proprioception in those with traumatic neck pain (34). The multifidus muscle contains numerous muscle spindles that play a critical role in providing accurate cervical proprioception (26). Our ultrasound investigation revealed symmetrical multifidus thickness and stiffness in both groups, corresponding to the symmetric repositioning errors observed. In addition, our control group consisted of healthy individuals without a history of neck pain, which further supports the finding of symmetric cervical proprioception in this group.

Finally, baseball pitchers exhibited significantly greater MVC for neck extensors compared to controls, which was anticipated given their extensive training regimen, including shoulder and rotator cuff strengthening exercises (35). A review by Hrysomallis in 2016 (36) has shown that athletes generally have higher neck and shoulder isometric strength when compared to non-athletes, mostly due to their rigorous training programs typically conducted three to four times a week. In addition, baseball pitchers track the ball after throwing and actively stabilize their necks against the rotating trunk, which likely contributes to increased thickness of the splenius capitis and greater strength in neck extensor muscles.

Significant differences in age and height were observed between the two groups. However, the mean ages of individuals in both groups were found to be below the threshold of 30 years, thereby mitigating the potential influence of age-related physiological variations on the study outcome (37). Furthermore, it is important to consider that neck muscle size is primarily associated with weight rather than height (23). Therefore, we believe that these differences between the two groups did not impact our results.

Our study results are interpreted with consideration of some limitations. We measured the thickness and stiffness of dorsal neck muscles at rest. However, assessing their thickness and stiffness during muscle contraction would provide valuable insights into their function and response during activities. Future studies should consider investigating these aspects. In addition, our baseball pitchers did not have a history of shoulder injury or shoulder pain, which may contribute to observing symmetric neck muscles. Nonetheless, evaluating baseball pitchers who have experienced injuries could reveal a potential link between asymmetries and risk of injury. Future studies focusing on pitchers with shoulder injuries could provide valuable insights into these aspects.

5 Conclusion

Baseball pitching, a repetitive unilateral activity performed by pitchers, may not be linked with unilateral development of deep dorsal neck muscles. Deep neck muscles, such as the multifidus muscle, contribute to neck stability during arm movements (13, 14). Our results indicate that despite the unilateral throwing motion in baseball pitching, both cervical multifidus muscles are involved in stabilizing the neck during arm movements. However, it appears that unilateral neck rotation toward the non-dominant side may result in greater thickness of the splenius capitis on the non-dominant side.

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 California State University, Los Angeles (Cal State LA) IRB, Los Angeles, CA. Board Reference No. 23-147 Rep 22-95. 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

LR: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. CA: Formal Analysis, Investigation, Methodology, Resources, Software, Writing – original draft. CD: Conceptualization, Data curation, Investigation, Methodology, Resources, Validation, Writing – review & editing. SK: Conceptualization, Investigation, Methodology, Validation, Writing – review & editing.

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Conflict of interest

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

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The role of playing position in soccer injury characteristics: evidence from sub-elite athletes

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This study examines the association between playing position and injury characteristics among sub-elite male soccer players in South Africa. Using a cross-sectional survey, 223 players from four universities were assessed for injury prevalence, type, mechanism, and severity during the 2023 soccer season. Midfielders experienced the highest injury frequency (43.6%), followed by defenders (30.0%), forwards (17.9%), and goalkeepers (8.6%). Lower limb injuries were predominant across all positions (89.6%), with defenders (94.6%) and midfielders (95.1%) at greatest risk, while goalkeepers sustained a significant proportion of upper limb injuries (44.4%) due to their specialized role. Soft tissue injuries were most common among midfielders (78.0%) and defenders (67.6%), whereas goalkeepers reported higher rates of bone-related injuries (66.7%). Defensive actions, such as tackling, accounted for most injuries among defenders (56.8%), while aerial play contributed substantially to goalkeeper injuries. No statistically significant differences in injury severity were found across positions. These findings highlight the influence of playing position on injury characteristics and underscore the need for position-specific injury prevention strategies tailored to sub-elite soccer players.

KEYWORDS
soccer injuries, playing position, sub-elite athletes, injury prevention, South Africa

1 Introduction

Soccer, widely recognized as the most popular sport globally, boasts over 240 million participants across more than 200 nations (1, 2). Despite its appeal and numerous benefits, soccer presents significant injury risks, particularly among sub-elite players who lack the resources and protective measures available to their elite counterparts. Elite players typically benefit from advanced medical facilities, professional physiotherapy, individualized strength and conditioning programs, access to sports science technology (e.g., GPS tracking and load monitoring), and comprehensive injury prevention strategies, which are often unavailable to sub-elite athletes (3, 4). Access to sports physiotherapy ensures appropriate rehabilitation for injuries, while conditioning programs tailored to player-specific needs help improve strength, flexibility, and endurance. Advanced tools such as GPS monitoring aid in managing player workload, thereby minimizing overuse injuries (3, 5). Furthermore, structured warm-up programs such as the FIFA 11+ have been shown to reduce injury risk by enhancing neuromuscular control (2, 4).

Research into injury epidemiology in soccer has primarily focused on elite and professional players, often neglecting sub-elite athletes, who represent a competitive tier between amateur and professional levels (6, 7). Sub-elite players frequently participate in intense competition and training sessions without access to the same medical and conditioning resources, leaving them more vulnerable to injuries.

The occurrence of injuries in soccer is influenced by several factors, including the physical demands of the sport, environmental conditions, and intrinsic player characteristics. Characteristics associated with player position have been linked with injury susceptibility, as the role dictates the intensity, frequency, and type of physical activities performed during matches. Positional demands often lead to differing injury risks among players, with defenders, midfielders, and forwards exposed to unique challenges due to their roles in tackling, ball control, or offensive strategies (8, 9). Sarmento et al. (10), in their systematic review, found that positional roles in soccer significantly influence physical, physiological, and technical demands, with midfielders and external defenders covering greater distances at high speeds and performing more sprints, while central defenders and midfielders executed more passes, emphasizing the importance of position-specific training practices.

Seminal research has highlighted positional variations in injury risk, with Ekstrand et al. (3) showing that midfielders experience the highest injury rates due to their extensive field coverage and physical demands, while Junge & Dvorak (4) identified positional-specific mechanisms contributing to injury susceptibility. Overall, characteristics associated with the physicality of their role predispose defenders to a higher injury risk, particularly due to the demands of tackling and other high-impact actions (11, 12).

Theoretical perspectives suggest that positional demands in soccer directly influence injury mechanisms. Midfielders experience a high prevalence of overuse injuries due to their extensive field coverage and frequent high-intensity actions. For example, Ekstrand et al. (3) reported that midfielders accounted for 40% of overuse injuries in elite European soccer. Similarly, Della Villa et al. (13) and Rahnama et al. (14) highlighted that the physical and cognitive demands placed on midfielders significantly contribute to repetitive strain injuries, such as hamstring and groin strains, which are among the most common (13, 14).

Goalkeepers, in contrast, are exposed to acute injury risks due to explosive actions like diving, jumping, and reaction-based movements, which often lead to upper limb injuries (4, 11). Positional demands also vary in their cognitive requirements, with midfielders managing complex decision-making under sustained physical exertion, further compounding their injury susceptibility (15).

In South Africa, the lack of comprehensive research on soccer injuries at the sub-elite level further exacerbates the challenge of implementing effective injury prevention strategies. While South African universities actively participate in soccer leagues with growing player enrollment, the use of scientific methods to address injuries remains limited (16). Although focused on professional players, Calligeris et al. (16) offers a useful baseline for comparing injury patterns, emphasizing the unique challenges sub-elite players face due to limited access to injury prevention resources. This gap highlights the need to analyze injury patterns specific to this demographic to improve player safety and performance.

This study aims to explore the characteristics of soccer injuries concerning playing positions among sub-elite male athletes in South Africa. Existing injury prevention programs, such as the FIFA 11+, could be adapted and tailored to suit the specific needs of sub-elite players in this context.

By examining the prevalence, mechanisms, and types of injuries across different positions, the findings will provide valuable insights for developing targeted injury prevention programs tailored to the specific demands of sub-elite soccer players.

2 Materials and methods

2.1 Study design

This study utilized a cross-sectional survey design to examine the prevalence, mechanisms, and types of injuries experienced by sub-elite male soccer players. The design was selected for its ability to capture a snapshot of injury patterns and their associations with playing positions during a specific soccer season (17).

2.2 Study population and sampling

The study was conducted during the 2023 competitive season, with data collected between March and October from 223 male soccer players representing four South African universities: North-West University (Potchefstroom, Mahikeng), Tshwane University of Technology, Nelson Mandela University, and the University of Limpopo. The distribution of participants by playing position reflects the natural composition of soccer teams, where goalkeepers are fewer compared to outfield players. While this limits statistical power for certain subgroups, the overall sample remains representative of sub-elite soccer teams in South Africa. Players were purposively sampled, as they met specific inclusion criteria relevant to the study. The participants were registered students, aged 18 years or older, actively playing in university soccer teams under the jurisdiction of University Sport South Africa (USSA). Players who did not meet these criteria or declined to provide informed consent were excluded from the study.

2.3 Data collection instruments

Data were collected using a self-administered online questionnaire hosted on the Survey Monkey platform. The questionnaire, adapted from validated tools by Hawkins and Fuller (18) and Twizere (19), was divided into two sections. The first section collected demographic and player-specific information, such as age, playing position, dominant leg, and years of experience. The second section focused on injury details, including the number, type, and severity of injuries sustained, as well as their mechanisms and recurrence. Injuries were recorded separately for training sessions and matches to identify contextual variations. Injuries were categorized into time-loss injuries, defined as any physical complaint resulting in the inability to participate in soccer activities for at least 24 h, and non-time-loss injuries, which did not impede participation (20). Injury severity was categorized based on the duration of time lost from participation: minimal (1–3 days), mild (4–7 days), moderate (8–28 days), and severe (>28 days), as per the definitions established by Fuller et al. (20).

2.4 Data collection procedure

Participants were provided with a link to the questionnaire, accompanied by an information sheet explaining the study's purpose, procedures, and confidentiality measures. Only players who sustained injuries during the season were required to complete the injury-specific section. To minimize recall bias, players with multiple injuries were instructed to report on their most recent injury (21, 22). Injuries unrelated to soccer activities were excluded.

2.5 Ethical considerations

Ethical approval was obtained from the Tshwane University of Technology Research Ethics Committee (REC/2023/01/003). Participants provided informed consent via an online consent form embedded in the questionnaire. Anonymity was ensured through the assignment of numerical codes, and data access was restricted to the research team. Participants were informed of their right to withdraw at any time without penalty. To reduce the likelihood of the study findings influencing coaches' decisions about player participation, only team-level results (excluding individual data) were shared with the coaching staff.

2.6 Data analysis

Data were analyzed using IBM SPSS Statistics for Windows, Version 28.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics summarized injury patterns and player demographics, while Pearson's chi-squared tests assessed associations between playing position and other variables, including injury type, injury location, mechanism of injury, and injury severity. Effect sizes (Cramér's V) were calculated for significant chi-squared results to quantify the strength of associations. Assumptions for the test, including a minimum expected cell frequency of 5, were verified and satisfied for all analyses. Statistical significance was set at $p < 0.05$ to identify meaningful associations between variables while maintaining a balance between Type I and Type II error risks. Given the exploratory nature of the study, no formal corrections for multiple comparisons were applied to avoid inflating the likelihood of false negatives. Injuries were expressed as time-loss injuries, defined as any injury resulting in the inability to participate in training sessions or matches for a specified duration. Subgroup analyses for goalkeepers and forwards were primarily descriptive due to smaller sample sizes, and the results should be interpreted cautiously in light of reduced statistical power.

2.7 Reliability and validity

The questionnaire demonstrated strong reliability and validity, as evidenced by Cronbach's alpha values exceeding 0.80 for internal consistency. Content validity was ensured through pre-testing with a pilot sample of sub-elite players. The pilot sample consisted of 15 sub-elite male soccer players, who provided feedback on the clarity, relevance, and ease of use of the questionnaire. The questionnaire was further validated by referencing established tools and literature in soccer injury research (18, 19).

3 Results

3.1 Player demographics

The study included 223 male sub-elite soccer players from four South African universities (Table 1). The players had an average age of 21.36 years, with the majority being right-leg dominant (68.2%). The positional distribution revealed that midfielders constituted the largest group (41.7%), followed by defenders (32.3%), forwards (17%), and goalkeepers (9%).

3.2 Distribution of injuries by playing position

According to Table 2, midfielders experienced the highest proportion of injuries, accounting for 43.6% of all reported cases. A substantial portion of these injuries occurred during matches (40.2%), while a slightly higher percentage (49.1%) occurred during training. Defenders represented the second largest group, contributing to 30.0% of injuries, with 33.3% of these injuries sustained in matches and 24.5% in training. Forwards experienced 17.9% of the injuries, and goalkeepers accounted for

TABLE 1 Demographic data of participants.

Variable	Category	*n*	%
Age	Mean	21.36	SD = 2.55
Position	Defender	72	32.3
	Forward	38	17.0
	Goalkeeper	20	9.0
	Midfielder	93	41.7
	Total	223	100.0
Dominant leg	Both	26	11.7
	Left	45	20.2
	Right	152	68.2
	Total	223	100.0

TABLE 2 Distribution of injuries by playing position.

Position	Match		Training		Total	
	n	%	*n*	%	*n*	%
Defenders	29	33.3	13	24.5	42	30.0
Forwards	17	19.5	8	15.1	25	17.9
Goalkeepers	6	6.9	6	11.3	12	8.6
Midfielders	35	40.2	26	49.1	61	43.6
Total	**87**	**100.0**	**53**	**100.0**	**140**	**100.0**

the lowest percentage at 8.6%. These findings highlight the variations in injury rates across different playing positions.

3.3 Association between playing position and injury characteristics

The analysis in Table 3 revealed significant associations between playing position and injury characteristics.

A significant association was found between playing position and injury location, X^2 (3, $n = 223$) = 19.303, $p = 0.004$, Cramér's $V = 0.38$, indicating a moderate association. Lower limb injuries were most prevalent across all positions, especially for defenders (94.6%) and midfielders (95.1%), while goalkeepers showed a higher proportion of upper limb injuries (44.4%).

A strong association between playing position and injury type was observed, X^2 (3, $n = 223$) = 27.692, $p < 0.001$, Cramér's $V = 0.46$. Soft tissue injuries predominated among midfielders (78.0%) and defenders (67.6%), while goalkeepers experienced more bone-related injuries (66.7%).

A significant moderate association was found between playing position and injury mechanism, X^2 (4, $n = 223$) = 23.561, $p = 0.023$, Cramér's $V = 0.32$. Defensive actions accounted for most injuries among defenders (56.8%), whereas aerial play was a prominent mechanism for goalkeepers (22.2%).

No significant association was found between playing position and injury severity, X^2 (3, $n = 223$) = 7.715, $p = 0.563$, Cramér's $V = 0.18$. However, defenders reported a slightly higher proportion of severe injuries (40.5%).

4 Discussion

The findings of this study highlight the significant influence of playing position on injury frequency, location, type, mechanism, and severity among sub-elite soccer players. These results build upon and reinforce previous research while offering new and valuable insights.

4.1 Injury frequency by playing position

The injury distribution in our study aligns with prior research in sports medicine and injury epidemiology. Midfielders, frequently involved in offensive and defensive plays, experience the highest

TABLE 3 Association of playing position with injury characteristics.

Variable	Goalkeeper	Defender	Midfielder	Forward	Total	X^2	*p*-value
Body part							
Head to neck	0	0	0	1 (5.3%)	1 (0.9%)	–	–
Upper limb	4 (44.4%)	2 (5.4%)	2 (4.9%)	2 (10.5%)	10 (9.4%)	–	–
Lower limb	5 (55.6%)	35 (94.6%)	39 (95.1%)	16 (84.2)	95 (89.6%)	–	–
Total	**9**	**37**	**41**	**19**	**106**	**19.303**	***0.004**
Type							
Soft Tissue	1 (11.1%)	25 (67.6%)	32 (78.0%)	9 (47.4%)	67 (63.2%)	–	–
Bone-related	6 (66.7%	8 (21.6%)	8 (12.2%)	9 (47.4%)	28 (63.2%)	–	–
Head	0	0	3 (7.3%)	0	3 (2.8%)	–	–
Pelvic and Pubic	2 (22.2%)	4 (10.8%	1 (2.4%)	1 (5.3%)	8 (7.5%)	–	–
Total	**9**	**37**	**41**	**19**	**106**	**27.692**	***0.001**
Mechanism							
Physical actions	4 (44.4%)	12 (32.4%)	11 (26.8%)	3 (15.8%)	30 (28.3%)	–	–
Aerial Play	2 (22.2%)	1 (2.7%)	5 (12.2%)	1 (5.3%)	9 (8.5%)	–	–
Defensive actions	0	21 (56.8%)	16 (39.0%)	12 (63.2%)	49 (46.2%)	–	–
Ball vcontrol/movement	3 (33.3%)	0	5 (12.2%)	2 (10.5%)	10 (9.4%)	–	–
Physical demands	0 (0.0%)	3 (8.1%)	4 (9.8%)	1 (5.3%)	8 (7.5%)	–	–
Total	**9**	**37**	**41**	**19**	**106**	**23.561**	***0.023**
Severity							
Minimal	1 (11.1%)	6 (16.2%)	2 (4.9%)	3 (15.8%)	12 (11.3%)	–	–
Mild	4 (44.4%)	8 (21.6%)	15 (36.6%)	5 (26.3%)	32 (30.2%)	–	–
Moderate	3 (33.3%)	8 (21.6%)	11 (26.8%)	6 (31.6%)	28 (26.4%)	–	–
Severe	1 (11.1%)	15 (40.5%)	13 (31.7%)	5 (26.3%)	34 (32.1%)	–	–
Total	**9**	**37**	**41**	**19**	**106**	**7.715**	**0.563**

Note. Values in brackets represent the percentage of the total within each playing position (values below 1% not shown).
*$p < 0.05$.

injury rates. Ekstrand et al. (3) reported midfielders accounted for 40% of injuries in elite European football, closely matching our finding of 43.6%. Similarly, Waldén et al. (23) observed defenders constituted 30% of injuries, consistent with our 30.0%. In contrast, forwards and goalkeepers have lower injury rates, as noted by Hägglund, Waldén, and Ekstrand (5), who reported 18% for forwards and 10% for goalkeepers, comparable to our findings of 17.9% and 8.6%, respectively. Some studies report differing injury distributions across positions. Hawkins et al. (24) observed a higher injury rate among defenders (35%) than midfielders, contrasting with our findings of 30.0% for defenders and 43.6% for midfielders. Arnason et al. (25) found forwards accounted for 22% of injuries in Icelandic and Swedish elite football, exceeding our result of 17.9%.

4.2 Injury location by playing position

The significant association between playing position and injured body part (Chi-square = 19.303, $p = 0.004$) reveals distinct injury patterns. Goalkeepers predominantly sustained upper limb injuries (44.4%), consistent with Hawkins et al. (24) and Junge and Dvorak (4), who attributed this to their diving and catching roles. Defenders (94.6%) and midfielders (95.1%) were more prone to lower limb injuries, reflecting the demands of high-intensity, continuous play, as noted by Ekstrand et al. (3) and Waldén et al. (23). Della Villa et al. (13) corroborated these observations, emphasizing that the intensity of high-intensity running and physical demands contribute significantly to injury risks for midfielders. Conversely, Fuller et al. (20) reported a more even distribution of upper and lower limb injuries across positions, suggesting that training and match variability may influence these patterns, warranting further investigation.

4.3 Injury type by playing position

Significant differences in injury types ($X^2 = 27.692$, $p = 0.001$) reveal that soft tissue injuries are most frequent among midfielders (78.0%) and defenders (67.6%), reflecting the high-intensity demands of these roles. This aligns with Arnason et al. (25) and Woods et al. (26), who linked such injuries to repetitive movements and physical strain. Bone-related injuries were more common in goalkeepers (66.7%) and forwards (47.4%) due to sporadic high-impact actions like collisions and falls, as noted by Junge et al. (27) and Hawkins and Fuller (18). However, Hawkins and Fuller (18) suggest that bone injuries in goalkeepers are not significantly higher than in other positions, indicating potential reporting biases or league-specific differences, emphasizing the complexity of injury patterns.

4.4 Injury mechanism by playing position

The mechanisms of injury varied significantly across positions, reflecting the diverse demands of the game. Defensive actions, such as tackling, accounted for the majority of injuries among defenders (56.8%), a finding that aligns with studies by Arnason et al. (25) and Hawkins et al. (24), who emphasized tackling as a common and hazardous mechanism in soccer.

Aerial play, including actions such as heading the ball and jumping to contest for possession, was a notable cause of injuries, particularly among goalkeepers. Physical actions, such as collisions, landing from jumps, and running at high intensity, also significantly contributed to the injury mechanisms observed, echoing findings by Bailey et al. (28), who highlighted the unique risks faced by goalkeepers due to their specialized roles. Aiello et al. (29) expanded on these patterns, noting the specific mechanisms leading to injuries in high-intensity actions like saves and aerial duels. Midfielders and forwards exhibited injuries linked to ball control and movement, which were less frequent but nonetheless significant.

The elevated injury risk among midfielders reflects their unique positional demands. High cognitive load, coupled with repetitive high-intensity running and directional changes, significantly contributes to soft tissue overuse injuries, consistent with findings by Della Villa et al. (13) and Woods et al. (26). Goalkeepers' susceptibility to upper limb injuries stems from their reliance on reaction-based actions and aerial challenges, as highlighted by Junge et al. (27) and Bailey et al. (28). These results emphasize how biomechanical and cognitive demands interact to influence injury patterns across positions. Theoretical perspectives suggest that midfielders' roles, involving constant decision-making under physical exertion, further compound their risk of injury (15).

These patterns resonate with earlier research by Rahnama et al. (14) and Twizere (19), who emphasized that the dynamic nature of soccer positions influences the type and mechanism of injuries sustained. Furthermore, a recent studies has highlighted the role of workload management and cumulative physical stress in injury risk, particularly for defenders and midfielders (10, 30). Players with a high acute-to-chronic workload ratio or extensive injury histories are especially vulnerable, underscoring the impact of the physical demands and rapid transitions inherent to these roles. Strategic workload management, including planned rest periods, has been shown to mitigate such risks while maintaining performance (30).

4.5 Injury severity by playing position

The severity of injuries did not show statistically significant differences across positions; however, defenders reported a slightly higher proportion of severe injuries (40.5%). This finding is consistent with Junge and Dvorak (4), who noted that high-intensity physical contact in defensive roles increases the likelihood of severe injuries. Recent research supports these observations, highlighting that defenders are more prone to ligament tears due to intense workloads and critical defensive actions (30, 31). Contrastingly, midfielders, despite their high injury frequency, predominantly reported soft tissue injuries, which are generally less severe (24, 31). The economic and performance impact of severe injuries is also well-documented in European soccer, with Pulici et al. (32) estimating significant financial costs associated with ligament and muscle injuries. This underscores the broader implications of injury severity on teams and organizations.

5 Practical implication for injury prevention

The findings reinforce the importance of developing position-specific injury prevention strategies. For midfielders, workload management strategies, including recovery protocols and neuromuscular training, are crucial in mitigating overuse injuries. Recent studies have emphasized the role of acute-to-chronic workload ratios in predicting injury risks, highlighting the importance of monitoring player workloads to prevent overexertion (31, 33). For defenders, training programs should prioritize agility, safe tackling techniques, and workload balancing to minimize high-risk situations (30, 31). Goalkeepers, with their unique demands, would benefit from upper limb strengthening, protective gear, and jump technique optimization to address their specific injury risks (30).

Position-specific injury prevention strategies are justified by the differing injury profiles identified in this study. While certain foundational strategies (e.g., agility training and safe tackling) may benefit multiple positions, tailoring interventions to positional demands, such as upper limb strengthening for goalkeepers, ensures a comprehensive approach to injury prevention (10).

6 Study limitations and recommendations

The reliance on self-reported data in this study introduces potential recall bias, a limitation commonly noted in retrospective injury epidemiology research (22). To mitigate such biases, recent advancements advocate the use of objective tracking technologies, such as mobile health devices, which provide continuous and accurate data collection, reducing the reliance on subjective recall (34). Moreover, the study's focus on male sub-elite players limits its generalizability to female and elite athletes. Future research could incorporate longitudinal designs, advanced tracking technologies, and a broader demographic scope, as highlighted by recent work emphasizing multilevel and spatially integrated longitudinal models for more comprehensive insights (35).

While this study draws on literature predominantly from elite and professional soccer, its findings contribute novel insights into the underrepresented sub-elite population. Future studies should focus on expanding sub-elite-specific data to strengthen generalizability.

The absence of standardized clinical tools, such as the Oslo Sports Trauma Research Centre questionnaire, is a limitation of the study. This was due to logistical constraints in a multi-institutional setting. Future research should prioritize the use of clinical tools to standardize injury diagnoses and improve data precision.

The sample size for specific playing positions, particularly goalkeepers (9% of the total sample), was limited due to the typical distribution of players in soccer teams. This uneven representation may reduce statistical power and the generalizability of findings for underrepresented positions. Future studies should explore strategies to improve positional representation, such as oversampling goalkeepers or utilizing pooled datasets from multiple studies, to increase statistical power for subgroup analyses.

7 Conclusion

The relationship between playing position and soccer injury characteristics is multi-dimensional, with each position presenting distinct injury risks and mechanisms. The findings contribute valuable insights into injury patterns, which can inform the development of targeted prevention strategies aimed at improving player safety and performance over time. The identification of positional factors associated with injury characteristics, align with the Translating Research into Injury Prevention Practice (TRIPP) framework (36). This framework emphasizes the importance of understanding injury mechanisms and risk factors as foundational steps to developing and implementing effective injury prevention strategies tailored to specific contexts.

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 Tshwane University Research Ethics Committee. 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

MT: Investigation, Methodology, Writing – original draft, Writing – review & editing. SJ: Conceptualization, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. LB: Investigation, Methodology, Writing – original draft, Writing – review & editing. AS: Writing – original draft, Writing – review & editing. MM: Investigation, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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Effect of different load of shoulder external rotation exercises on changes in muscle activity and exerted torque

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The effects of shoulder external rotation exercises on the EMG amplitude of the infraspinatus, and teres minor, and torque in healthy individuals remain uncertain. In this study, we aimed to determine the effects of varying loads during shoulder external rotation exercises on exerted torque and muscle activity of the infraspinatus, teres minor, and deltoid. Twenty-four upper limbs from 12 healthy adult males (22.5 ± 1.9 years) were included. Participants performed shoulder external rotation exercises with low-, medium-, and high-load conditions using elastic bands of three different tensions. The number of exercises was set so that the total workload during the exercise was equal for each loading condition. The torque of the shoulder external rotation and electromyography (EMG) amplitude of the infraspinatus, teres minor, and the posterior deltoid were measured during the concentric shoulder external rotation task, before and after the exercise. In addition, the muscle activity ratio of the three muscles was calculated. Analysis divided into 30° intervals, under the low-load condition, shoulder external rotation torque and EMG amplitude of the infraspinatus and teres minor did not change; However, the EMG amplitude of the posterior deltoid increased significantly. The muscle activity ratio in the posterior deltoid showed exercise range × time interaction, with a significant increase from pre-exercise (Pre) (13.59 ± 5.70%) to 20 min after the exercise (15.40 ± 6.03%) in the 61°–90° external rotation range. In the medium- and high-load conditions, the EMG amplitude significantly increased for all muscles. However, under the medium-load condition, significant differences were observed between 0–30° (Pre: 25.4 Nm, 20 min: 26.0 Nm), 31–60° (Pre: 24.3 Nm, 20 min: 25.4 Nm), and 61–90° (Pre: 23.7 Nm, 20 min: 24.6 Nm). There was also an increase in the muscle activity ratio in the posterior deltoid, with a main effect on time in the medium load condition ($p < 0.05$). The changes in torque, EMG amplitude, and muscle activity ratio after the shoulder external rotation exercises were not uniform across different exercise loads. Therefore, it is necessary to use different tensions depending on the purpose of the exercise.

KEYWORDS

rotator cuff, muscle activity ratio, shoulder conditioning, sports & exercise medicine, external rotation torque

1 Introduction

The infraspinatus and teres minor, parts of rotator cuff muscles, help to dynamically stabilize the glenohumeral joint and to generate shoulder external rotation torque during shoulder movement. The low shoulder external rotation torque and the low external/internal rotation torque ratio are the risk factors for shoulder joint disorders and maintaining their function is essential for prevention of injuries (1, 2). Especially in overhead athletes, stronger contractions of the shoulder external rotators are required to keep the humeral head in an afferent position for rapid swinging of the upper extremity during pitching. The high electromyography (EMG) amplitude was reported during pitching motion, with approximately 74% and 84% maximum voluntary isometric contraction (MVIC) in the infraspinatus and teres minor, respectively (3). Therefore, incorporating shoulder external rotation exercises to promote muscle activity in the shoulder external rotator muscles and increase shoulder external rotation torque is important to prevent shoulder joint injuries.

The infraspinatus, teres minor and superficial posterior deltoid work together in a coordinated manner during shoulder external rotation, but the function of each muscle is different due to the varying orientation of their muscle fibers and attachments. The infraspinatus and teres minor rest on the greater tuberosity of the humerus and prevent the humeral head from leaving the afferent position of the glenohumeral fossa during shoulder joint motion. The posterior deltoid is located superficially around the shoulder joint, has a large muscle cross-sectional area and produces a shearing force on the humeral head. Therefore, if it has a greater muscle activity relative to the infraspinatus and teres minor, this may lead to a risk of shoulder impingement (4, 5). Hence, it is important to focus on the muscle activity ratio of these muscles to maintain the glenoid fossa and humeral head in an afferent position during shoulder motion.

Yu et al. reported that the muscle activity ratio of the infraspinatus to the posterior deltoid during exercise was smaller when the exercise load was higher (6). In contrast, Park et al. showed no difference in the infraspinatus/posterior deltoid muscle activation ratio when the exercise load was increased (7). Thus, there is no consensus on the effect of different exercise loads on the activity ratio of the infraspinatus and posterior deltoid. Exercises targeting the rotator cuff are often performed with low loads using elastic bands or light dumbbells to reduce a shearing force of the deltoid while promoting the rotator cuff's contribution (8, 9). However, the effects of shoulder external rotation exercises on the EMG amplitude and torque of the shoulder external rotation muscles remain unclear and there is little evidence to determine the load of the exercises. It is necessary to investigate the effects of different exercise loads on torque, EMG amplitude, and muscle activity ratio. It is then important to consider adjusting the load to suit the purpose of the exercise.

Hence, we aimed to determine the effects of shoulder external rotation exercises at different loads (low-, medium-, and high-load) on changes in external rotation torque, the EMG amplitude, and muscle activity ratio of the infraspinatus, teres minor, and deltoid. We hypothesized that increasing the load of shoulder external rotation exercises would increase shoulder external rotation torque and EMG amplitude without altering the muscle activity ratio of the shoulder external rotators after the exercise.

2 Materials and methods

2.1 Participants

We examined twenty-four upper limbs of 12 healthy adult males (age: 22.5 ± 1.9 years, height: 172.3 ± 4.8 cm, weight: 65.6 ± 9.2 kg) included in this study. The participants had not engaged in strength training or other strenuous exercise continuously for the past 1 year. Furthermore, they were fully informed about the experimental procedures, possible risks, and the purpose of this study. Exclusion criteria included individuals with a history of neuromuscular disease or disorder, musculoskeletal trauma or disorder to the shoulder joint within the past 6 months, a history of shoulder joint surgery, and hypersensitivity or allergy for skin treatment. Written informed consents were obtained from all participants before the experiment, and the study was approved by the Juntendo University Faculty and Graduate School of Sports and Health Science and the Research Ethics Committee (No. 2023-71).

The sample size was determined through a power analysis to ensure adequate statistical power. Based on an observed effect size ($f = 0.38$), an alpha level of 0.05, and a desired power of 0.80, the power analysis indicated that a sample size of 12 participants would be sufficient to detect meaningful effects. This sample size exceeds the required threshold for achieving the desired power, suggesting that the study is adequately powered.

To acquire electromyography (EMG) signals, a wireless EMG system, Ultium EMG (Noraxon, Scottsdale, Arizona, USA), was synchronized with the Biodex System 4. The EMG signals were sampled at 2000 Hz and bandpass filtered at 20–500 Hz to remove motion artifacts. Disposable electrodes (diameter 34 mm, Blue Sensor, M-00-S) were affixed at a distance of 35 mm between electrodes. The measurement areas were wiped with alcohol prior to electrode application to minimize skin impedance. Electrodes were placed while the shoulder joint was held in 90° abduction to align with the exercise position. The EMG signals were recorded at two sites, the cranial part and the caudal part, located in the superficial layer because the infraspinatus is structurally divided into three parts (10). For the cranial part of the infraspinatus, electrodes were placed 3–4 cm below the scapular spine (7, 11, 12) on the line connecting the posterior angle of the acromion and the midpoint of the medial edge of the scapular spine with the inferior angle. For the caudal part, they were positioned 1/3 of the way down the line connecting the medial edge of the scapular spine and the inferior angle, along the muscle fibers. Electrodes for the teres minor were placed in the upper 1/3 of the line connecting the posterior angle of the acromion to the inferior angle (13, 14), and for the posterior deltoid, they were positioned 2 cm below the posterior angle of the acromion along the muscle fibers (7, 12, 15). The electrodes were applied while the shoulder joint was held in 90° abduction aligning with the exercise position (Figure 1).

2.2 Procedure

We used a crossover design in this study. First, an MVIC test of shoulder external rotation was performed. Subsequently, shoulder external rotation torque during shoulder external rotation was recorded before and 10, 20, and 30 min after exercises in each exercise condition. The measurements were taken during concentric contraction at an angular velocity of 60°/sec and EMG amplitude of the cranial part and caudal part of the infraspinatus, teres minor, and posterior deltoid. Furthermore, measurements at 10, 20, and 30 min were taken on separate days to avoid the influence of the measurement on the results (Figure 2). In addition, we used a random assignment table to determine the order in which all nine sessions were performed, ensuring that neither the measurement of shoulder external rotation torque nor the familiarity with exercises using the Thera-Band® affected the results. In addition, the EMG amplitude of each muscle was recorded during the exercises to ascertain differences in muscle activity during the exercises due to tension.

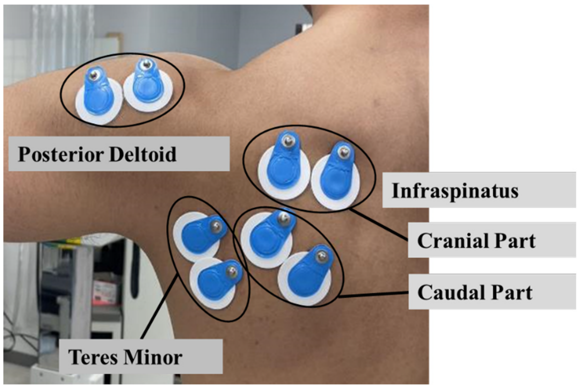

FIGURE 1
Electrodes on the infraspinatus, teres minor, and posterior deltoid.

2.3 Maximum voluntary isometric contraction test

We performed an MVIC test of the shoulder external rotation before each session to normalize the EMG amplitude data and calculate the intensity during the exercises. The test was performed for 5 sec using the Biodex System4 (Biodex Medical Systems, Shirley, NY, USA) while participants were seated with the shoulder joint in 90° abduction, intermediate internal and external rotation, and elbow in 90° flexion. It was performed after practice with verbal encouragement and visual feedback of torque curves to demonstrate maximal isometric muscle strength. The intraclass correlation coefficient (1,1) in the shoulder external rotation torque during this test was 0.921 (95% confidence interval: 0.853–0.962).

2.4 Shoulder external rotation exercise

Exercises were performed using Thera-Band® (Thera-Band® Hygenic Corporation, Akron, OH, USA) in yellow, black, and silver with different tensions for low-, medium-, and high-load conditions, respectively. Furthermore, the shoulder's external rotation exercises were performed in the 90° shoulder abducted position, which is similar to the overhead movement and is considered by many competitors to be incorporated as an exercise during warm-up. The upper body was immobilized with two attached belts in a seated position on the Biodex System 4 isokinetic muscle testing device (Figure 3) to reduce the compensatory effect of thoracic extension during the exercise. The participant was asked to grasp a 50 cm Thera-Band® extended to 1 m in a position with the shoulder abducted at 90°, the arm intermediate (midway between internal and external rotation), and the elbow flexed at 90°. The range of motion and

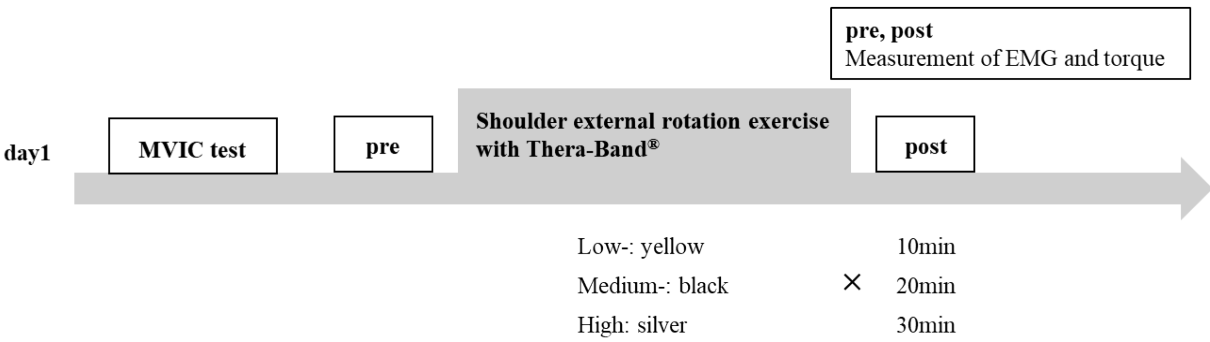

FIGURE 2
Procedure. Low-, medium-, and high-load 10 min, 20 min, and 30 min measurements were performed on separate days. A random assignment table was used to determine the order. MVC, maximum voluntary isometric contraction.

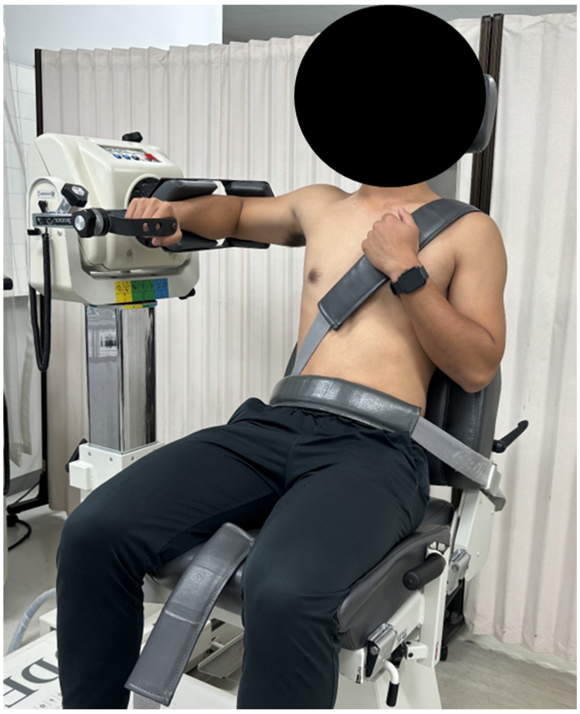

FIGURE 3
Shoulder external rotation exercise. External rotation exercises were carried out with the shoulder at 90 of abduction and the elbow at 90 of flexion. The participant sat on the dynamometer with the trunk fixed by a cross seatbelt.

velocity were equivalent to that of shoulder external rotation under concentric contraction before and after the exercise, the participants performed shoulder external rotation exercises ranging from 0°–90°at a constant rhythm of 40 bpm using a metronome. Notably, the 0°–90° external rotation and 90°–0° external rotation were performed at the same speed.

We adjusted the repetition of the exercise to ensure that the total workload across the conditions was equal. Specifically, the number of repetitions was set to 20 for the low-load condition, 11 for the medium-load condition, and 6 for the high-load condition. Furthermore, the forearm length was set to 0.25 m in this study based on the mean forearm length of healthy adult males shown in previous studies (16, 17). The length of Thera-Band® at the beginning of the exercise was 1 m, hence the cosine theorem was applied to the triangle made by the sum of the lengths of Thera-Band® and forearm at the beginning of the exercise (1.25 m), forearm (0.25 m), and Thera-Band® during shoulder external rotation exercise. The cosine theorem was used to calculate the length of the Thera-Band® for each degree of external rotation (Thera-Band length) (Figure 4). The results showed that the Thera-Band® lengthened from 1–1.28 m during movement from 0°–90° of shoulder external rotation. Next, the Thera-Band® was fixed to the shoulder joint attachment of Biodex System 4, with the arm length adjusted to 0.25 m to determine the torque required to pull the Thera-Band® (Thera-Band torque). The Thera-Band® torque was measured by extending the arm in 3 cm increments from 1 m. The tension of a 50 cm Thera-Band stretched to 1 m, measured using BIODEX, was calculated by subtracting the arm length of 0.25 m from the recorded values. The tensions were 16.6 N for the yellow band, 30.3 N for the black band, and 54.2 N for the silver band. Using Hooke's law, we calculated an approximate formula with the amount of displacement of Thera-Band® on the horizontal axis and the Thera-Band® torque obtained earlier on the vertical axis. The Thera-Band® torque per degree of shoulder external rotation from 0°–90° was calculated using the values of the approximate formula obtained. Notably, the vector of the Thera-Band® torque and the shoulder external rotation torque coincide between 78° and 79°, hence the following equations were used to calculate the Thera-Band® torque for each degree of external rotation from 0°–78° and from 79°–90°. The workload from 0°–90° was calculated using the following equation, and the value was multiplied by two to calculate the workload required to make one round trip from 0°–90°. The results showed that the workload per exercise for the low-, medium-, and high-load conditions were 10.28 J, 18.59 J, and 34.47 J, respectively. It is recommended that rotator cuff exercises be performed at a low-load for approximately 20 repetitions per set (9); therefore, the number of repetitions was set to be equivalent to a total workload of approximately 205 J, which is the total workload of 20 at low-load. This resulted in 11 repetitions at medium load and 6 at high load.

Shoulder external rotation from 0°–78°.

$$\sum \{(\text{Thera} - \text{Band torque}) \times \cos\theta 1 \times 0.017\}$$
$$\cos\theta 1 = \{(0.25 \times \tan\theta)^2 + (\text{Thera} - \text{Band length})^2 - \left(1.25 - \frac{0.25}{\cos\theta}\right)^2 \div \{2 \times (0.25 \times \tan\theta) \times (\text{Thera} - \text{Band length})\}$$

Shoulder external rotation from 79°–90°.

$$\sum \{(\text{Thera} - \text{Band torque}) \times \sin\theta 2 \times 0.017\}$$
$$\cos\theta 2 = \{0.25^2 + (\text{Thera} - \text{Band length})^2 - 1.25^2\} \div \{2 \times 0.25 \times (\text{Thera} - \text{Band length})\}$$

0.017: 1 radian.
θ: Angle of shoulder external rotation.

2.5 Electromyography amplitude, torque, and frequency

The participants performed concentric contraction shoulder external rotation tasks on the Biodex System 4 before and after the exercises. During these tasks, shoulder external rotation torque and EMG amplitude of the infraspinatus, teres minor, and posterior deltoid muscles were measured. The task was performed three times at an angular velocity of 60°/second in the

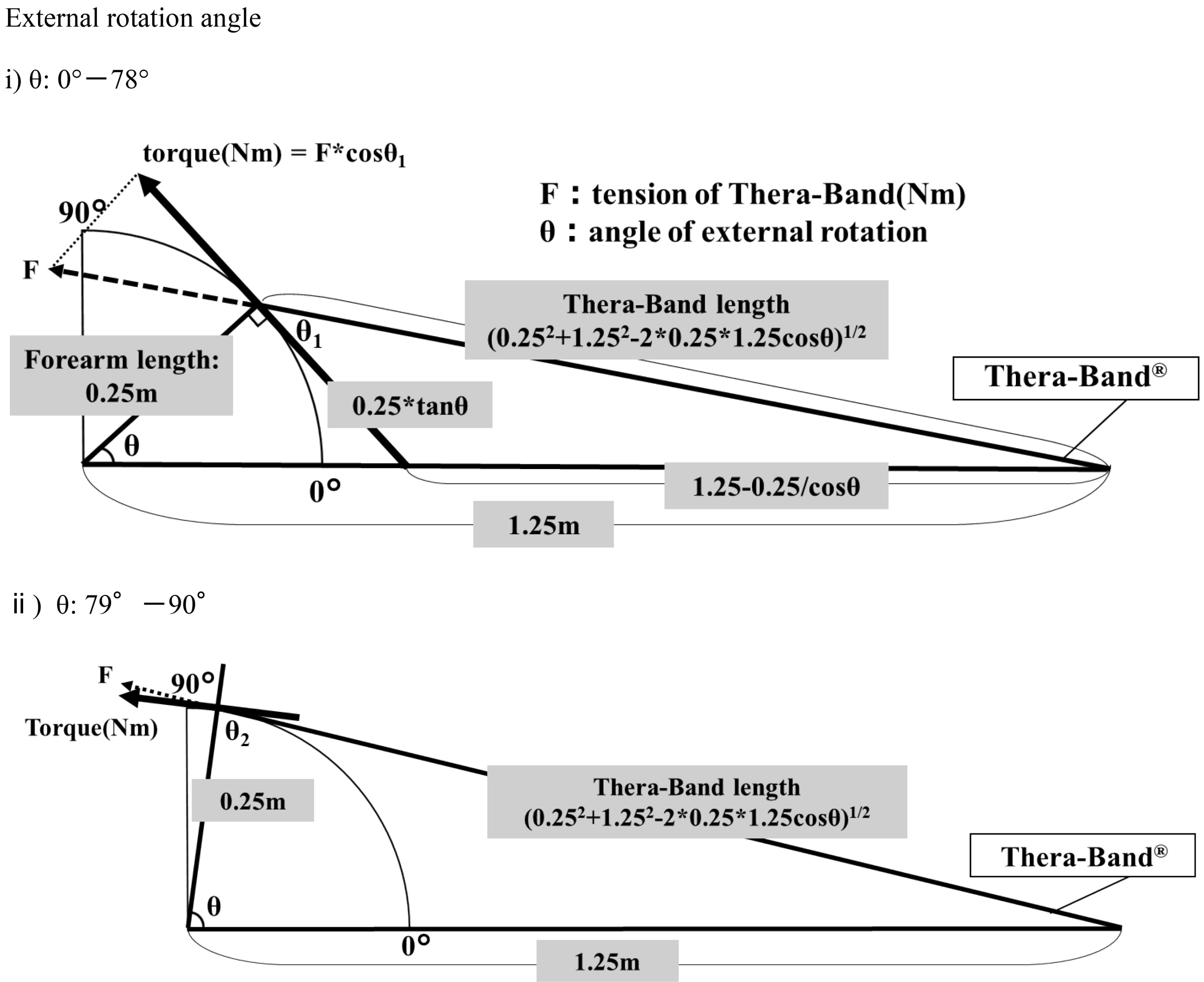

FIGURE 4
Calculation of workload during shoulder joint external rotation exercises. The direction of tension of Thera-Band and shoulder joint external rotation torque coincided at 78°.

range of 0°–90°of the shoulder rotation. During the measurements, the participant was seated with the shoulder joint positioned at 90° abduction on the Biodex, and the upper body immobilized using the non-stretchable straps provided on the Biodex during the Thera-Band® exercises. The position was set so that the center of rotation of the shoulder joint coincided with the dynamometer.

2.6 Data processing

The torque and angle signals obtained by synchronizing the Biodex System 4 to the Ultium EMG wireless myoelectric system were used to analyze the shoulder external rotation torque before and after the shoulder external rotation exercise. The maximum value of the torque at 0°–90° of external rotation was calculated, and the highest value among the three trials was considered as the peak torque based on the angle signal. Furthermore, in exercises using rubber bands, the tension increases as the external rotation angle increases due to the characteristic of rubber, which shows increasing tension with greater displacement. Therefore, the workload was calculated to understand the ability of exerting torque throughout the entire exercise. The value obtained from the angle signal was converted to radians, the product of radians and torque was summed from 0°–90° of shoulder external rotation, and the highest of the three was used in the analysis as the maximum work capacity. For peak torque and maximum workload, the relative values with respect to the pre-exercise (Pre) values were calculated using the following equations.

$$\text{Relative values for peak torque and maximum workload} = \{\text{after exercise} - \text{Pre}\} \div \text{Pre} \times 100$$

EMG amplitude data before and after shoulder external rotation exercises were full-wave rectified using a digital filter (Noraxon) and subsequently smoothed in a 100 ms window. The values were normalized [percentage (%) MVIC] for analysis as muscle activity using the mean of the mid 3 s of a 5 s MVIC test. The %MVIC was used as the amount of EMG amplitude in the analysis. Furthermore, the muscle activity ratio was calculated by dividing the EMG amplitude (%MVIC) of each muscle by the sum of the EMG amplitude of the cranial part and caudal part of the infraspinatus, teres minor, and posterior deltoid. Because of the characteristics of the elastic bands, the effects of the exercise could differ depending on the angle of shoulder external rotation, hence, the exercise range was divided into 0°–30°, 31°–60°, and 61°–90° for analysis. For the EMG amplitude and muscle activity ratio for each muscle, the average for each exercise range was calculated, and the peak torque for each exercise range was calculated and analyzed for the shoulder external rotation torque. The average frequency during concentric contraction shoulder external rotation before and after the exercise was also analyzed because fatigue from the exercise may have affected the results.

In shoulder external rotation exercises using the Thera-Band®, the longer the distance the Thera-Band® is pulled, the greater the tension. Thus, the intensity of the exercise increases as the external rotation angle increases. The shoulder external rotation torque when Thera-Band® was pulled for each 10° of external rotation, was divided by the peak torque during the MVIC test for each participant to calculate the intensity during the exercise (%) (Table 1). For EMG amplitude during the exercise, the average of the first five EMG amplitudes for each exercise condition was calculated, and normalized to the value during the MVIC test. The relative value was calculated as one using the low-load condition (Table 2).

TABLE 1 Intensities during exercise.

Angle (°)	Low (%)	Medium (%)	High (%)
10	3.16 ± 0.67	5.73 ± 1.29	9.92 ± 2.29
20	6.22 ± 1.33	11.27 ± 2.54	19.59 ± 4.51
30	9.10 ± 1.94	16.45 ± 3.70	28.77 ± 6.63
40	11.70 ± 2.50	21.09 ± 4.75	37.19 ± 8.57
50	13.94 ± 2.98	25.08 ± 5.65	44.61 ± 10.28
60	15.75 ± 3.36	28.27 ± 6.37	50.77 ± 11.70
70	17.09 ± 3.65	30.60 ± 6.89	55.45 ± 12.78
80	17.92 ± 3.83	32.00 ± 7.21	58.49 ± 13.48
90	18.54 ± 3.96	33.04 ± 7.44	60.88 ± 14.03

Mean ± SD.
The value was calculated by dividing the external rotation torque of the shoulder joint required to pull the Thera-Band by the maximum muscle force during the maximum isometric voluntary contraction.

TABLE 2 Muscle activity during exercises with elastic bands.

	Low	Medium	High	*p* value
Infraspinatus				
Cranial Part	1	1.48 ± 0.36	2.40 ± 0.77	<0.001
Caudal Part	1	1.38 ± 0.51	2.02 ± 0.54	<0.001
Teres Minor	1	1.43 ± 0.27	2.52 ± 0.69	<0.001
Posterior Deltoid	1	1.29 ± 0.34	2.29 ± 0.58	<0.001

The average of the first five cycles of low, medium, and high-intensity exercises was calculated, and the relative activity was calculated with the low-intensity set as 1.
1-way repeated-measures analysis of variance (ANOVA) (parametric) or the Kruskal–Wallis test (nonparametric) was performed.

2.7 Statistical processing

We performed a repeated-measure two-way analysis of variance (ANOVA) for load (low-, medium-, and high-load) × time (Pre, 10 min, 20 min, and 30 min) on peak shoulder external rotation torque and maximal workload across the entire range of motion before and after exercise. Furthermore, a repeated-measures 2-way ANOVA was performed for exercise range (0°–30°, 31°–60°, 61°–90°) × time for shoulder external rotation torque, the muscle activity ratio, and EMG amplitude of each muscle. Normality tests were conducted using the Shapiro–Wilk test, and for the variables that did not follow a normal distribution, the Wilcoxon signed-rank test was performed instead. Statistical analysis was performed using the Statistical Package for Social Sciences version 29 (IBM) and the significance level was set at 5%.

3 Results

3.1 Change in peak torque and maximal workload

There was no interaction ($p = 0.168$) between load (low-, medium-, high-load) × time (Pre, 10 min, 20 min, 30 min) for peak torque during 0°–90° shoulder external rotation. However, a main effect of time was observed, with the peak torque increasing significantly from Pre to 10 min. Regarding maximal workload, there was an interaction between load × time ($p = 0.033$) and a main effect of time ($p < 0.001$). Furthermore, *post-hoc* test showed a significant increase in peak torque at 10 min with low-load (7.68 ± 8.87%: $p < 0.001$) and high-load (8.92 ± 10.29%: $p < 0.001$) compared with Pre. At 20 min after exercise, the peak torque of medium-load condition (4.92 ± 5.31%) increased compared with Pre ($p = 0.01$). Post-activity potentiation (18), characterized by an increase in exerted torque lasting up to 10–15 min after submaximal muscle contraction without fatigue, is believed to include effects due to phosphorylation of myosin light chains rather than changes in muscle activity (19). Therefore, the change at 10 min was likely due to post-activation potentiation effect. Furthermore, 30 min after exercise, there was no difference from Pre in either peak torque or maximal workload. Therefore, we focused on the changes at 20 min from Pre under low-, medium-, and high-load conditions. The results showed that there were no significant differences in shoulder external rotation torque between Pre and 20 min under the low- and high-load conditions. However, at medium-load condition, there were significant differences between 0°–30° (Pre: 25.35 ± 5.43 Nm, 20 min: 25.96 ± 5.24 Nm: $p = 0.027$), 31°–60° (Pre: 24.28 ± 5.52 Nm, 20 min: 25.42 ± 5.45 Nm: $p = 0.003$), 61°–90° (Pre: 23.65 ± 5.41 Nm, 20 min: 24.58 ± 5.95 Nm: $p = 0.007$), with the torque increasing from Pre to 20 min.

3.2 Muscle activity ratio

Results for muscle activity ratio before and 20 min after exercise are shown in Table 3 and Figure 5. In the cranial part and caudal

TABLE 3 Changes in muscle activity ratio for each muscle before and after exercise.

		Infraspinatus		Teres minor (%)	Posterior deltoid (%)
		Cranial part (%)	Caudal part (%)		
Low					
0°–30°	Pre	23.8 ± 2.9	28.8 ± 4.6	26.4 ± 4.3	21.0 ± 6.0
	20 min	24.0 ± 3.2	28.9 ± 5.7	26.5 ± 4.0	20.7 ± 5.5
31°–60°	Pre	23.2 ± 4.1	32.5 ± 7.1	28.0 ± 5.1	16.3 ± 5.5
	20 min	22.6 ± 4.0	32.7 ± 8.1	27.3 ± 5.6	17.4 ± 5.5
61°–90°	Pre	23.2 ± 4.8	34.0 ± 8.8	29.3 ± 7.1	13.6 ± 5.7
	20 min	22.8 ± 5.4	33.8 ± 11.4	28.1 ± 7.3	15.4 ± 6.0*
Interaction effect	*p* value	0.581		0.175	0.044
Time	*p* value	0.551		0.277	0.185
Angle	*p* value	0.254		0.033	<0.001
Statistical Method		RM-2wayANOVA	Wilcoxon	RM-2wayANOVA	RM-2wayANOVA
Medium					
0°–30°	Pre	24.9 ± 4.8	28.6 ± 6.6	27.1 ± 5.1	19.4 ± 4.7
	20 min	24.3 ± 5.0	28.9 ± 7.6	26.6 ± 3.9	20.2 ± 4.2
31°–60°	Pre	23.2 ± 5.0	34.0 ± 10.4	29.0 ± 6.2	13.8 ± 5.1
	20 min	22.9 ± 5.6	32.7 ± 11.4	28.6 ± 6.2	15.8 ± 5.4*
61°–90°	Pre	22.7 ± 5.9	35.3 ± 11.6	29.3 ± 7.3	12.7 ± 5.4
	20 min	22.4 ± 6.6	33.7 ± 12.6	29.6 ± 6.9	14.4 ± 5.6*
Interaction effect	*p* value			0.497	0.370
Time	*p* value			0.837	0.023
Angle	*p* value			0.011	<0.001
Statistical Method		Wilcoxon	Wilcoxon	RM-2wayANOVA	RM-2wayANOVA
High					
0°–30°	Pre	24.6 ± 3.1	27.6 ± 6.2	26.2 ± 3.8	21.6 ± 5.6
	20 min	24.5 ± 3.9	26.8 ± 6.1	25.9 ± 5.4	22.8 ± 5.8
31°–60°	Pre	23.8 ± 4.3	29.2 ± 8.6	29.0 ± 6.5	18.1 ± 7.1
	20 min	24.5 ± 5.0	27.9 ± 8.4	28.5 ± 6.4	19.2 ± 6.7
61°–90°	Pre	23.4 ± 4.2	30.2 ± 9.9	29.1 ± 7.7	17.3 ± 7.5
	20 min	23.8 ± 4.6	28.8 ± 9.5	29.7 ± 8.3	17.6 ± 8.0
Interaction effect	*p* value	0.511	0.775	0.446	
Time	*p* value	0.377	0.011	0.934	
Angle	*p* value	0.327	0.282	0.007	
Statistical Method		RM-2wayANOVA	RM-2wayANOVA	RM-2wayANOVA	Wilcoxon

Mean ± SD; Pre, pre-exercise.
*$p < 0.05$ compared to Pre.

part of the infraspinatus and teres minor, there was no significant differences before and 20 min after exercise in the low-, medium-, and high-load conditions. In the posterior deltoid, at low-load, an interaction was observed between exercise range × time ($p = 0.044$), with an increase in the muscle activity ratio from 61°–90° at 20 min (15.40 ± 6.03%) compared with Pre (13.59 ± 5.70%). At medium-load, there was no exercise range × time interaction ($p = 0.370$); however, increase in the muscle activity ratio increased from 31°–60° of shoulder external rotation (Pre: 13.80 ± 5.05%, 20 min: 15.78 ± 5.37%: $p = 0.023$) and 61°–90° (Pre: 12.74 ± 5.44%, 20 min: 14.35 ± 5.55%: $p = 0.047$), increased from Pre to 20 min, indicating a main effect of time. At high-load, there was no significant differences before and 20 min after exercise.

3.3 Electromyography amplitude of each muscle

Results of EMG amplitude before and 20 min after exercise are shown in Table 4 and Figure 6, and further information is available in Table 5. At low-load, no significant differences were observed between Pre and 20 min in the cranial part and caudal part of the infraspinatus and teres minor. However, there was an increase in EMG amplitude from Pre to 20 min in the posterior deltoid, with significant differences observed at 31°–60° (Pre: 63.43 ± 27.36% MVIC, 20 min: 73.87 ± 30.61% MVIC, $p = 0.034$) and at 61°–90° (Pre: 62.10 ± 39.00% MVIC, 20 min: 74.70 ± 37.76% MVIC, $p = 0.002$). At medium- and high-loads, EMG amplitude increased from Pre to 20 min in the infraspinatus, teres minor, and posterior deltoid, respectively.

3.4 Average frequency

The results of the average frequencies before and 20 min after the exercise are presented in Table 6. No significant decreases were observed in any of the cranial or caudal parts of the infraspinatus, the teres minor, or the posterior deltoid from Pre to 20 min under low-, medium-, or high-load conditions, based on the Wilcoxon signed-rank test.

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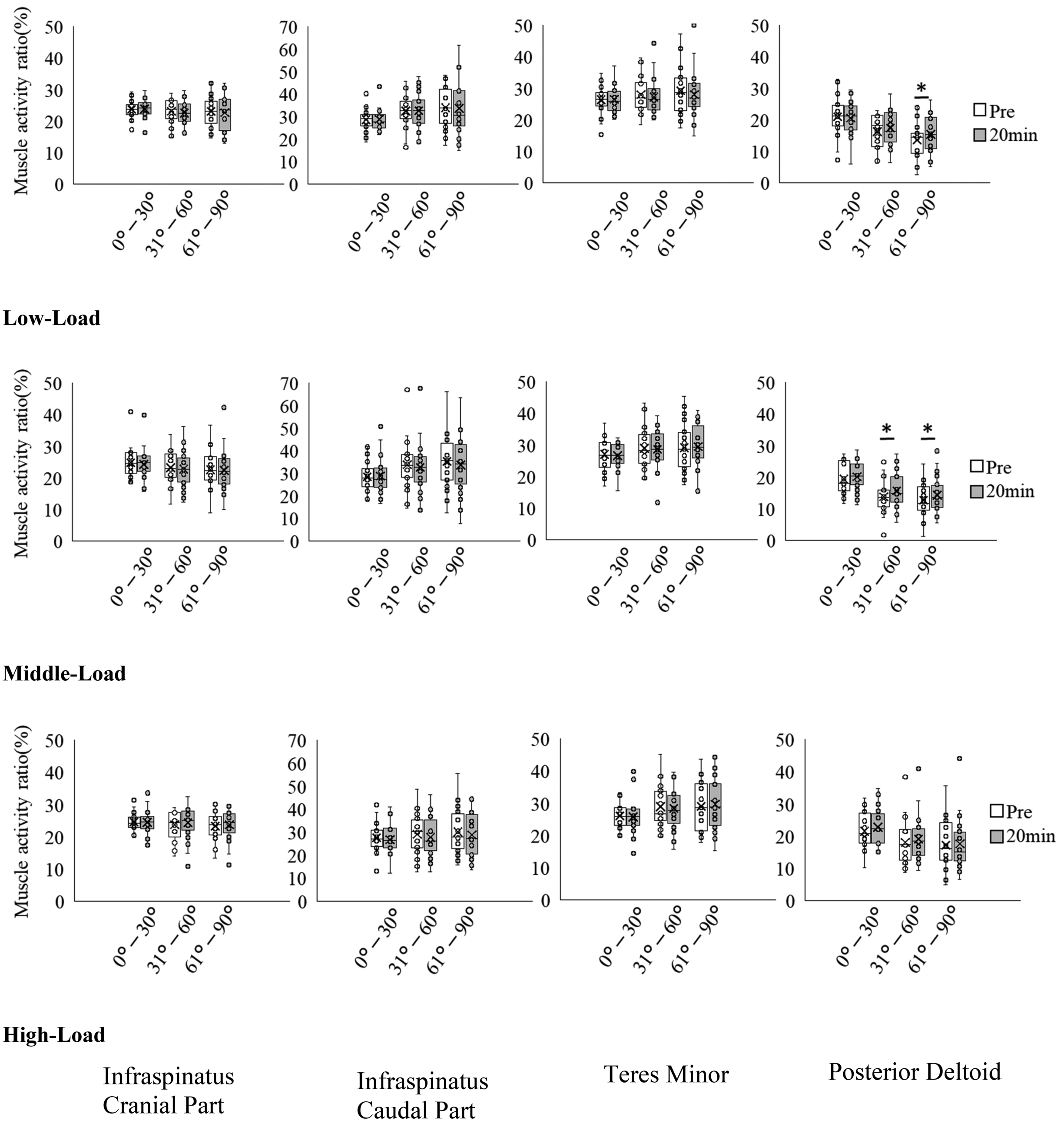

FIGURE 5
Changes in muscle activity ratio for each muscle before and after exercise. $*p < 0.05$.

4 Discussion

In this study, we aimed to determine the effects of shoulder external rotation exercises at different loads on external rotation torque and changes in the EMG amplitude and muscle activity ratio of the infraspinatus, teres minor, and deltoid, by using three types of Thera-Band® with different tensions. Results showed that after 20 min of exercise, the muscle activity ratio in the posterior deltoid muscle increased only in the range of 61°–90° of shoulder external rotation in the low-load condition, whereas, in the medium-load condition it increased regardless of the angle of external rotation. In contrast, there was no change in the muscle activity ratio in the high-load condition. Moreover, the EMG amplitude of all muscles increased regardless of external rotation angle in the medium- and high-load conditions; however, shoulder external rotation torque increased only in the medium-load condition.

We hypothesized that increasing the load of shoulder external rotation exercises would not change the muscle activity ratio in the shoulder external rotators after the exercise. However, the muscle activity ratio did change before and after the exercises under low-and medium-load conditions. Notably, the muscle activity

TABLE 4 Changes in the muscle activity before and after exercise.

		Infraspinatus		Teres minor (% MVIC)	Posterior deltoid (% MVIC)
		Cranial part (% MVIC)	Caudal part (% MVIC)		
Low					
0°–30°	Pre	90.7 ± 27.3	112.0 ± 45.5	100.8 ± 33.7	78.5 ± 30.2
	20 min	96.1 ± 25.3	117.0 ± 40.1	106.2 ± 28.2	81.6 ± 28.3
31°–60°	Pre	91.7 ± 32.8	132.0 ± 62.8	111.9 ± 43.4	63.4 ± 27.4
	20 min	96.4 ± 31.6	140.4 ± 53.9	116.3 ± 40.6	73.9 ± 30.6*
61°–90°	Pre	101.1 ± 37.7	150.9 ± 68.5	129.0 ± 51.6	62.1 ± 39.0
	20 min	109.3 ± 34.7	171.1 ± 90.7	136.4 ± 55.8	74.7 ± 37.8*
Interaction effect	*p* value	0.771			
Time	*p* value	0.099			
Angle	*p* value	0.007			
Statistical Method		RM-2wayANOVA	Wilcoxon	Wilcoxon	Wilcoxon
Medium					
0°–30°	Pre	82.2 ± 33.3	93.7 ± 34.7	86.4 ± 21.7	61.8 ± 18.0
	20 min	96.0 ± 29.0*	117.7 ± 58.3*	104.3 ± 25.0*	78.0±16.9*
31°–60°	Pre	83.4 ± 27.4	128.4 ± 70.5	103.8 ± 32.9	49.0 ± 22.5
	20 min	99.3 ± 30.4*	157.2 ± 120.3*	123.9 ± 39.2*	68.1 ± 26.1*
61°–90°	Pre	98.0 ± 29.6	168.1 ± 98.9	127.6 ± 42.6	55.6 ± 28.9
	20 min	109.3 ± 36.9	184.9 ± 148.2	143.8 ± 44.3*	71.6 ± 31.6*
Interaction effect	*p* value	0.783			
Time	*p* value	<0.001			
Angle	*p* value	0.006			
Statistical Method		Wilcoxon	Wilcoxon	Wilcoxon	RM-2wayANOVA
High					
0°–30°	Pre	90.4 ± 27.7	106.6 ± 53.6	94.6 ± 25.3	78.5 ± 30.5
	20 min	101.0 ± 34.8*	113.8 ± 53.0	104.5 ± 31.0*	90.7 ± 26.8*
31°–60°	Pre	93.1 ± 31.0	117.1 ± 47.7	110.9 ± 32.1	72.2 ± 42.9
	20 min	106.5 ± 35.1*	124.9 ± 54.1	122.4 ± 36.4*	83.2 ± 38.0*
61°–90°	Pre	102.1 ± 31.5	137.9 ± 69.7	124.1 ± 35.9	77.3 ± 43.1
	20 min	114.8 ± 37.7*	148.3 ± 84.9	140.1 ± 48.2*	86.2 ± 53.4
Interaction effect	*p* value	0.765	0.824	0.447	
Time	*p* value	0.002	0.075	0.010	
Angle	*p* value	0.008	0.004	<0.001	
Statistical Method		RM-2wayANOVA	RM-2wayANOVA	RM-2wayANOVA	Wilcoxon

%MVIC, percentage of maximum voluntary isometric contraction; Pre, pre-exercises.
*$p < 0.05$ compared to Pre.; Mean ± SD.

ratio in the posterior deltoid increased under low- and medium-load conditions. Conversely, the muscle activity ratio in the infraspinatus and teres minor decreased; however, each muscle did not significantly differ before or after the exercises. In this study, the repetition of exercises differed among conditions to unify the total workload of the exercises: 20 repetitions in the low-load condition, 11 repetitions in the medium-load condition, and 6 repetitions in the high-load condition. Additionally, the exercises in all conditions were performed at the same tempo; however, the time required for the exercises in the high-load condition was 1/3 of that in the low-load condition. Therefore, it is likely that the shoulder external rotation exercise in the high-load condition with fewer repetitions were not enough to change the muscle activity ratio in the posterior deltoid. Furthermore, the muscle activity ratio in the posterior deltoid did not change in the low-load condition from 0°–60° of external rotation. Notably, the shoulder external rotation torque required to pull the Thera-Band® in the low-load condition was 4.5 Nm at 61° of shoulder external rotation; however, it was 8.2 Nm at the same angle for medium-load. In the low-load condition, the tension of the Thera-Band® was not strong enough to increase the muscle activity ratio of the posterior deltoid from 0°–60° of shoulder external rotation.

The EMG amplitude increased only in the posterior deltoid in the low-load condition, whereas it increased in all muscles after the exercise in the medium- and high-load condition. After the exercises performed in this study, the EMG amplitude of the infraspinatus and teres minor did not increase in the low-load condition, whereas this amplitude in all muscles increased in the medium- and high-load conditions. Previous studies examining EMG amplitude during shoulder external rotation exercises have reported increases in both infraspinatus and posterior deltoid EMG amplitude with increasing exercise load for both exercises in the 90° shoulder abduction position (20) and in the 0° shoulder abducted position (7, 21). In the present study, the EMG amplitude of the cranial part and caudal part of the

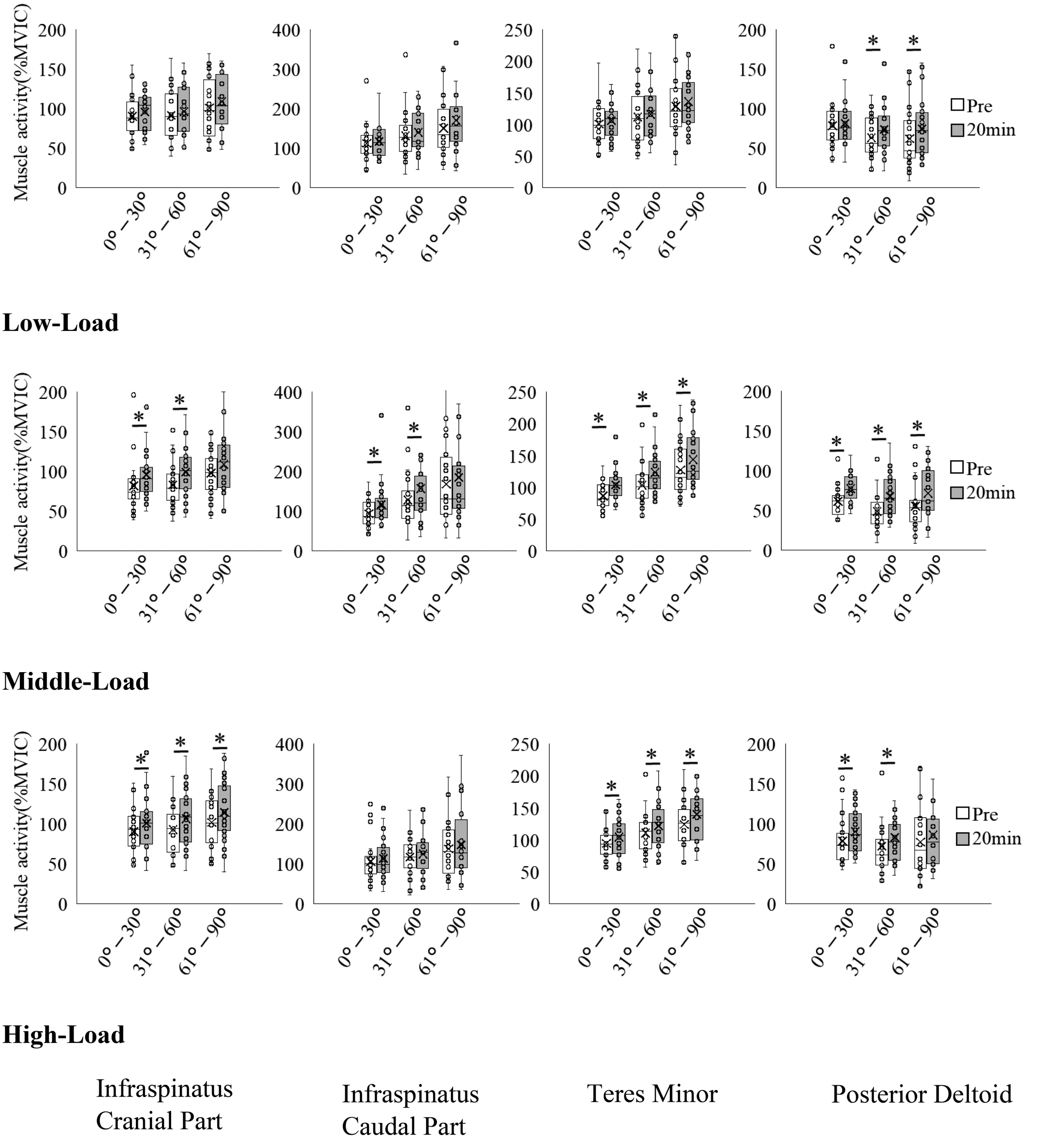

FIGURE 6
Changes in the muscle activity before and after exercise. $^{*}p < 0.05$.

infraspinatus, teres minor, and the posterior deltoid during the exercises was greater at high-, medium-, and low-loads, in the same order as in the previous studies. It was also reported that shoulder external rotation exercises in the 90° shoulder abducted position resulted in greater EMG amplitude in the infraspinatus and posterior deltoid compared with the 0° shoulder abducted position (13, 22). In addition, the infraspinatus/posterior deltoid muscle activation ratio was greater during low-load exercises than during high-load exercises (6). Therefore, it is likely that performing the exercise in the 90° shoulder abduction position increased the EMG amplitude in the shoulder external rotation muscle group and increased the muscle activity ratio in the deltoid during the exercise, which also led to an increase in the EMG amplitude after the exercise. We believe that the medium-load condition of this study, performed at 90° shoulder abduction, is effective in increasing short-term shoulder external rotation torque based on these results. On the other hand, the increased activation of the

TABLE 5 Raw EMG data: changes in the muscle activity before and after exercise.

		Infraspinatus		Teres minor (μV)	Posterior deltoid (μV)
		Cranial part (μV)	Caudal part (μV)		
Low					
0°–30°	Pre	342.5 ± 145.5	441.0 ± 291.3	303.3 ± 95.7	394.5 ± 167.4
	20 min	358.2 ± 116.8	452.6 ± 200.2	328.4 ± 113.3	418.3 ± 187.6
31°–60°	Pre	336.8 ± 129.4	508.0 ± 330.2	329.3 ± 99.6	330.8 ± 192.7
	20 min	351.8 ± 109.3	526.7 ± 232.5	347.7 ± 104.0	394.6 ± 226.2
61°–90°	Pre	374.5 ± 150.8	558.9 ± 253.0	376.8 ± 115.5	311.1 ± 206.4
	20 min	399.1 ± 122.0	614.1 ± 273.0	403.3 ± 119.8	392.4 ± 254.2
Medium					
0°–30°	Pre	314.0 ± 130.4	377.5 ± 156.6	280.1 ± 100.1	361.0 ± 161.1
	20 min	374.6 ± 148.6	490.3 ± 256.1	336.1 ± 111.0	470.7 ± 228.0
31°–60°	Pre	320.2 ± 122.5	491.3 ± 211.1	333.4 ± 119.7	289.6 ± 169.6
	20 min	381.1 ± 142.4	618.5 ± 407.8	392.8 ± 122.9	427.9 ± 277.8
61°–90°	Pre	375.7 ± 138.2	629.6 ± 301.3	408.2 ± 153.8	320.5 ± 196.0
	20 min	424.7 ± 180.2	695.2 ± 448.6	455.2 ± 135.4	454.1 ± 334.6
High					
0°–30°	Pre	334.6 ± 125.9	463.5 ± 190.2	303.5 ± 77.6	444.7 ± 182.2
	20 min	370.2 ± 146.7	504.2 ± 225.5	332.8 ± 95.9	527.7 ± 224.8
31°–60°	Pre	328.9 ± 78.2	523.8 ± 240.5	351.8 ± 88.2	405.3 ± 208.1
	20 min	380.2 ± 109.1	574.0 ± 349.2	387.1 ± 100.3	489.2 ± 250.3
61°–90°	Pre	368.7 ± 104.2	606.3 ± 286.4	392.0 ± 96.7	447.0 ± 270.9
	20 min	415.9 ± 138.5	646.0 ± 413.6	440.6 ± 125.7	506.7 ± 315.4

Mean ± SD; Pre, pre-exercise.

TABLE 6 Changes in the frequency before and after exercise.

		Infraspinatus		Teres minor (Hz)	Posterior deltoid (Hz)
		Cranial part (Hz)	Caudal part (Hz)		
Low	Pre	61.19 ± 22.02	56.07 ± 24.39	55.35 ± 20.82	56.60 ± 25.66
	20 min	61.90 ± 26.82	56.70 ± 29.50	56.24 ± 26.53	59.75 ± 30.11
	p value	0.9320.607	0.797		0.004
Medium	Pre	63.45 ± 26.05	58.77 ± 27.07	58.08 ± 25.17	58.51 ± 30.42
	20 min	63.56 ± 28.40	58.46 ± 28.03	58.34 ± 28.34	60.80 ± 30.08
	p value	0.954	0.668	0.864	<0.001
High	Pre	68.16 ± 32.11	60.08 ± 29.24	59.40 ± 25.21	60.10 ± 29.31
	20 min	64.29 ± 24.29	57.43 ± 25.30	58.08 ± 25.30	59.41 ± 27.41
	p value	0.732	0.278	0.354	0.067

Mean ± SD; Pre, pre-exercise.
The Wilcoxon signed-rank test was used to analyze the differences between conditions, as the data did not follow a normal distribution according to the Shapiro–Wilk test.

posterior deltoid muscle during shoulder joint exercises may generate a shearing force on the humeral head. Repeated daily performance of shoulder external rotation exercises could potentially lead to shoulder joint pain, as this force may displace the humeral head from its centered position in the glenoid fossa. Future studies are needed to assess the risk of developing shoulder joint pain with continuous practice of these exercises and to explore optimal exercise protocols that minimize this risk.

The high-load condition did not increase shoulder external rotation torque, despite increased EMG amplitude in all muscles. Exercises with Thera-Band® in this study were performed in the 90° shoulder abducted position; however, the entire arm was not fixed. Therefore, compensations such as scapular elevation, shoulder abduction or horizontal extension may have appeared. The uncontrolled compensatory movements of the shoulder joint during the exercises may have resulted in increased EMG amplitude other than the external rotator muscles. A previous study showed that the shoulder external rotators and the anterior and middle deltoid, supraspinatus, upper trapezius, and serratus anterior were more active in the 90° shoulder abducted position than in the 0° abducted position (22). Our study did not record EMG amplitude other than the shoulder external rotator muscles. It is possible that muscles other than the shoulder external rotators also worked during the high-load exercise, resulting in an increase in EMG amplitude after the exercise. Furthermore, the posterior deltoid muscle, whose EMG amplitude was measured in this study, also has abduction and horizontal extension actions along with shoulder external rotation. It is possible that the posterior deltoid was involved in the compensatory movements of shoulder abduction and horizontal extension that may have emerged during the high-load condition exercise. Based on the above, we believe that the high-load condition in this study did not lead to an increase in shoulder external rotation torque despite the increase in the EMG amplitude of the shoulder external rotators. We believe that the fatigue of exercise is not a factor resulting in the lack of increase in shoulder external rotation torque for the following reasons. The average frequency of concentric shoulder external rotation did not change after the exercise, the post-exercise measurements were taken 20 min after the exercise and the number of exercises in the high-load condition was only six.

Although peak torque did not change from pre-exercise, maximal workload significantly increased at 20 min post-exercise under medium-load condition. Additionally, there was no significant difference in external rotation torque between pre and 20 min after exercise within the range of 0°–30°; however, significant increases were observed in the range of 31°–60° and 61°–90°. The increase in shoulder external rotation torque beyond 31° is likely due to the properties of the Thera-Band®, as the resistance increases with increasing angle of external rotation. On the other hand, peak torque in shoulder external rotation is reported to occur in the early range of external rotation (11). The fact that the exercise tasks in this study did not lead to an increase in peak torque may be due to the relatively low workload imposed by the Thera-Band® in the early range of external rotation, where peak torque is typically exerted. Furthermore, the increase in maximal workload is considered to be due to the increase in external rotation torque within the larger external rotation ranges where Thera-Band® resistance increased in the latter half of the rotation.

4.1 Limitation

In this study, the elbow position was not fixed during the exercises with Thera-Band®, which may have resulted in the appearance of compensatory movements; however, no evaluation was made regarding compensatory movements. In addition, the EMG amplitude of muscles other than that of the shoulder external rotators was not recorded, so the influence of EMG amplitude other than those on the results remains unclear. Therefore, it is necessary to record the EMG amplitude other than the shoulder external rotators and examine the influence of muscles in this context. In addition, this study used the same type of Thera-Band® in all participants. The relative exercise intensity differed from one participant to the other due to differences in muscle strength among the participants. In this study, we used an elastics tool, Thera-Band®, in order to examine the method commonly used in the field. However, we believe that further investigation using equipment such as dumbbells is needed so that we can fine-tune the exercise load.

5 Conclusion

The changes in torque, EMG amplitude, and the muscle activity ratio of each muscle after shoulder external rotation exercises were not uniform depending on the load of the exercises. Therefore, it is necessary to use different exercise loads based on the purpose of the exercise.

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 Juntendo University Faculty and Graduate School of Sports and Health Science and the Research Ethics Committee. 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

YS: Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. AK: Writing – review & editing. KK: Writing – review & editing. MI: Writing – review & editing. TI: Writing – review & editing. YT: Supervision, Writing – review & editing.

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Conflict of interest

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

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Tensiomyography, functional movement screen and counter movement jump for the assessment of injury risk in sport: a systematic review of original studies of diagnostic tests

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Background: Scientific research should be carried out to prevent sports injuries. For this purpose, new assessment technologies must be used to analyze and identify the risk factors for injury. The main objective of this systematic review was to compile, synthesize and integrate international research published in different scientific databases on Countermovement Jump (CMJ), Functional Movement Screen (FMS) and Tensiomyography (TMG) tests and technologies for the assessment of injury risk in sport. This way, this review determines the current state of the knowledge about this topic and allows a better understanding of the existing problems, making easier the development of future lines of research.
Methodology: A structured search was carried out following the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines and the PICOS model until November 30, 2024, in the MEDLINE/PubMed, Web of Science (WOS), ScienceDirect, Cochrane Library, SciELO, EMBASE, SPORTDiscus and Scopus databases. The risk of bias was assessed and the PEDro scale was used to analyze methodological quality.
Results: A total of 510 articles were obtained in the initial search. After inclusion and exclusion criteria, the final sample was 40 articles. These studies maintained a high standard of quality. This revealed the effects of the CMJ, FMS and TMG methods for sports injury assessment, indicating the sample population, sport modality, assessment methods, type of research design, study variables, main findings and intervention effects.
Conclusions: The CMJ vertical jump allows us to evaluate the power capacity of the lower extremities, both unilaterally and bilaterally, detect neuromuscular asymmetries and evaluate fatigue. Likewise, FMS could be used to assess an athlete's basic movement patterns, mobility and postural stability. Finally, TMG is a non-invasive method to assess the contractile properties of superficial muscles, monitor the effects of training, detect muscle asymmetries, symmetries, provide information on muscle tone and evaluate fatigue. Therefore, they should be considered as assessment tests and technologies to individualize training programs and identify injury risk factors.

Systematic Review Registration: https://www.crd.york.ac.uk/PROSPERO/view/CRD42024607563, PROSPERO (CRD42024607563).

KEYWORDS

injury prevention, risk factors, functional tests, recovery, assessment

1 Introduction

Scientific research should be carried out to prevent sports injuries. For this purpose, valid and reliable assessment methods are needed to reduce the number of sports injuries (1–6). As a result of the investigations (3, 5) different methods and technologies have been proposed to assess and identify injury risk factors.

Sports injuries can affect the health and performance of athletes. Therefore, studies and research should be conducted to assess the risk of injury in athletes, thus contributing new knowledge to science (3, 5). In addition, there is a need to preserve the health and well-being of professional players when faced with a high frequency of extremely demanding matches (7). Consequently, strategies must be designed to optimize player availability and minimize factors such as fatigue (7).

These risk factors for sports injuries include characteristics of the athletes, sports and the environment (4). Another factor that has a decisive influence on the probability of suffering an injury as a result of sports practice is the workload (8). Therefore, it is necessary to analyze and study the risk factors that can produce an injury (1–6).

Based on these criteria, there is a need to assess the athlete's risk of injury, taking into account the different intrinsic and extrinsic risk factors that can have a decisive influence on an injury (1, 4). Among the factors to be studied are asymmetries (9), neuromuscular imbalances between limbs (4), muscle stiffness (10, 11), postural control deficits (12, 13) or fatigue (14).

To carry out these analyses, functional tests and muscle assessment methods or technologies are used to detect fatigue, monitor the training load, detect asymmetries or functional imbalances, as possible risk factors for injury (3, 5, 8, 14, 15).

One of the functional tests used to evaluate performance during the vertical jump is the Countermovement Jump (CMJ), as it is a Gold Standard (16). The CMJ is a valid and reliable tool (16) for assessing lower limb power capacity, either unilaterally or bilaterally, as well as detecting asymmetries between limbs.

Similarly, the performance of the CMJ jump on a jumping platform allows the measurement of flight time, contact time, height and power. Starting from this fundamental database, the software designed allows to obtain in real time these parameters linked to the athlete's performance (16). The CMJ can also be used to assess neuromuscular fatigue.

Along with this test, the Functional Movement Screen (FMS) is a valid and reliable tool (12, 13, 17) to assess an individual's fundamental movement patterns. Additionally, this system can be used at the end of the rehabilitation process to help determine if an athlete is ready to return to training. The main purpose of the FMS tool is to identify functional asymmetries and postural or motor control deficits (12, 13).

The FMS is composed of 7 fundamental movement patterns (test), with a numerical value from 0 to 3 according to certain observable markers that require a balance between mobility and stability (12, 13).

Another tool used in the evaluation is Tensiomyography (TMG) is a valid and reliable tool (10, 11, 18, 19) to evaluate the contractile properties of superficial muscles. TMG is a technique to evaluate the mechanical muscle response based on the displacement of the radial muscle belly to a single electrical stimulus (9). As a result of this electrical stimulus, a displacement-time curve is recorded where the following parameters are integrated: maximum radial muscle displacement (Dm), contraction time (Tc), delay time (Td), sustained contraction time (Ts) and relaxation time (Tr) (10, 11, 18, 19).

TMG is a non-invasive tool (11, 18, 19) used to monitor the effects of training during a specific period or throughout the season, to detect bilateral muscle asymmetries, to detect fatigue and to individualize training loads for athletes (11, 18, 19).

Given the existing reality, it is expected to analyse the current technologies, considering the starting existing capacities and the experts in the physical activity and sports, biomechanics and medicine, using the application of the information technology.

Individualized training is key to improving sports performance and preventing injuries. To do so, it is necessary to use new technologies that allow for the assessment of injury risk.

To date, and to the best of our knowledge, there are no previous level studies or evidence 1A demonstrating the use of CMJ, FMS and TMG tool variables for injury assessment.

Therefore, the main aim of this systematic review was to compile, synthesize and integrate international research published in different scientific databases on CMJ, FMS and TMG tests and technologies for the assessment of injury risk in sport. This way, this review determines the current state of the knowledge about this topic and allows a better understanding of the existing problems, making easier the development of future lines of research.

2 Methods

2.1 Searching strategies

This article is a systematic review focused on the methods of sports injury assessment. This systematic review was carried out following the guidelines of the Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA®) (20)

guidelines, which helped to improve the integrity. And registered at PROSPERO (ID = CRD42024607563). The methodological issues were solved with the guidance of the Cochrane Handbook for Systematic Reviews of Interventions (21).

The PICOS model was used to determine the inclusion criteria (22): P (Population): "athletes of different sports," I (Intervention): "injury prevention," C (Comparators): ""group comparison with multidisciplinary interventions and controls," O (Outcome): "physical and/or neuromuscular performance measurements, physiological responses, and risk of injury," and S (study design): "any type of design"."

A structured search was conducted in MEDLINE/PubMed, Web of Science (WOS), ScienceDirect, Cochrane Library, SciELO, EMBASE, SPORTDiscus and Scopus. The investigation ended on November 30, 2024. Search terms included a mix of medical subject headings (MeSH) and free-text words for key concepts related to assessment methods, high performance athletes and sports injury prevention. Specifically, we used the following search equation: ["injury prevention" (MeSH Terms) OR "injury assessment" (All Fields) OR "sports injuries" (All Fields) OR "injury risk factors" (All Fields)] AND ["Assessment test" (MeSH Terms) OR "TMG" (All Fields)] OR "FMS" (All Fields) OR "CMJ" (All Fields)] AND ["sport" (MeSH Terms) OR "football" (All Fields)] OR "sports" (All Fields) OR "athletes" (All Fields)]. Through this equation, all relevant articles in the field were obtained. The reference sections of all identified articles were also examined by applying the "snowball methods" strategy (23), based on examining the reference sections of the identified articles. All titles and abstracts from the search were cross-referenced to identify duplicates and any potential missing studies (Á.V.-S. and J.C.-G). Titles and abstracts were screened for a subsequent full-text review. The search for published studies was independently performed by two different authors (Á.V.-S. and J.C.-G) and disagreements were resolved through discussions between them.

2.2 Inclusion and exclusion criteria

We selected studies providing effectivity results in terms of diagnostic accuracy or diagnostic performance for the different tests used in the assessment of sports injuries were included. The systematic review included original studies of diagnostic tests designs included and systematic reviews, meta-analysis, abstracts of conferences and opinion articles were excluded. In addition, we selected studies that contained a minimum of 10 participants. And for effectiveness studies only those that used at least one technique for the prevention and analysis of sports injuries were considered. The CMJ, the FMS and the TMG were considered as comparison techniques.

For the articles obtained in the search, the following inclusion criteria were applied to final selected studies: (I) studies published in peer-reviewed journals and full text available; (II) the articles examined the effects of sports injury assessment methods; (III) original articles published in peer-reviewed peer-reviewed journals with impact factor; (IV) participants were assessed with the CMJ, FMS or TMG; (V) the study population consisted of athletes; (VI) included the assessment of the risk of injury; (VII) performed on any number or type of athlete regardless of category, experience, competitive level or sex; (VIII) published in English. The following exclusion criteria were applied to the experimental protocols of the investigation: (I) the absence of reliable measurements; (II) studies with less than 10 participants; (III) studies conducted using participants with a previous cardiovascular or musculoskeletal disorder; (IV) studies that will not be performed with athletes; (V) abstracts, non-peer-reviewed papers, and book chapters.

2.3 Study selection

Titles and abstracts of publications identified by the search strategy were screened for a subsequent full-text review and were cross-referenced to identify duplicates. All trials assessed for eligibility and classified as relevant were retrieved, and the full text was peer reviewed (Á.V.-S. and J.C.-G). Moreover, the reference section of all relevant articles was also examined using the snowball (23). Based on the information within the full articles, the inclusion and exclusion criteria were used to select the trials eligible for inclusion in this systematic review. Disagreements were resolved through discussions between two authors (Á.V.-S. and J.C.-G).

2.4 Data extraction

Once the inclusion/exclusion criteria were applied to each study, the following data were extracted: study source (author/authors and year of publication); population of the sample, indicating the number of participants; sport modality; assessment methods and tests; type of research design; study variables; main findings; characteristics of the intervention; significant differences among the study groups and effects of the intervention.

For each study, we carefully collected information for all eligible publications. Average (±) data and standard deviation (SD) data and size of the sample were extracted from the tables of all the included documents. Subsequently, disagreements were resolved through discussion until a consensus was achieved.

2.5 Quality assessment and risk of bias

Methodological quality and risk of bias were assessed by two authors independently (Á.V.-S. and D.M.-J), and disagreements were resolved by third-party evaluation (J.C.-G), in accordance with the Cochrane Collaboration Guidelines (24).

In the Cochrane Risk of Bias tool, the following items were included and divided into different domains: (1) selection bias (items, random sequence generation, allocation and concealment), (2) performance bias (blinding of participants and personnel), (3) detection bias (blinding of outcome assessment), (4) attrition bias (incomplete outcome data), (5) reporting bias (selective reporting), and (6) other bias (other sources of bias).

For each investigation, criteria were shown as "low" if the criteria were fulfilled for a low-risk bias (improbable to severely alter the results) or "high" if the criteria were high risk bias (severely weakening the reliability of the results). If the risk of bias was unknown, it was considered "not clear" (it brings doubts about the results).

The systematic review was based on the established principles by the PRISMA statement (20), a verification list which has as main aim to look for the transparency of the important systematic reviews in the scientific rating of these studies. It has got 27 items and a flow chart with four stages, which includes items considered as essential for the transparent communication of a systematic analysis.

The "Physiotherapy Evidence Database (PEDro)" scale was also used to analyse the methodological quality of all the selected articles. This scale is a tool designed to evaluate the methodological quality of the clinical designs (Table 1) and used in many bibliographic reviews. The aforementioned tool is based on a list developed by Verhagen (25) using the Delphi technique (26).

The PEDro scale has got a total of 11 items. Item 1 refers to the external validity of the study, while items 2–9 refer to the internal validity; items 10 and 11 show if the statistic information provided by the authors allows the accurate interpretation of the results. All items in the list are dichotomised as "yes", "no" or "not reported". Each "yes" item is given one point, while "no" or "not reported" items do not receive any points at all.

The first item of the PEDro scale was not taken into account in this review, as it was related to the evaluation of the external validity of the studies. Therefore, only items 2–11 were selected for the assessment of the methodological quality. Due to this, the maximum score of an article could not be higher than 10 points, and the minimum, not lower than 0 points.

The evaluation of the heterogeneity was another point to analyse. In this case, we can consider, on the one hand clinical heterogeneity, due to the differences among the types of patients, treatments and endings, and on the other hand, methodological heterogeneity, due to the variability in the designs and bias control.

TABLE 1 "Physiotherapy evidence database (PEDro)" scale to analyse the methodological quality of the studies.

PEDro scale			
1	The criteria of election were specified	Yes	No
2	The subjects were randomly assigned to the groups	Yes	No
3	The assignment was hidden	Yes	No
4	The groups were similar at the beginning in relation to the indicators of prognosis	Yes	No
5	All subjects were blinded	Yes	No
6	All the sports scientists providing therapy were blinded	Yes	No
7	All assessors evaluating at least one of key results were blinded	Yes	No
8	All the measures of at least one of the key results were obtained from more than 85% of the subjects initially assigned to the groups	Yes	No
9	The results of all the subjects receiving treatment or assigned to the control group were given, or when not possible, the data for at least one key result were analysed "in order to treat"	Yes	No
10	The results of statistic comparisons among groups were reported for at least one key result	Yes	No
11	The study provides specific and variability measures for at least one key result	Yes	No

3 Results

3.1 Main search

The search on data base reported 510 publications. A digital search was made from sources which generated 65 relevant studies, included in the review. After the detailed review of titles, abstracts and complete articles (60), the publications which fulfilled the criteria of inclusion were a total of 40, in English. A limitation of 15 years of publication was applied. Of the 60 articles included, 5 were excluded due to the fact that they were duplicated. A limitation of 15 years of publication was applied. Of the 60 articles included, 5 were excluded due to the fact that they were duplicated, remaining 55 complete articles for the review. In the last stage of the inclusion of articles, 15 articles were excluded, which were not related to the sports area or which studied different variables.

From the final selection, 40 studies were included. A total of 21 articles were included (27–47) with significative data referring to CMJ, 12 articles (48–59) with significative data referring to the use of FMS, 12 articles (10, 27–30, 46, 60–65) referring to the use of TMG (Figure 1).

3.2 Study characteristics

The source of the study (author/authors and year of publication); population of the sample, indicating the number of participants; sport modality; assessment methods and tests; type of research design; study variables; main findings and effects of the intervention are represented on Table 2. 21 articles with significative data referring to CMJ, 12 articles were included with significative data referring to the use of FMS and 12 articles referring to the use of TMG, and Important differences were shown in size, age, gender, design of studies, sport and the evaluation methods used.

3.3 Risk of bias

The methodological quality and the risk of bias were evaluated following the guidelines of the Cochrane Collaboration (24). For each investigation, criteria were shown as "low" if the criteria were fulfilled for a low risk of bias (improbable to severely alter the results) or "high" if the criteria were high risk bias (severely weakening the reliability of the results). If the risk of bias was unknown, it was considered "not clear" (it brings doubts about the results). Every included study was assessed for the risk of bias (24). The full assessments of study quality are shown in Figure 2.

3.4 Methodological quality assessment

The methodological quality of the analysed studies varied between 5 and 7 points, with an average of 5.92 points. 33 Articles got 6 points, 5 articles got 5 points and 2 article got 7 points.

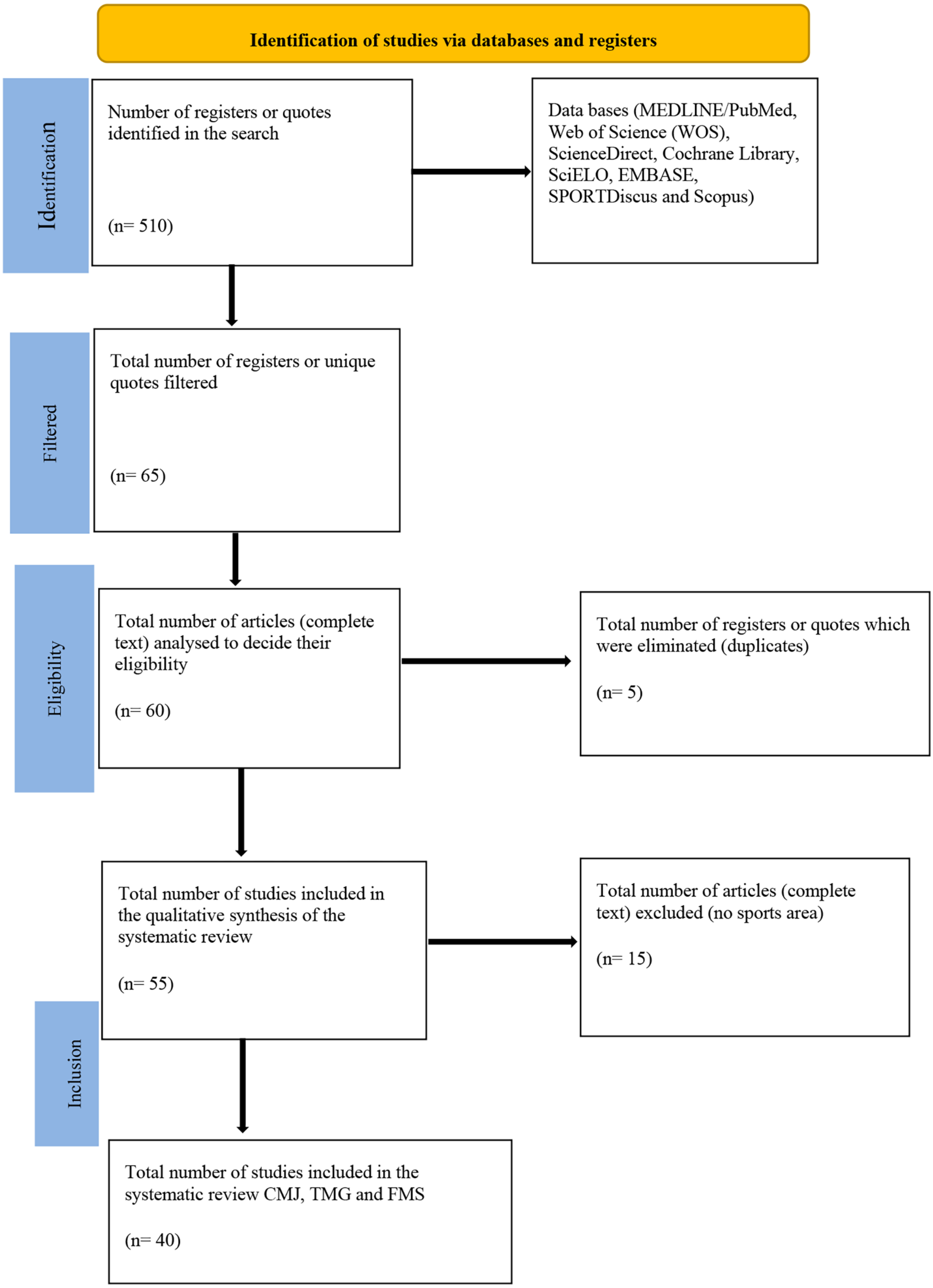

FIGURE 1
Flow diagram of the study selection.

Despite the relative heterogeneity of the analysed studies, certain criteria were consistent in all of them. Table 3 shows the criteria which more frequently were obtained belong to item 4, "the groups were similar at the beginning in relation to the most important indicators of prognosis", to item 8 "the measures of at least one of the key results were obtained from more than 85%

TABLE 2 Methodology and results of the interventions.

Study	N	Sport	Assessment test	Design	Variables	Main findings	Effects
Li et al. (48)	290	Elite athletes	FMS	Exploratory factor analysis	Internal consistency and factor structure of the 7 tasks	The 7 tasks have got low internal consistency and are not indicative of an only factor. More attention must be paid to the score of each task than to the total score	→
Harshbarge et al. (49)	52	Athletics	FMS	Correlational design	Star Excursion Balance Test, and Balance Error Scoring System	The score for FMS and SEBT asymmetry can show a relation between asymmetry of movement and postural stability. The associations between FMS deep squats and BESS tasks can be related to subjacent neuromuscular control factors.	→
Nicolozakes et al. (50) 2017	38	Football	FMS	Cross-sectional study	Body mass index, body fat percentage	The increase of fat percentage and BMI are related to results in the lower individual FMS.	↑
Duke, et al. (51)	73	Rugby	FMS	Experimental Approach	Injury risk	The quality of movement, analysed by FMS, predicts the risk of injuries by lost time in experienced rugby athletes and it must be considered as an important tool for assessment. Athletes FMS ≤14 have got a significantly higher probability of suffering injuries by lost time in the competitive season.	↑
Yeung et al. (52)	16	Football	FMS	Observational study	Mobility, proprioception, strength	The asymmetry in strength was significant in the prediction of the injury and the FMS score showed a sufficient positive difference.	↑
Chimera et al. (53)	200	Athletics	FMS	Cross-sectional design	Injury History, Sex, and Performance	The injury history and the gender affected the performance of FMS and YBT.	↑
Sannicandro et al. (54)	30	Football	FMS	Correlation study	Asymmetry, Hop Test, Side Hop and Hop Crossover	Better quality movement in FMS, related to a high performance in CMJ and a low percentage of endurance capacity in lower limbs, respectively.	↑
Tous-Fajardo et al. (10)	18	Healthy men	TMG	Observational study	Inter-rater reliability of vastus medialis muscle contractile	The results legitimise the use of TMG for the assessment of the contractual properties of the vastus medialis muscle, particular for Dm and Tc. It is recommended to avoid the quantification Tr and the modifications of IED during many measurements, as it showed an unsatisfactory reliability.	↑
Gil et al. (60)	20	Football	TMG	Correlation study	TMG parameters from rectus and biceps femoris, jumping and sprinting abilities, lateral symmetry	There were no correlations between tensiomyography parameters and power-related motor tasks. In addition, no differences in tensiomyography parameters between dominant and non-dominant legs were found.	↓
Loturco et al. (27)	24	Football	TMG, CMJ	Correlation study	Isokinetic assessments, jump tests, TMG, Asymmetry	Detected asymmetries in the three different methods were not interrelated. Lower-limb asymmetry is not necessarily related to impaired vertical jump performance in soccer players.	↓
García-García et al. (61)	37	Football	TMG	Experimental study	Tc, Dm, Td, knee extensor and flexor muscles	Tc, Td and Dm could be used to individualise the load and intensity of work and to control the effects of the neuromuscular training during the season.	↑
García-García et al. (62)	16	Football	TMG	Observational study	Dm, Tc, Td, Ts, Tr, Vc, muscular asymmetry	It was shown that TMG is a useful way to analyse the neuromuscular characteristics of the players at the beginning of the preseason, and to establish the initial values of the players individually.	↑
Ubago-Guisado et al. (28)	15	Rugby	TMG CMJ	Experimental study	RSA Test, Tc, Dm	The muscular response in the rectus femoris muscle after repetitive sprint actions differs in the different surfaces (sand and grass).	↑
Loturco et al. (29)	41	Athletics	TMG CMJ	A comparative study	Dm, Tc, Td, SJ, reactive strength index	Vertical jump as well as the analysis TMG could be useful to identify and select young athletes.	↑
Rey et al. (63)	31	Football	TMG	Experimental study	Dm, Tc, Td, heart rate and RPE	Significative effects were not found due to the recuperation strategy in the TMG parameters and the perceived muscle pain.	↓
Gonzalo-Skok et al. (31)	30	Basketball	CMJ	A crossover study design	Weight-bearing dorsiflexion test, a modified Star Excursion Balance test	Differences exist between functional movement tests and in jump and/or sprint performance tests between age groups. It could have implications to predict the risk of injury.	↑
Chena et al. (32)	434	Football	CMJ	Correlation study	Body composition, SJ, Abalakov Jump		↑

(*Continued*)

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TABLE 2 Continued

Study	*N*	Sport	Assessment test	Design	Variables	Main findings	Effects
						Besides the biological age and the development of the muscle mass, the position during the game must be taken into account as a relevant variable in the use of the body composition and the performance of the vertical jump as factors of the talent detection.	
Menzel et al. (33)	46	Football	CMJ	Correlation study	Lower Limb Asymmetries, isokinetic test	The maximum impulse and strength during CMJ on a strength platform seem to be proper additional variables for the identification of bilateral differences.	↑
Roe et al. (34)	12	Rugby	CMJ	Experimental study	Cycle-ergometer test, performance	The greater weekly changes in CMJ metrics in comparison with CET may indicate differences in the capacities of these tests to measure training-induced lower-body neuromuscular fatigue.	→
Bonato et al. (35)	160	Basketball	CMJ	Cluster randomized controlled trial	Y-Excursion Balance test, lower limb strength, postural control	Including body-weight neuromuscular training in the warm up routines reduced the occurrence of serious injuries in lower limbs in elite female basketball players.	↑
Roche-Seruendo et al. (36)	51	Athletics	CMJ	Experimental study	SJ, Spatiotemporal parameters, muscular performance parameters	The muscular performance parameters do not play a key role in the space-time adaptations experimented by the athletes with higher speed. The authors suggest that the muscular performance parameters would be much more determinant when there is fatigue.	↓
Fort-Vanmeerhaeghe et al. (37)	69	Volleyball and basketball	CMJ	A cross-sectional study	Flight time, jump height, asymmetry	A threshold of 10–15% asymmetry in vertical jump height between limbs can be considered as the physiological norm in basketball and volleyball players.	↑
Fort-Vanmeerhaeghe et al. (38)	29	Basketball	CMJ	A cross-sectional design	Star excursion balance test, sprint test asymmetry	Single leg countermovement vertical jump may be the most useful to predict injury.	↑
Ferioli et al. (39) 2018	28	Basketball	CMJ	Experimental study	Fatigue, power	The training period brought a few changes in CMJ, while the capacity to keep DQO repeated efforts was improved. Getting a high session score with loads in the effort training may affect partially and negatively the capacity to produce strength and power.	→
Heishman et al. (40)	10	Basketball	CMJ	Retrospective analysis design	External load, internal stress, fatigue	Omegawave and Catapult technologies provide independent information related to the efficiency and can be useful tools to monitor the performance of the athletes.	↑
Wing et al. (41)	15	Football	CMJ	Experimental study	Strength, power	Superior strength and power qualities have been shown to positively impact successful heading and tackling performance.	↑
Marqués-Jiménez, et al. (42)	10	Football	CMJ	Experimental study	Neuromuscular Fatigue	Internal and external load metrics may allow for predicting the extent of acute fatigue	↑
Fort-Vanmeerhaeghe et al. (43)	81	Young elite team-sports athletes	CMJ	Observational study	Interlimb asymmetries, injury incidence	Athletes with greater interlimb asymmetries, less vertical jump capacity, and lower intermittent aerobic fitness had a greater predisposition to injury	↑
Morgan et al. (55)	45	Students	FMS	Observational Laboratory Study	Interrater Reliability between Raters	The updated FMS has acceptable interrater reliability between minimally, but adequately trained individuals. The updated FMS may be reliably used to assess risk for future injury.	↑
Bernardes Marques et al. (56)	103	Football	FMS	Cross-sectional observational study	Asymmetries	High-performance young soccer players have important functional deficits, especially in tasks involving deep squat and trunk stability, as well as high prevalence of asymmetry between right and left body side.	↑
Dorrel et al. (57)	257	Athletics	FMS	Cross-sectional study	Injury risk	FMS had limited prognostic ability to accurately identify athletes who might be at risk of injury. FMS can be used to assess movement quality.	↓

(*Continued*)

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TABLE 2 Continued

Study	*N*	Sport	Assessment test	Design	Variables	Main findings	Effects
Fernández-Baeza et al. (64)	27	Football	TMG	A comparative study	Dm, Tc, Td	The variables of TMG (Tc, Dm) inform about the reaction and Tc, which is a key factor in soccer, as well as the muscle tone, to determine if a muscle has a deficit in tone or stiffness.	↑
Oliver Gonzalo-Skok et al. (44)	22	Basketball	CMJ	Experimental study	Power, between-limbs imbalance, bilateral deficit, change of direction.	Training programs substantially improved most of the physical-fitness tests, but only the unilateral reduced between-limbs asymmetry and achieved greater enhancements in actions that mostly required applying force unilaterally.	↑
Ruffieux et al. (45)	33	Volleyball	CMJ	Experimental study	Jump height	For non-professional female volleyball players and a training duration of six weeks, training with a high percentage of CMJ is more effective than one with a high percentage of DJ.	↑
García-García et al. (65)	48	Cycling	TMG	Experimental study	Dm, Tc, Td, Ts	An incremental effort until exhaustion produces peripheral fatigue associated with a decrease in Dm, Tc, Td, Ts, and The Vrd, being more pronounced in biceps femoris than in vastus lateralis and rectus femoris. Coaches can use these changes found in the contractile properties as a reference to detect the muscle fatigue.	↑
Warren et al. (59)	167	Basketball, football, volleyball, cross country, track and field, swimming/diving, soccer, golf, and tennis athletes	FMS	Prospective cohort	Injury, asymmetry	FMS, movement patterns, and asymmetry were poor predictors of noncontact and overuse injury in this cohort of division I athletes.	↓
Smith et al. (59)	19	Healthy men and women	FMS	Observational study	Interrater and intrarater reliability	The results showed that the FMS could be consistently scored by people with varying degrees of experience with the FMS after a 2-hour training session	↑
Huso Paravlic1 et al. (30)	35	Football	TMG, CMJ	Correlation study	Asymmetry	The overall significant, albeit inconsistent, correlations between the diverse performance scores obtained highlight the necessity for a multifaceted and thorough diagnostic strategy in female soccer players.	→
Buoite Stella et al. (46)	23	Football	CMJ, TMG	A cross-sectional observational study	Muscle Asymmetries	Findings suggest an association between lower-limb muscle asymmetries during a dynamic task, such as jumping, and muscle contractile properties evaluated with TMG; moreover, functional asymmetries may be present after ankle injuries.	↑
Delextrat et al. (47)	21	Football	CMJ	Experimental study	Strength-Endurance Training, height	As inadequate eccentric strength and fatigue are both risk factors for hamstring injury, SE training should be considered along with the development of peak eccentric strength, as a component of programs aimed at reducing injury risk in multiple-sprint sports.	↑

↑ positive effect; → no effect; ↓ negative effect; CMJ, counter movement jump; TMG, tensiomyography; FMS, functional movement screen; Dm, maximum radial muscle belly displacement; Tc, contraction time; Td, delay time: Ts, sustain time.

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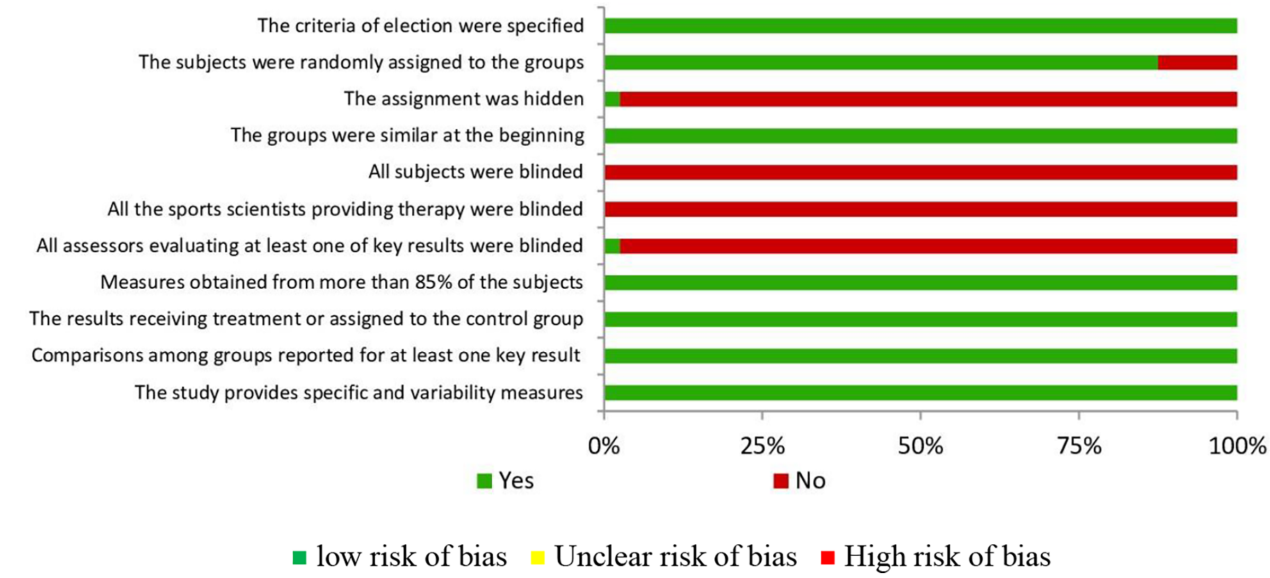

FIGURE 2
Risk of bias summary: review authors' judgements about each risk of bias item for each included study.

TABLE 3 Results according to PEDro scale (n = 40).

Clinical trial	1	2	3	4	5	6	7	8	9	10	11	Total
Li et al. (48)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Harshbarge et al. (49)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Nicolozakes et al. (50)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Duke, et al. (51)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Yeung et al. (52)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Chimera et al. (53)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Sannicandro et al. (54)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Tous-Fajardo et al. (10)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Gil et al. (60)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Loturco et al. (27)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
García-García et al. (61)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
García-García et al. (62)	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	5
Ubago-Guisado et al. (28)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Loturco et al. (29)	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	5
Rey et al. (63)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Gonzalo-Skok et al. (31)	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	5
Chena et al. (32)	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	5
Menzel et al. (33)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Roe et al. (34)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Bonato et al. (35)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Roche-Seruendo et al. (36)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Fort-Vanmeerhaeghe et al. (37)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Fort-Vanmeerhaeghe et al. (38)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Ferioli et al. (39)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Heishman et al. (40)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Wing et al. (41)	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	7
Marqués-Jiménez, et al. (42)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Fort-Vanmeerhaeghe et al. (43)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Morgan et al. (55)	Yes	Yes	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes	7
Bernardes Marques et al. (56)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Dorrel et al. (57)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Fernández-Baeza et al. (64)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6

(Continued)

TABLE 3 Continued

Clinical trial	1	2	3	4	5	6	7	8	9	10	11	Total
Oliver Gonzalo-Skok et al. (44)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Ruffieux et al. (45)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
García-García et al. (65)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Warren et al. (59)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Smith et al. (59)	Yes	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	5
Huso Paravlic1 et al. (30)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Buoite Stella et al. (46)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Delextrat et al. (47)	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6

Yes: it presents the studied criterium. No: it does not present the studied criterium.
1. The criteria of election were specified; 2. The subjects were randomly assigned to the groups; 3. The assignment was hidden; 4. The groups were similar at the beginning in relation to the most important indicators of prognosis; 5. All participants were blinded; 6. All the sports scientists providing therapy were blinded; 7. All assessors evaluating at least one of key results were blinded; 8. All the measures of at least one of the key results were obtained from more than 85% of the participants initially assigned to the groups; 9. The results of all the subjects receiving treatment or assigned to the control group were given, or when not possible, the data for at least one key result were analysed "in order to treat"; 10. The results of statistic comparisons among groups were reported for at least one key result; 11. The study provides specific and variability measures for at least one key result.

of the participants initially assigned to the groups", followed by item 9 the results of all the subjects receiving treatment or assigned to the control group were given, or when not possible, the data for at least one key result were analysed "in order to treat", item 10 "The results of statistic comparisons among groups were reported for at least one key result" and 11 "the study provides specific and variability measures for at least one key result". Finally, just to indicate that none of the studies fulfilled criteria 5 and 6 (subjects and sports scientists were blinded), and only one study fulfilled item number 3 and 7 (the assignment was hidden and all assessors of at least one of the key results were blinded).

4 Discussion

4.1 Summary of main findings

The main aim of this systematic review was to compile, synthesize and integrate international research published in different scientific databases on CMJ, FMS and TMG tests and technologies for the assessment of injury risk in sport. This way, this review determines the current state of the knowledge about this topic and allows a better understanding of the existing problems, making easier the development of future lines of research.

It was decided to carry out a revision of the most relevant bibliography, as well as of the most important published papers, in order to obtain the most outstanding aspects or data to which their authors refer, and this way work in all aspects to be taken into account, during and after the practice of sports, in order to avoid sports injuries.

The indicated measures were verified in terms of efficiency in the different studies analysed in this review. There currently exist many literary proposals which try to gather them in different ways in terms of prevention protocols, studying their effects in a complex way. In spite of this, it was observed that preventive actions are not currently used systematically.

Therefore, the current scientific bibliography describes different methods for the assessment and value of sports injuries, among which CMJ, FMS and TMG stand out.

4.2 Counter movement jump (CMJ)

Investigations reveal the validity and reliability of CMJ (16) to assess the power ability of lower extremities either unilaterally or bilaterally. For this reason, the CMJ vertical jump test can be used to monitor athletes' adaptations to training programs through measurements based on flight time, contact time, height and for estimation of lower extremity explosive power (16).

In addition to this, the studies (27, 33, 37, 38, 43, 44) indicate that the CMJ test can be used for the detection of asymmetries. In this regard, impulse and peak power during CMJ on a force platform appear to be additional variables appropriate for the identification of bilateral differences in sports such as basketball, volleyball, or football (33). Therefore, it would be appropriate to calculate the neuromuscular asymmetry of the lower extremities, because a greater neuromuscular asymmetry between legs could lead to a higher incidence of injury. To this end, some studies (37) indicate that a threshold of 10%–15% of vertical jump height asymmetry between limbs can be considered as the physiological norm in players.

As evidenced by (34, 39, 40, 42), CMJ can also be used to assess neuromuscular fatigue. The use of non-invasive strategies to monitor internal stress and external training load can be a valuable tool to identify player fatigue and stress (40). Neuromuscular fatigue can be quantified through CMJ performance, as suggested, its high repeatability and sensitivity proves its usefulness as a fatigue marker (42).

Similarly, the performance of the CMJ jump on a jumping platform allows the measurement of flight time, contact time, height and power. Starting from this fundamental database, the software designed allows to obtain in real time these parameters linked to the athlete's performance (16). Moreover, impulse and maximum strength during CMJ in a strength platform seem to be proper additional variables to identify bilateral differences. Therefore, it is relevant to carry out a vertical jump test in a strength platform to ensure a wide and reliable diagnostic information (33).

In the same way, the studies (41) support the idea that strength and power training is important for performance. It has also been indicated that CMJ training is more effective than drop jump training in improving jump height in female volleyball players (45). In addition, it has been shown that the inclusion of neuromuscular body mass training in warm-up routines can reduce the incidence of serious lower extremity injuries (35).

With respect to the risk of injury, some studies (43) indicate that athletes with greater asymmetries, lower vertical jump capacity and lower intermittent aerobic fitness have a greater predisposition to injury. Therefore, it is recommended to monitor CMJ and asymmetries given their sensitivity to detect significant differences between injured and healthy young athletes (43).

Therefore, the quantification of neuromuscular deficits through the CMJ is essential to identify individuals who may be at risk of injury (38). In addition, inadequate eccentric strength and fatigue are risk factors for injury (47). Therefore, eccentric strength development should be considered as a component of programs aimed at reducing the risk of injury (47).

4.3 Functional movement screen

Results show the use of the FMS to evaluate the quality of fundamental movement patterns, identify an individual's limitations or asymmetries as a potential risk factor for injury. This way, the studies (12, 13) show that 7 exercises (deep squat, hurdle step, lineal lunges, shoulder mobility, active straight leg raise, flexion in trunk stability and rotational stability) with a score of 0, 1, 2 and 3, allows evaluation of an athlete's basic movement patterns, mobility and stability.

In addition, the FMS could be used for asymmetry detection in athletes (58). Regarding asymmetry, some studies (52) have shown a significant difference between injured and non-injured professional football players, indicating that asymmetry could be used as a possible identifier of injury risk and has been found to be negatively associated with lower extremity injuries. This is also evidenced by relating the FMS to other assessment tests, such as the Star Excursion Balance Test (SEBT), and Balance Error Scoring System (BESS) scores (49). In this regard, it has been suggested (49) that associations between the FMS asymmetry score and the SEBT composite score may indicate a relationship between movement asymmetry and postural stability.

Also, the internal consistency and factorial structure of the 7 tasks of the functional movement test in elite athletes have been studied (48). In this regard, the results (55) of an updated version of the FMS indicate that it has acceptable inter-rater reliability among individuals with minimal but adequate training. The updated FMS can be used reliably to assess the risk of future injury (55). In addition, results have shown (59) that the FMS could be consistently scored by individuals with varying degrees of experience with the FMS after a 2-h training session. In a controlled laboratory study (66) with the FMS, intra-rater reliability was found to be strong and appears to be strengthened when individuals have experience using the FMS in addition to clinical experience.

In the same way, the different scores of FMS can be narrowly related to the athlete's height, weight, BMI and body fat percentage (50). As some studies show (50), the increase of body fat percentage and BMI is related to results in lower individual FMS, which prove potentially poor movement patterns in bigger athletes. Furthermore, other variables such as injury history or gender may influence performance on FMS tests (53). In this regard, Lower global FMS scores have been reported in athletes with a history of injury or surgery (53).

Finally, related to the results, many investigations (51, 55–57, 67) show that FMS ≤14 athletes have got a significantly higher probability of suffering injuries. In this regard, it is shown that participating subjects with scores ≤14 have a significantly higher probability of injury compared to those with higher scores.

Therefore, FMS could be used to assess the movement quality of athletes or active adults (66), with the aim of improving the movement pattern, which could reduce a risk factor for future injuries (51, 57, 58), so it should be considered as an assessment tool.

4.4 Tensiomyography

Studies show TMG as a valid and reliable (10, 11, 18, 19, 29) assessment tool to evaluate the contractile properties of superficial muscles. TMG is a technique to evaluate the mechanical muscle response based on the displacement of the radial muscle belly to a single electrical stimulus (10). As a result of this electrical stimulus, a displacement-time curve is recorded where the following parameters are integrated: maximum radial muscle displacement (Dm), contraction time (Tc), delay time (Td), sustained contraction time (Ts) and relaxation time (Tr) (10, 11, 18, 19).

In addition, TMG is shown to be a non-invasive method (11, 18, 19), which can be used to monitor the effects of training during a specific period or throughout the season, to detect muscle asymmetries in soccer players, basketball players and athletes (27, 30, 44, 46), lateral symmetry between dominant and non-dominant legs (60), provide information on muscle tone (64) and to detect fatigue (61).

Despite the reliability shown by this method, studies indicate that it is necessary to thoroughly follow a previously fixed protocol (10, 29, 46, 62–64) for each individual evaluation. In this sense, the recording of the radial displacement will be performed on the muscle belly after an external electrical stimulus (29). For this, the point of placement of the sensor must be taken into account, the placement of two adhesive electrodes, the duration of the electrical stimulus must be standardized at 1 millisecond of duration, of increasing intensity according to the protocol used, with varying intensity (50, 75 and 100 mAp) (68) and the recovery (periods of 10 s) between each electrical stimulus must be established (29, 64, 68).

Finally, it is important to highlight the results of the assessment of the variables TC and Dm in the biceps femoris and in the rectus femoris. As the studies (10, 64) conclude that the use of TMG for the evaluation of the contractile properties of the muscle, particularly for Dm and Tc, they can be an indicative to individualise the load and intensity of work. Therefore, TMG data (29, 61, 62, 64) can be used to individualize training programs, the intensity, to monitor the effects of neuromuscular training throughout the season and adjust the training load.

4.5 Strengths, limitations, and future lines of research

Our scientific research on a systematic review of original studies of diagnostic tests evidences the importance of conducting an assessment to identify the different risk factors for injury and to individualize training programs.

The sport modality, the sample, the terminology, the way to classify sports injuries and the technologies used, as it usually occurs in all the studies of similar characteristics, can be considered as limitations, as the election of some implies the rejection of others which could provide other type of data of wide interest.

The review could be biased when the bibliographic research was only carried out in classified magazines, having been rejected some published interventions which could have fulfilled the rest of the fixed requisites to be included.

It should be pointed out that the conclusions provided by our review have been carried out according to the articles found by our search strategy and selected under our eligibility criteria; therefore, there always exists the probability that there are studies which because of classification problems or search limits have not been included in this systematic review.

Future research should investigate the effectiveness of tests and assessment technologies for use in the injury rehabilitation process. Future studies should also investigate the effectiveness of a wider range of assessment technologies and test, which allow for the identification and detection of injury risk, as well as fatigue monitoring. Further studies are needed to evaluate the effectiveness of assessment technologies to individualize recovery.

5 Practical applications

We must note the importance of the assessment through valid and reliable technologies to identify the different injury risk factors. The CMJ can be used to assess lower limb power capacity unilaterally or bilaterally, to monitor athletes' adaptations to training programs through measurements based on flight time, contact time and height. In addition, it can be used to detect asymmetries, indicating that a threshold of 10%–15% of vertical jump height asymmetry between limbs can be considered the physiological norm in players, and to assess neuromuscular fatigue. FMS can be used to assess the quality of fundamental movement patterns and identify an individual's limitations as a potential risk factor for injury, through 7 exercises with a score of 0, 1, 2 and 3. Thus, the assessment of the different results which use FMS, shows that the participants with scores $\leq$14 have a significantly higher probability of injury compared to those with higher scores. TMG can be used for muscle assessment, particularly using Tc and Dm variables, with a variable intensity protocol (50, 75 and 100 mAp), and periods of 10 s between consecutive measurements, allowing individualization of training programs. Furthermore, inadequate strength and fatigue are risk factors for injury, so eccentric strength development should be considered as a component of programs designed to reduce injury risk. Therefore, quantification of neuromuscular deficits is essential to identify individuals who may be at risk for injury.

6 Conclusions

The results of this systematic review of the different studies presents the evidence of the technologies CMJ, FMS, and TMG, for the assessment of sports injuries. The CMJ vertical jump allows us to evaluate the power capacity of the lower extremities, both unilaterally and bilaterally, detect neuromuscular asymmetries and evaluate fatigue. Likewise, FMS could be used to assess an athlete's basic movement patterns, mobility and postural stability. Finally, TMG is a non-invasive method to assess the contractile properties of superficial muscles, monitor the effects of training, detect muscle asymmetries, symmetries, provide information on muscle tone and evaluate fatigue. Therefore, they should be considered as assessment tests and technologies to individualize training programs and identify injury risk factors.

Data availability statement

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

Author contributions

ÁV-S: Writing – original draft, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – review & editing. AB-C: Project administration, Resources, Software, Supervision, Writing – original draft. JA-I: Supervision, Writing – review & editing. JC-G: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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Anterior cruciate ligament rehabilitation and return to sport in rock climbing athletes: a practical concept paper

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Background: Acute ACL tears are becoming increasingly common among rock climbing athletes, particularly those who engage in bouldering.
Hypothesis/purpose: The purpose of the paper was to develop a rehabilitation and return to sport protocol for rock climbing athletes after an anterior cruciate ligament reconstruction.
Study design: The protocol is designed in 6 phases and emphasizes the importance of sport-specific postoperative rehabilitation protocols that address the unique needs of rock climbing athletes and stresses the need for sport-specific training prior to returning to full activity.
Methods: The proposed rehabilitation protocol follows the stages of typical postoperative ACL protocols but with an emphasis on climbing-specific demands, such as eccentric landing mechanics and penduluming into a wall during lead climbing.
Results: Climbers will be able to utilize the protocol to return to rock climbing.
Conclusion: This paper highlights the need for further research on the topic and provides a foundation for future studies examining ACL tears in climbing athletes.

KEYWORDS
ACL, bouldering, rock climbing, protocol, return to sport

Background

ACL tears are becoming an increasingly more common acute lower body injury in rock climbing, in particular within the discipline of bouldering (1). In a 4-year study of 71 patients with acute knee injuries in rock climbing, 7 ACL tears were reported bouldering, accounting for 9.1% of all acute lower body injuries (2). Although less common than medial meniscal tears and iliotibial band sprains, ACL injuries were the third most common acute knee injury reported in climbing (2). In contrast, ACL injuries in female soccer players, a sport with a reported high incidence of acute ACL ruptures have shown in studies to account for 6.6% of all acute lower body injuries (3). Although the increased prevalence of acute ACL injuries in bouldering compared to soccer may seem surprising, it shouldn't be, given the mechanical demands on the knee while falling during bouldering. Climbers often fall from height in uncontrolled positions, and it has been shown that insufficient landing control with immediate valgus loading is a contributing factor in the ACL injury mechanism (4).

In bouldering over ninety percent of injuries that caused at least a partial tear of the ACL resulted from a fall to the ground (1). Acute non-contact ACL tears falling from bouldering occur much differently when compared to court and field sports where the majority of ACL tears occur from a sudden deceleration prior to a change of direction (5). Boulderers must control high velocity landings on the ground from up to 3 meters while court and field athletes commonly need to control changes of direction at high speeds. Post-operative return-to-sport testing and training in court and field sports typically involve assessing distance, time, and movement performance in a variety of tasks, such as jogging, cutting, and multi-directional jumping. However, these assessments often overlook the eccentric component of landing from heights, such as the act of falling from a boulder problem and onto pad or uneven surface. Since the demands on the knee during bouldering and court/field sports are considerably different, it is important that post operative ACL protocols address the differences; both in sport-specific training and return to sport criteria. In addition to falls that occur during bouldering, the knee is also subjected to increased mechanical stress during lead falls in lead climbing. Lead climbing is a discipline in which the climber ascends while clipping the rope into protection points below them, which can result in longer falls that often involve a pendulum-like swing and impact with the wall (6). Therefore, a comprehensive post-operative return-to-sport training and testing program has been proposed for both bouldering and lead climbing. A recent publication on ACL injuries in climbing and bouldering named the following physical therapy goals: improvement of range of motion, muscle strengthening, and dynamic stability exercises progressing to functional performance (2). However, no detailed postoperative physical therapy protocol was suggested up to date. Further, no sport-specific return to sports test are available for climbing and bouldering yet; although they have been suggested for other climbing related injuries such as acute hamstring strains and growth plate fractures (7, 8). Therefore, we now aimed to introduce a postoperative rehabilitation protocol as well as sports specific return to climbing tests for rock climbing athletes following ACL repair/reconstruction.

Post operative ACL reconstruction protocol for climbing athletes

The below is a post operative ACL reconstruction protocol for climbing specific rehabilitation. This protocol is a suggested guideline that can be used with the climber's post operative protocol. Phases are listed with estimated timeframes and criteria are given for phase progression. Rehabilitation progressions may vary based on the unique characteristics of each climber, the specific type of graft used during the operation, and any concurrent operations that may have been performed (i.e., meniscus repair). The protocol focuses on phase based rehabilitation with specific progression criteria rather than time based rehabilitation since there is considerable individual differences in biological healing, impairment resolution, neuromuscular control, functional skills, and psychological readiness with patients after ACL reconstruction (9). Suggested minimum timeframes for return to sport are provided to protect high functioning climbers from returning to sport too soon Table 1 (10).

Phase 1 (0–4 weeks)—early post operative

During the early postoperative phase, the interventions primarily revolve around pain management, edema control, range of motion, gait training, proprioception, and neuromuscular re-education. Alongside the standard postoperative interventions, it is important to prioritize early attention toward improving ankle and hip mobility. Research has highlighted the potential link between restrictions in dorsiflexion range of motion and an elevated risk of ACL injury due to altered landing mechanics and heightened ground reaction forces (11). Additionally, hip flexibility into abduction and flexion has been linked to rock climbing performance (12–14) and the greater amount of hip motion a climber can achieve, the less likely the knee joint will be stressed during end range motions.

Finger strength is a strong predictor for climbing performance (14) so it is important to keep the fingers conditioned for climbing while rehabilitating from an ACL surgery. Over 40 percent of rock-climbing injuries occur in the hand and fingers (15). Climbers are restricted from climbing during the early stages of rehabilitation, so are recommended to maintain their finger strength by performing seated or supine gripping exercises. These can be progressed to standing and using a portable fingerboard at their side. Once the climber has demonstrated appropriate wound healing and has demonstrated that they are comfortable hanging, they can initiate fingerboard training. The fingerboard is suggested to be mounted at a height that allows the climber to reach without lifting their legs off the ground. The proposed criteria for advancing to the next phase include achieving full active range of motion of knee extension and passive range of motion of knee flexion up to 90 degrees.

Phase 2 (4–8 weeks)—late post operative

During the late postoperative phase the climber continues to improve range of motion and begins conditioning of the knee extensors, knee flexors, ankle plantar flexors, hip abductors, and hip extensors and increases the challenge of the proprioceptive, balance, and neuromuscular re-education exercises (16).

Shoulder girdle muscle endurance are a strong predictor for climbing performance (14) and the shoulder is second most injured climbing body region (17), so it is important to keep the upper body conditioned for climbing. During this phase, climbers are encouraged to maintain upper body endurance by performing pull-ups and 90-degree elbow flexion bent arm

TABLE 1 Post operative ACL reconstruction protocol for climbing athletes.

Phase	Intervention focus	Climbing specific activities	Phase goals: criteria for phase progression
Phase 1: (0–4 weeks) Early Post Operative	• Reduce pain • Decrease swelling • Initiate proprioceptive, balance, and neuromuscular re-education exercises • Gait train • Perform passive and active mobilizations of the tibiofemoral and patella femoral joint • Improve hip mobility (flexion and abduction) • Improve ankle mobility (dorsiflexion)	• Initiate seated or supine finger training • It is recommended that climbers wait until wound healing is complete to begin hangboarding	• Full knee extension AROM • Knee flexion PROM to 90°
Phase 2: (4–8 weeks) Late Post Operative	• Continue to improve range of motion • Improve conditioning of the knee extensors, knee flexors, ankle plantar flexors, hip abductors, and hip extensors • Increase challenge of proprioceptive, balance, and neuromuscular re-education exercises • Maintain/build finger strength and shoulder girdle strength for climbing • Initiate climbing movement specific isolated exercises • Improve upper extremity assisted step up ability	• Hanging shoulder girdle strength and endurance exercises • Initiation of hamstring strength heel hook training (if no contraindications) • Initiation of high step training starting at 10 cm	• Adapted Grant Foot Raise 80% • High Step Pull 0.5 meters×10 • Able to ascend 6 flights of stairs skipping 1 step each stride • Knee effusion ≤1+ with sweep test • Active range of motion knee flexion 90% of uninvolved side • Two weeks of single limb balance proprioceptive exercises with upper and lower extremity movement with the knee extended and flexed • Knee extensor, knee flexor, and hip abductor dynamometer MVIC > 70% of opposite leg
Phase 3: (8–16 weeks) Early Strengthening	• Initiate low risk vertical climbing movement • Improve strength of the knee extensors, knee flexors, ankle plantarflexors, hip abductors, and hip extensors	• Start top roping 3 grades below (VIII -> VI) estimated top rope ability on the UIAA scale (recommend to initiate after at least 12 weeks)	• Knee extensor, knee flexor, and hip abductor dynamometer MVIC 80% of uninvolved • At least 80% limb symmetry with single leg squat repetitions to 60 degrees of knee flexion with adequate control and quality • Y Balance anterior and posteromedial within 4 cm
Phase 4: (16–24 weeks) Late Strengthening	• Incorporate low risk lateral climbing movement • Regain quadruped weight bearing movement and coordination • Increase intensity and exercise selection challenge of the knee extensors, knee flexors, ankle plantarflexors, hip abductors, and hip extensors • Education on fall technique • Initiate beginner landing and plyometric training	• Submaximal boulder traversing no greater than.5 meters off the ground. Hinge stabilization brace recommended. • Top rope challenge progressed to 2 grades below (VIII -> VII+) top rope ability on the UIAA scale • Closed kinetic chain upper extremity and quadruped exercises mimicking climbing movements • Early stage landing training. Begin at low heights and progress up to 0.5 meters	• ACL-RSI ≥ 56 Points • Drop Hang score 90% • Lead Fall score 100% • Limb symmetry index of 85% with single hop for distance, 6-meter timed hop, triple hop for distance, and crossover hop for distance • Knee extensor, knee flexor, and hip abductor dynamometer MVIC 85% of uninvolved • Single limb leg press 85% of uninvolved
Phase 5: (24–36 weeks) Return to Sport	• Retrain proper landing mechanics (both boulder and lead climbing) • Strengthen and coordinate climbing specific movements • Progress to intermediate landing and plyometric training	• Start lead climbing 3 grades below (VIII -> VI) current top rope ability on the UIAA scale • Start vertical "no fall" bouldering two grades below (V8 -> V6) estimated bouldering ability • Drop knee training • Allowed to challenge climbing specific exercise technique practice on the wall in controlled situations with top rope. i.e., heel hook, high step, drop knee and progressing into utilizing those movements in bouldering and/or lead climbing • Landing training progression	• At least 9 months post operative • Maintains consistency with performing either strength training and plyometric training at least 3 times per week • Can demonstrate heel hooks, high steps, and drop knees while bouldering and/or lead climbing • Demonstrates ability to climb up to ability level for lead or bouldering • ACL RSI with a score of 75 points or greater • Limb symmetry index of ≥90% of uninvolved with hop testing • Knee extensor, knee flexor, and hip abductor MVIC ≥ 90% of uninvolved • Single limb leg press ≥ 90% of uninvolved

(*Continued*)

TABLE 1 Continued

Phase	Intervention focus	Climbing specific activities	Phase goals: criteria for phase progression
Phase 6: (36+ weeks) Return to Performance	• It is recommended that this phase begins no sooner than 36 weeks post operatively • Lower limb depth jumping at great heights • Advanced strengthening with proprioceptive challenge • Progress to advanced landing and plyometric training	• Competition lead climbing • Project lead climbing • Competition bouldering • (recommend to initiate after at least 12 months) • Projecting bouldering (recommend to avoid boulder problems over 3 meters until at least 12 months)	• The climber is recommend to continue performing therapeutic exercise up to 3 years after surgery to reduce the risk of reoccurrence of ACL injury

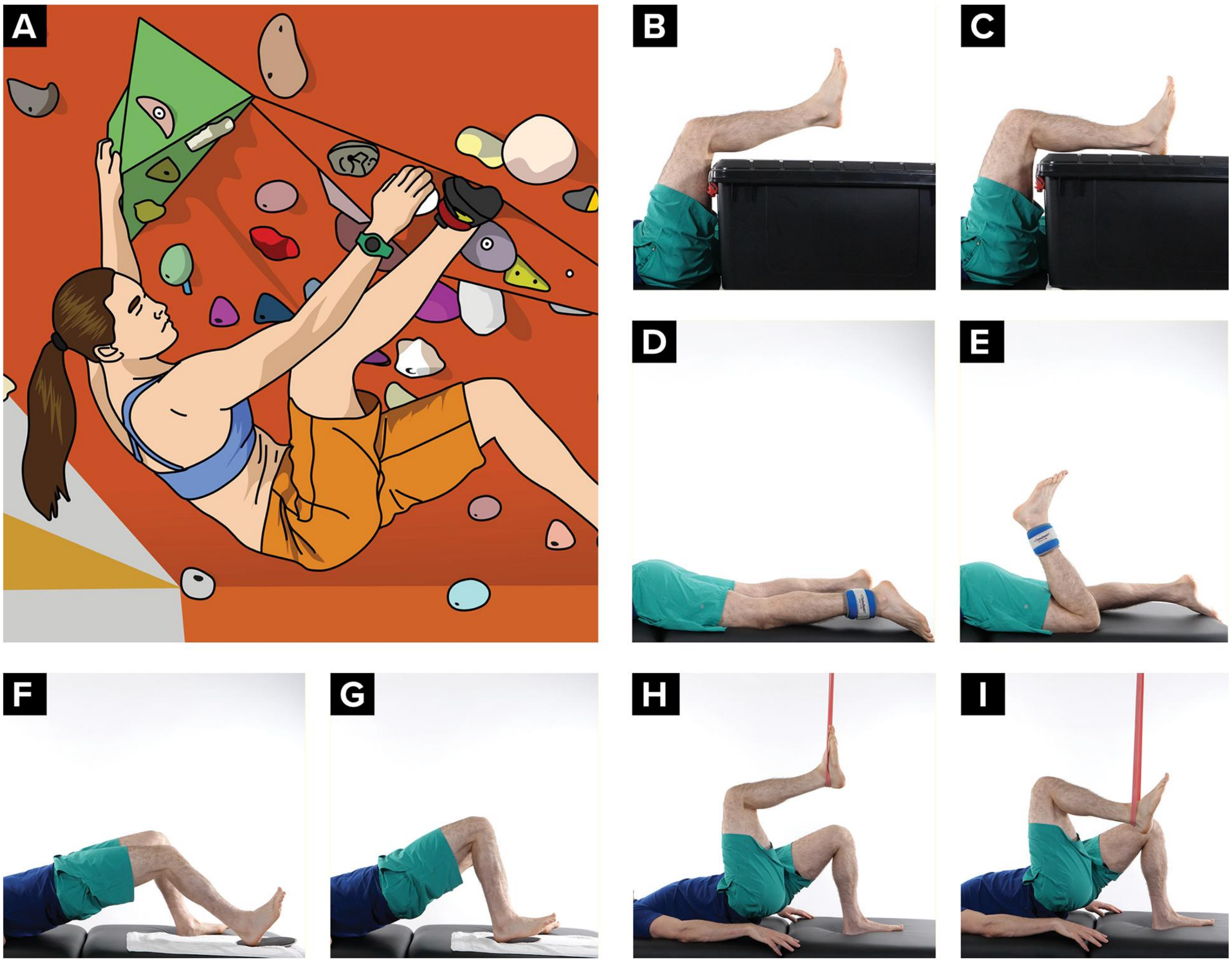

FIGURE 1
Heel hook progressive exercises. **(A)** Climber using a heel hook, **(B,C)** Hamstring exercise with hip flexed, **(D,E)** Hamstring exercise with hip extended, **(F,G)** Hamstring exercise in a double limb bridge, **(H,I)** Hamstring exercise in a single limb bridge.

hangs. The pull-up bar is suggested to be mounted at a height that allows the climber to reach them without lifting their legs off the ground.

Climbers can begin focusing on early climbing specific lower extremity flexion and extension activities such as conditioning the hamstrings to pull (for a heel hook position) and conditioning the quadriceps and hip extensors to push (stepping up into a high step).

A heel hook uses the lower extremity in a pulling fashion to help stabilize a climber, prevent extraneous body movement, or pull them further up the wall. The posterior aspect of the heel creates pressure and friction on a hold (Figure 1A) (18). This movement places significant force on the hamstrings and often places the climber's lower extremity in a position of external rotation. Since the hamstring provides control of tibial anterior translation, it is important to initiate hamstring strengthening early in the rehabilitation process (unless contraindicated until later with surgical precautions or a hamstring autograft). Exercises should begin with low velocity hamstring strengthening and progress to high load strengthening and functional reconditioning (7). In the early stages a climber can start with small range active knee flexion with hip flexion (Figures 1B,C) and then progress toward prone weighted full range knee flexion (Figures 1D,E). In the later stages of recovery, exercises can be progressed toward double limb bridging with slider (or exercise ball) curls (Figures 1F,G) and single limb bridging with resistance band curls (Figures 1H,I). The climber is encouraged to vary their hip position in the frontal plane (abduction and adduction), their ankle position in the sagittal plane (plantarflexion and dorsiflexion), and their tibial position in the transverse plane (medial rotation and lateral rotation) to mimic the positions while heel hooking on the rock wall.

A high step is used during climbing when there is a high foothold that a climber needs to place their foot on to so that they can make the next move. A high step requires adequate ipsilateral hip flexion and abduction, and contralateral hip extension. To simulate the demands on the knee during a high step maneuver the climber is encouraged to use upper extremity support with suspension straps and portable fingerboards attached and then vary the challenge (Figure 2). The climber can start at a step of 10 centimeters and progress up to 0.5 meters.

The suggested criteria for progressing to the next phase include the knee effusion ≤1+ with the sweep test, active knee flexion range of motion at 90% of the uninvolved side, two weeks of single-limb balance proprioceptive exercises involving upper and lower extremity movements with both extended and flexed knees, and knee extensor, knee flexor, and hip abductor dynamometer maximum voluntary isometric contraction (MVIC) measurements exceeding 70% of the unaffected side. Additionally, the climber needs to demonstrate the capability to execute 10 repetitions of a high step pull at a height of 0.5 meters. However, it is important to consider the possibility that a climber might rely excessively on their upper extremities while performing the high step pull. To address this potential concern, they must also exhibit the proficiency to ascend 6 flights of stairs, skipping 1 step with each stride. This stair-climbing test aims to replicate the uncompensated strength of the lower extremity, simulating the approximate vertical gain encountered during an indoor climbing route. Furthermore, a standardized assessment known as the Adapted Grant Foot Raise is recommended to evaluate high step mobility, a critical aspect for determining the climber's readiness to progress to the subsequent phase of top rope climbing (13). In this evaluation, the climber positions themselves 23 centimeters away from a wall, places their hands on the wall beyond shoulder width, and elevates their foot using a sliding motion to attain maximal hip flexion. The resulting height reached is measured, and it is expected that the achieved height falls within 80% of the maximal height on each side (Figure 3).

Phase 3 (8–16 weeks)—early strengthening

The climber focuses on improving the strength of various muscle groups, including knee extensors, knee flexors, ankle plantar flexors, hip abductors, and hip extensors. Once the climber has achieved the milestones outlined in phase two and are minimum of 12 weeks post operative, clearance can be granted for climbing on vertical rock surfaces (where high stepping is frequently required), particularly on low-risk overhang routes secured by a top rope at a difficulty of three grades below (VIII -> VI) the climber's estimated top rope ability on the International Union of Alpine Associations (UIAA) scale. Climbers are recommended to use a hinged functional brace when they first start top rope climbing. The choice of beginning with overhang climbing before transitioning

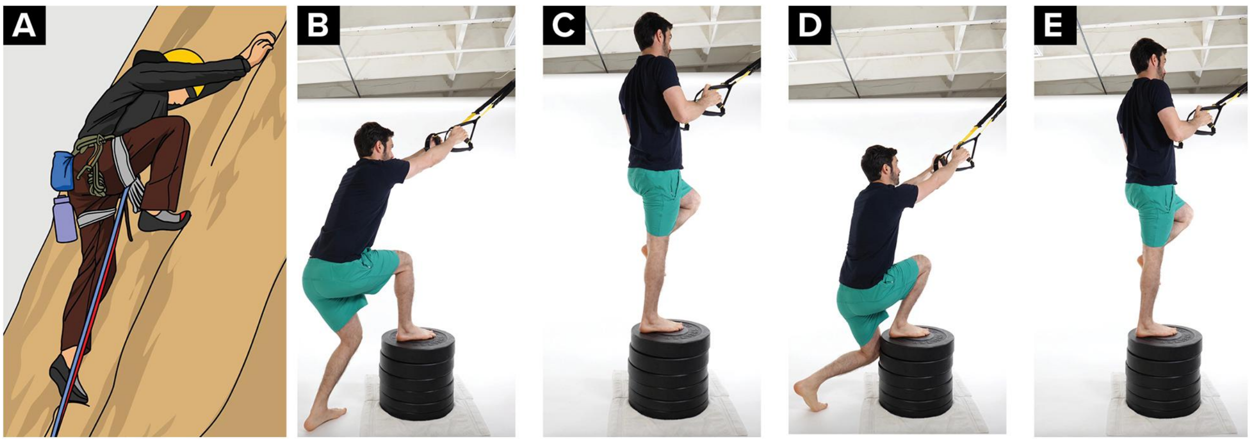

FIGURE 2
High step progressive exercises. **(A)** Climber performing a high step, **(B,C)** climber performing a high step and pull exercise with hip and knee flexed to 90 degrees in the starting position, **(D,E)** climber performing the exercise with greater amounts of hip and knee flexion in the starting position.

FIGURE 3
Drop knee progressive exercises. Adapted grant foot raise performed by a climber.

to vertical climbing aims to reduce the likelihood of foot entanglement with the rock wall in the event of a fall or an awkward step.

The suggested criteria to progress to the next phase are knee extensor, knee flexor, and hip abductor MVIC within 80% on dynamometry, and at least 80% limb symmetry with adequate motor control (defined as absence of trunk lean, knee valgus, and loss of balance) during single leg squats to 60 degrees of knee flexion. Previous research has indicated that individuals who have undergone ACL reconstruction who exhibit Y Balance Test deficits exceeding 4 cm are less likely to attain a limb symmetry index of 90% during hop testing (19). Considering these findings, an additional criterion of a Y balance test within a 4 cm range should be incorporated into the phase progression criteria. This criterion holds particular significance, given the next phase's clearance for boulder traversing—an activity demanding dynamic single-leg balance and outward reach capabilities.

Phase 4 (16–24 weeks)—late strengthening

In this phase, the climber elevates the intensity and diversifies the selection of exercises to increase the demands on the knee extensors, knee flexors, ankle plantar flexors, hip abductors, and hip extensors. It is recommended to perform closed kinetic chain upper extremity exercises targeting the shoulder girdle and adjacent musculature with suspension equipment and weight bearing quadruped exercises that mimic rock climbing movement. Suspension training exercises have been shown to have greater levels of muscle activation (measured via electromyographic signal intensity) when compared to floor exercises (Figures 4A,B) (20) which is a benefit in rock climbing movements that require high levels of muscular demand. Quadruped exercises such as bear birddog mimic the cross-body movements (left arm reach, right leg extension) that are similar to climbing (Figures 4C,D).

Furthermore, the climber is recommended to initiate beginner plyometric jumps and landing training. This includes “drop hang training” where the climber hangs from a pull-up bar (or steps off from a box), releases their grip, and lands into a 90-degree knee flexion angle squat (Figure 5). Drop hang training begins at a height of 10 centimeters at the start of the phase and progresses up to 0.5 meters by the end of the phase. Foot positions can vary to train the variation during boulder landing. This “drop hang training” will eventually utilize a standardized scoring criteria that a climber will need to achieve progress to the next phase (Table 2).

The climber is cleared for boulder traversing or treadwall climbing in this phase. Boulder traversing is lateral climbing at a height of 0.5 meters from the ground. Climbers should take into consideration the ACL stresses of tibial external rotation during boulder traversing (21) and are recommended to use a hinged functional brace both as a psychological reminder to not step off or fall on the affected leg and to provide additional stability to the healing ligament. Previous studies have shown the benefits of early-stage neuromuscular control exercises in the rehabilitation of post operative ACL injuries (22). So as long as the climber maintains a safe boulder traverse height, wears a brace, and is trained to step off the boulder with their non-surgical limb, submaximal boulder traversing is considered safe.

Additionally, in the case the climber does fall onto their feet, they should be taught how to help attenuate the force on

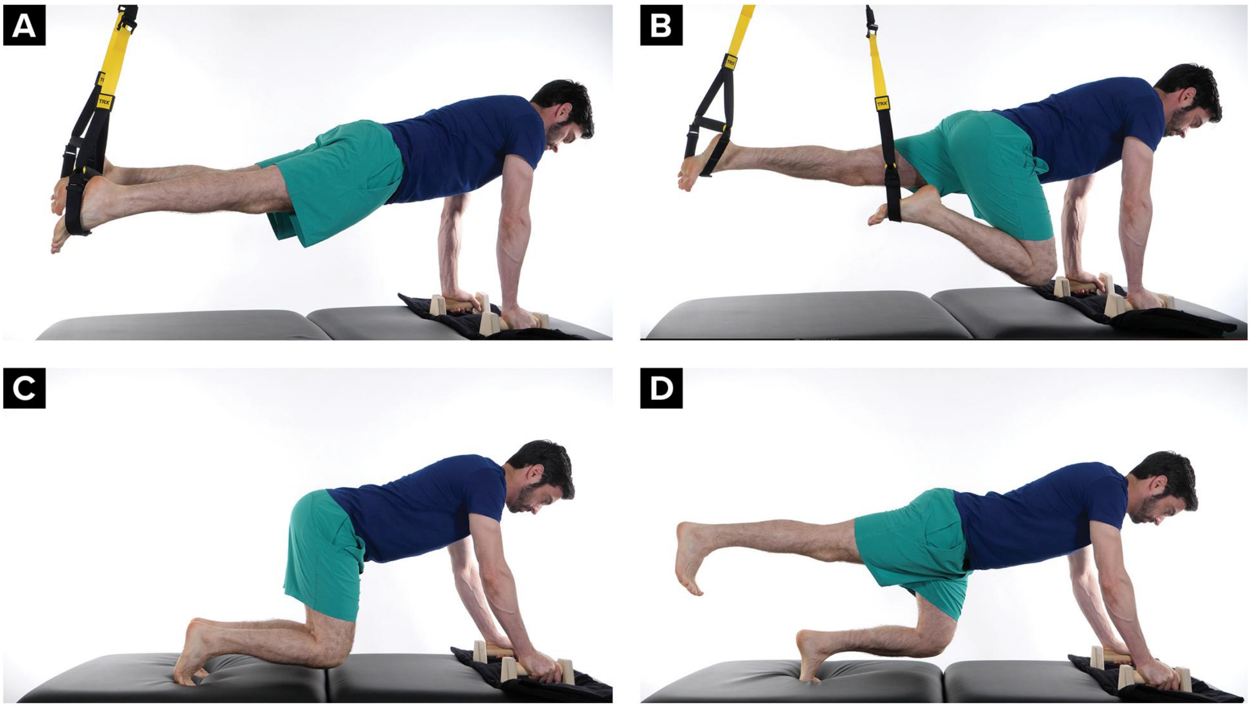

FIGURE 4
Closed kinetic chain upper extremity and quadruped exercises mimicking climbing movements (A,B) suspension training in a plank position with lower extremity movement, (C,D) quadruped bear position with lower body movement.

FIGURE 5
Image of a climber performing drop hang testing and training.

the knee with the four steps for falling on their back; stay relaxed, bend knees and arms, tuck arms in, and roll back (Figure 6).

The climber will also be educated on how fall on their side. The climber will be educated if they fall toward one side to look at the landing zone, bend knees and arms, tuck arms in, and let the pads do the work (Figure 7). Climbers should be cautioned to not lock their knees while landing and to not use their upper extremity to break the fall.

Once the climber has acknowledged they understand fall technique, they can be coached from a squatting position how to control a roll onto their back and side in the case they fall off the wall and are unable to land on their back while boulder traversing.

TABLE 2 Drop hang scoring system (five drops per level).

Level	Description	
Level 1	Release grip and land on bouldering pad with both legs neutral	
Level 2	Release grip and land on bouldering pad with operative leg in front of non-operative leg	
Level 3	Release grip and land on bouldering pad with non-operative leg in front of operative leg	
Criteria	**Yes (1)**	**No (0)**
Knee flexion angle is ≥90°		
Performs repetitions without dynamic knee valgus (patella falls medial to the great toe)		
Lands with the correct foot orientation		
Rolls onto their backside		

Total Points: _______/20.

The suggested criteria to progress to the next phase (return to climbing) includes the following: ≥56 points on the ACL return to sport after injury, 90% score on the 18 inch (0.5 meter) Drop Hang Test, 100% score on the Lead Fall Test, and a limb symmetry index of 85% with single hop for distance, 6-meter timed hop, triple hop for distance, and crossover hop for distance. Additionally, knee extensor, knee flexor, and hip abductor dynamometer peak force within 85%, single limb leg press at 85% of the non-surgical leg. If the climber meets these criteria and has reached a minimum of 24 weeks post-operation, they are eligible to progress to the next phase, which encompasses "no fall" bouldering and lead climbing.

ACL—return to sport after injury (ACL-RSI)

It has been shown that athletes who have undergone ACL reconstruction surgery have high levels of fear-avoidance and

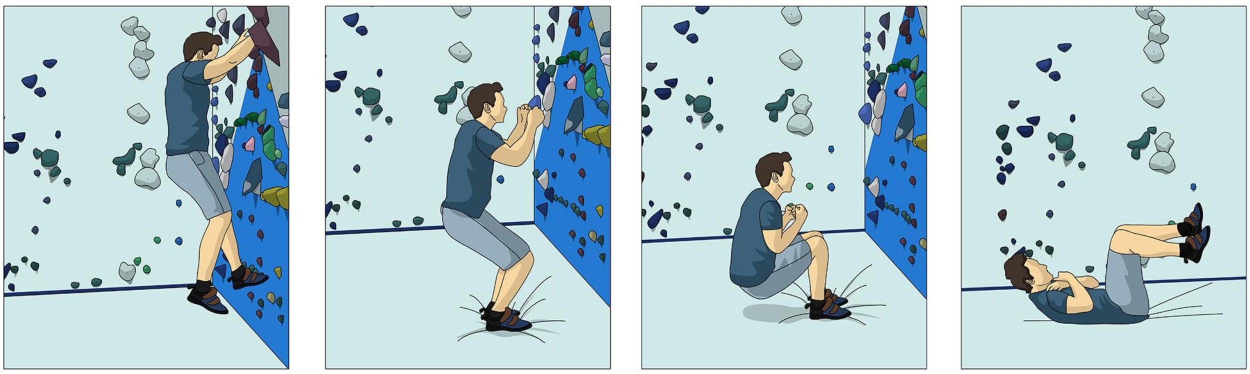

FIGURE 6
Backward falling from a boulder problem.

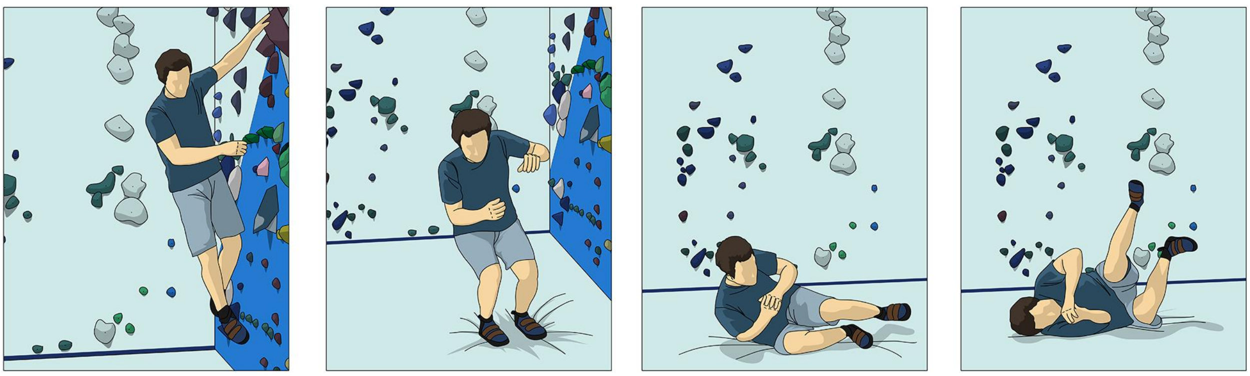

FIGURE 7
Sideways falling from a boulder problem.

anxiety with returning to sport (23). If a climber is fearful when returning to climbing and the psychological components are not addressed beforehand, they may overgrip, poorly sequence movements, or struggle on moves they are physically capable of performing. In climbing, this can increase stress on the operative leg or result in a catastrophic fall. It is for these reasons that psychological testing should be performed for all climbing athletes to determine their readiness to return to sport. It is recommended that climbers achieve a score of ≥56 points on the ACL RSI before proceeding with Drop Hang Testing, Lead Fall Testing, and advancing to the subsequent phase to return back to boulder and lead climbing (24).

Drop hang scoring

Research has shown that hop testing, such as single hop for distance, 6-meter timed hop, triple hop for distance, and crossover hop for distance, are reliable and valid performance-based outcome measures for return to sport after ACL reconstruction in court/field sports (25). Additionally, tests involving movements such as squatting, lateral bounding, jogging, and directional changes are also commonly used (26). However, although these tests provide reliable and valid performance-based outcome measures for returning patients after ACL reconstruction to court/field sports, they do not reproduce the demands needed to return back to bouldering.

The drop hang is used to determine a climber's readiness to fall safely from a boulder problem. The scoring uses a 20-point scale to grade the ability for the climber to land safely. The climber is recommended to use their climbing shoes to simulate the same environment that they would land if they fell from a boulder problem. The test requires a pull-up bar or rings and a soft-landing surface, commonly a bouldering crash pad. The climber starts by grasping the pull-up bar or rings with the elbows flexed or extended. The clinician will then adjust the rings or have the climber flex their elbows until their feet lift to 0.5 meters from the pad (Figure 5—at an increased height). If the set-up is difficult to adjust, a stable 0.5 meters surface to step backwards off can be used instead.

The climber will release their grip and land onto the pad five times while the clinician scores them based on four criteria: knee flexion angle, knee stability, accuracy of landing, and ability to attenuate shock by rolling onto their backside. Each category earns the climber 1 point for each repetition that meets the criteria.

The clinician will test the climber in three different levels: a neutral stance (level 1), operative leg in front of non-operative leg with the toe of the back foot aligned with the heel of the front foot (level 2) and non-operative leg in front of operative leg with the toe of the back foot aligned with the heel of the front foot (level 3). Climbers will start at level one and must score a minimum of 18 out of 20 points (90%) to advance to the next level (Table 2).

Prior to initiating drop hang testing, climbers should have advanced beyond the initial stage of landing training. This advancement entails performing box step-offs and systematically elevating the height until they have attained a sense of ease landing from 0.5 meters in a squat position in a variety of foot positions.

TABLE 3 Lead fall scoring system.

Criteria	Yes (4)	No (0)
Knee flexion angle is ≥60°		
Hip flexion angle is ≥60°		
Demonstrates appropriate technique and safety considerations of identifying the fall zone		
Keeps the rope between the climber and the wall		
Exhales upon release and keeps a relaxed body		

Total Points: _______/20.

Lead fall scoring

A lead fall test is used to determine the climber's readiness to return to lead climbing. It is scored on a 20-point scale and requires the climber to have access to a lead climbing route and a belaying partner who can catch their lead fall.

The climber is advised to begin with a graded progression of clipping and falling on overhung routes with the last quick draw at the level of the hip, knee, and then foot level. Once the climber can safely demonstrate this progression, they can progress to a pendulum fall on a vertical or slightly overhung terrain.

For each category in the scoring system, the climber receives 4 points if they meet the specified criteria. The climber must score 20/20 (100%) to pass the test. If there are pre-existing or other physical impairments, some leeway may need to be allowed for the test (Table 3).

Phase 5 (24–36 weeks)—return to sport

Returning to lead climbing and bouldering should be approached with caution because of the possible fall risk. Although the window to enter phase 5 starts at 6 months, many climbers don't achieve the needed milestones to return to climbing until closer to 9 months. Between 6 and 9 months post-operative, each month of delayed return to sport may decrease the risk of re-injury by 51% (10).

However, once the climber has achieved the necessary milestones and has entered this stage, they are cleared to lead climb 3 grades below (VIII -> VI) current top rope ability on the UIAA scale and are cleared to boulder 2 grades below their projected bouldering ability (V8 -> V6). The climber is cautioned to climb only boulder routes where they will not fall. The climber is encouraged to return to climbing first indoors in a controlled environment and then progress toward outdoor climbing.

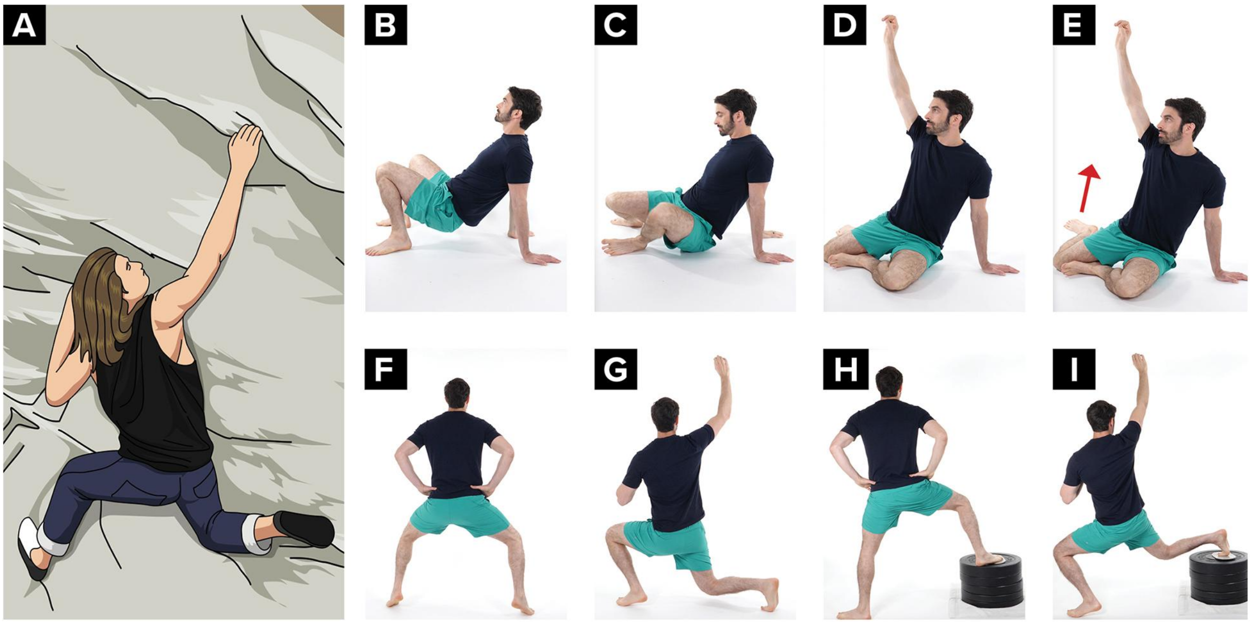

FIGURE 8
Drop knee progression from sitting, to standing, to an elevated foot (A) climber demonstrating a drop knee, (B–E) on the ground hip internal rotation exercise, (F,G) standing drop knee exercise, (H,I) standing drop knee exercise progression with foot on an elevated surface.

The climber is encouraged to begin training the knee to withstand the controlled valgus stresses that may occur during a climbing movement called a drop knee. A drop knee is used while climbing when there are two foot holds that need to be utilized with opposing foot pressure. The climber puts their weight on the outside of one foot, rotates their hip in toward the wall and lowers their knee; the opposite foot presses against an opposing hold for support. A drop knee requires adequate rectus femoris muscle length and adequate hip internal range of motion. A drop knee can be trained starting on the ground with the hip and knee bend to 90 degrees and then progressed into squat standing, and then with the foot on an elevated the surface (Figure 8).

Drop knees, heel hooks, high steps, and falls have all been shown to be the primary mechanism acute knee injuries (2). So in addition to adding drop knee specific exercise progressions, climbers are encouraged to begin slowly and conservatively utilizing drop knees, high steps, and heel hook progressions from maximum assistance to minimum assistance while climbing.

Progressing landing training in a variety of environments is an essential component of returning to boulder training. A heavy emphasis should be placed on controlled fall practice. This includes controlling the height, base of support, strategy, and landing surface, in addition to providing cueing to help attenuate shock and technique training to improve protective mechanisms while falling. Drop hang training can be challenged by increasing the height. The base of support can be progressed from wide, to narrow, with variations of symmetric/offset alignment and neutral/toed out foot position. Landing strategy can be progressed from a forward trunk lean to an upright trunk position. Starting with a forward trunk lean helps to distribute forces in the gluteal muscles, while progressing to a more upright trunk landing position helps to distribute forces to the knee extensor mechanism (27). Climbers are cued to land softly as this has been shown as an external verbal cue that helps decrease loads on the ACL when landing (28).

The suggested criteria to progress to the next phase are that the climber is least 9 months post operative, ACL RSI with a score of 75 points or greater, maintains consistency with performing either strength training and plyometric training at least 3 times per week, can demonstrate heel hooks, high steps, and drop knees while bouldering and/or lead climbing, and demonstrates the ability to climb up to ability level for lead or bouldering.

While much of this phase emphasizes movement specific loading, fall retraining, and psychological readiness, it is equally important to consider the broader physical and physiological demands of climbing. Although climbing is not typically classified as an aerobic sport, research has shown that both lead climbing and bouldering place meaningful demands on the cardiovascular and respiratory systems, including increased heart rate, elevated oxygen uptake, and tidal volume constraints (29, 30). Additionally, fatigue can negatively impact technique, motor control, and decision making, and has been shown to be a risk factor related to ACL injuries (31). Therefore, return to sport programming should incorporate simulated maximal effort climbing in safe, controlled environments, such as low to the ground bouldering and top rope scenarios for lead climbers, to prepare athletes for the intensity of full height bouldering and lead climbing.

Phase 6 (36+ weeks)—return to performance

At this stage the climber's limb symmetry index with hop testing, MVIC, and single limb leg press should all be greater than or equal to 90% of the uninvolved leg. It is encouraged to continue performing therapeutic exercise up to 3 years after surgery to reduce the risk of reoccurrence of ACL injury. This includes advanced strengthening with proprioceptive challenge, advanced landing training, and advanced plyometric drills. Rehabilitation includes lower limb fall practice at great levels of challenge, plyometric training, and advanced strengthening with proprioceptive challenges. The climber works toward competition lead climbing and project lead climbing. It is recommended to begin competition and project bouldering no sooner than 12 months and to refrain from attempting boulder problems exceeding 3 meters in height.

Conclusions

ACL tears are a growing concern in rock climbing, particularly in bouldering, and a comprehensive postoperative rehabilitation protocol with sport-specific return-to-sport testing is necessary to address the unique demands of the sport. Our research detailed a new rehabilitation protocol for climbers following ACL reconstruction, including return-to-sport tests tailored to the physical demands of both bouldering and lead climbing. These tests account for climbing-specific variables such as eccentric landing mechanics and pendulum-style falls during lead climbing. Early use of the protocol with individual climbers has shown promise (32). Further studies are needed to evaluate its safety and effectiveness.

Data availability statement

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

Ethics statement

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

JV: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. VS: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. JO: Project administration, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. WP: Writing – original draft, Writing – review & editing. CL: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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