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Functional kinesiology in health and performance

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Functional kinesiology in health and performance

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Editorial: Functional kinesiology in health and performance

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Editorial on the Research Topic
Functional kinesiology in health and performance

1 Introduction

Functional kinesiology is a discipline that plays a crucial role in promoting optimal health and athletic performance. By combining biomechanics, anatomy, physiology, psychology, and neuroscience, it provides a comprehensive framework for understanding and enhancing human movement and function. In today's era of growing interest in health and athletic achievement, functional kinesiology represents an innovative approach that goes beyond traditional methods and transforms the way we study movement science. This editorial serves as an introduction to a series of articles that explore the various aspects of functional kinesiology and its impact on both health and performance.

2 Contributing articles

2.1 Exploring muscle synergies, loading effects, and training impact

This collection of articles explores different aspects of functional kinesiology, analyzing the complex relationship between muscle synergies, loading effects, and the impact of training on human movement and performance. Researchers use a combination of empirical studies and theoretical analyses to investigate the underlying mechanisms that govern motor control strategies, biomechanical adaptations, and physiological responses to exercise stimuli.

2.2 Insights into performance optimization and injury prevention

By analyzing various training methods, loading positions, and exercise interventions, these studies provide valuable insights into optimizing performance and preventing injuries (1). Researchers investigate the immediate and long-term effects of resistance training, endurance exercise, and neuromuscular conditioning on muscle function, body composition, functional asymmetries, joint stability, and movement efficiency. The results offer evidence-based guidelines for creating effective training programs tailored to individual needs and specific sports demands, ultimately improving athletic performance, and reducing the risk of musculoskeletal injuries (2, 3).

2.3 Implications for health, wellness, and long-term athletic development

Furthermore, this research contributes to our understanding of the wider impact of functional kinesiology on health, wellness, and long-term athletic development. Researchers are exploring the psychophysiological effects of training interventions, nutritional strategies, and recovery methods to enhance the physical and mental well-being of athletes over the course of their careers. The findings emphasize the significance of taking a holistic approach to training (4) and rehabilitation, which includes not only physical conditioning but also psychological or individual resilience (5), nutritional support, and lifestyle management.

2.4 Review of functional kinesiology in athletes

This section examines functional kinesiology research among male and female athletes of different age groups, with an emphasis on youth and adult categories. It integrates findings from various studies to provide an understanding of how kinesiological principles can enhance athletic performance and contribute to sustained health and well-being in competitive scenarios. This review highlights innovative approaches and emerging data linking functional kinesiology to improved athletic health and performance metrics.

2.5 Exploring the quality of training load and Bio-motor ability

This review focuses on examining studies that evaluate the quality of training load in athletes, specifically emphasizing bio-motor ability and wellness variables (6). By analyzing the relationship between training load metrics and performance outcomes, valuable insights are offered for optimizing training program design and workload management strategies to maximize athletic potential and minimize the risk of non-functional overreaching syndrome and injury (7).

3 Conclusion

In conclusion, this collection of articles provides a comprehensive exploration of functional kinesiology in health and performance contexts. Researchers have used a multidisciplinary approach to unravel the intricate mechanisms governing human movement and function, shedding light on the practical implications for optimizing athletic performance and promoting long-term health and well-being. These studies bridge the gap between theory and practice, paving the way for evidence-based interventions and strategies to empower athletes, coaches, and practitioners to achieve their full potential. Gratitude is extended to all the authors, reviewers, and contributors for enriching this collection with their valuable insights, and there is anticipation for further advancements in the field of functional kinesiology.

Author contributions

HN: Writing – original draft, Writing – review & editing. AF: Writing – review & editing. KJ: Writing – review & editing. EM: Writing – review & editing.

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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More than just a side effect: Dynamic knee valgus and deadbug bridging performance in youth soccer players and alpine skiers have similar absolute values and asymmetry magnitudes but differ in terms of the direction of laterality

Jonas Hanimann[1,2]*, Lynn Ellenberger[1,2,3], Thomas Bernhard[4,5], Martino V. Franchi[6], Ralf Roth[4], Oliver Faude[4] and Jörg Spörri[1,2]

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From a preventative perspective, leg axis and core stabilization capacities are important for soccer players and alpine skiers; however, due to different sport-specific demands, the role of laterality clearly differs and may result in functional long-term adaptations. The aims of this study are 1) to determine whether there are differences in leg axis and core stability between youth soccer players and alpine skiers and 2) between dominant and non-dominant sides, and 3) to explore the outcomes of applying common sport-specific asymmetry thresholds to these two distinct cohorts. Twenty-one highly trained/national-level soccer players (16.1 years, 95% CI: 15.6, 16.5) and 61 alpine skiers (15.7 years, 95% CI: 15.6, 15.8) participated in this study. Using a marker-based 3D motion capture system, dynamic knee valgus was quantified as the medial knee displacement (*MKD*) during drop jump landings, and core stability was quantified as the vertical displacement during deadbug bridging exercise ($DBB_{displacement}$). For the analysis of sports and side differences, a repeated-measures multivariate analysis of variance was used. For the interpretation of laterality, coefficients of variation (CV) and common asymmetry thresholds were applied. There were no differences in *MKD* or $DBB_{displacement}$ between soccer players and skiers or between the dominant and non-dominant sides, but there was an interaction effect side*sports for both variables (*MKD*: $p = 0.040$, $\eta^2 p = 0.052$; $DBB_{displacement}$: $p = 0.025$, $\eta^2 p = 0.061$). On average, *MKD* was larger on the non-dominant side and $DBB_{displacement}$ laterality on the dominant side in soccer players, whereas this pattern was reversed in alpine skiers. Despite similar absolute values and asymmetry magnitudes of dynamic knee valgus and deadbug bridging performance in youth soccer players and alpine skiers, the effect on the direction of laterality was opposite even though much less pronounced. This may imply that sport-specific demands and potential

laterality advantages should be considered when dealing with asymmetries in athletes.

KEYWORDS

athletes, alpine skiing, soccer, performance, injury prevention, exercise test

1 Introduction

Humans typically prefer one side for the execution of motor tasks, hence resulting in a more skilled side, often called laterality or side dominance (Carpes et al., 2010; Maloney, 2019; Hart et al., 2020; Westin et al., 2022b). In this context, laterality describes a difference in body morphology or function (Hart et al., 2020). Several sports-related motor tasks, such as throwing or kicking, are strongly related to unilateral execution, thus manifesting in a high degree of laterality as a consequence of functional long-term adaptations (Newton et al., 2006; Parrington and Ball, 2016; Bishop et al., 2018b; Lijewski et al., 2021), while others are more symmetrical with less pronounced, but still present, laterality (e.g., running, cycling, or swimming) (Parrington and Ball, 2016; Maloney, 2019). One sport with high laterality is soccer, a globally popular team sport where physical, tactical, and technical components are crucial for team success (Stolen et al., 2005). In terms of physical demands, well-performed changes of direction are the key and have been described as the best discriminant variable among young players regarding selection into superior teams (Gil et al., 2007a; Gil M. et al., 2007b). Although fast changes of direction in soccer are made as a reaction to game situations and, therefore, are multidirectional, the dominant leg can usually perform faster change of direction maneuvers than the non-dominant leg (Rouissi et al., 2016). Another central aspect in soccer is kicking, with players favoring one limb, which is referred to as the dominant limb (DeLang et al., 2019). In total, more than 80% of the ball contacts are performed with the dominant leg (Carey et al., 2001). Hence, soccer activity is strongly characterized by the asymmetrical nature of the sport. By contrast, for athletes from alpine skiing, i.e., a more symmetric sport, less laterality can be expected. Alpine skiing places high loads on the athletes' bodies, forces up to 1.75 times their body weight on each leg (Kröll et al., 2016), combined with high knee flexion angles and valgus (Zorko et al., 2015), and enormous force and stabilization capacity are required. The interaction with snow causes vibration loads and impact-like shocks that are largely absorbed by the knee and its stabilizing muscles (Spörri et al., 2017; Supej et al., 2018). When compared to soccer, however, the physical demands are more symmetric, and thus, side dominance may play a subordinate role. Such different demands are likely to result in functional long-term adaptations that have to be considered when dealing with asymmetries in athletes.

Injuries are common in soccer players (Eirale et al., 2013; Hagglund et al., 2013). Anterior cruciate ligament (ACL) injury incidences are high (0.06–3.7 per 1,000 h of training and competition) (Bjordal et al., 1997; Fauno and Wulff Jakobsen, 2006) and predominantly occur without player-to-player contact; hence, ACL injuries are referred to as non-contact injuries (Fauno and Wulff Jakobsen, 2006; Alentorn-Geli et al., 2009). Interestingly, the dominant leg, when compared to the non-dominant leg, is commonly associated with a decreased knee flexor (i.e., hamstrings) to knee extensor (i.e., quadriceps) strength ratio (Rahnama et al., 2005) and is more frequently subjected to injuries (DeLang et al., 2021). Typical situational patterns leading to ACL injuries are indirect or non-contact situations, such as pressing/tackling, regaining balance after kicking, landing from a jump, and being approached (Della Villa et al., 2020). In this regard, the following movements are at high risk: cutting maneuvers combined with deceleration, near- or fully extended jump landings, and pivoting with an extended knee and a planted foot (Boden et al., 2000; Fauno and Wulff Jakobsen, 2006). Similarly, alpine skiers are also at high risk of sustaining knee injuries (Florenes et al., 2009; Florenes et al., 2012), whereas ACL rupture represents the most frequent diagnosis (Florenes et al., 2009). ACL injuries almost exclusively occur while skiing; they are only rarely caused by a crash (Bere et al., 2011). In this regard, the following three main injury mechanisms are defined and described in detail elsewhere: slip-catch, landing back-weighted, and dynamic snowplow (Bere et al., 2011). In brief, when turning, the skier gets out of balance before the sudden edge catch of the outside ski forcing the knee into valgus and internal rotation (slip–catch mechanism) (Bere et al., 2011). Back-weighted jump landing results from losing balance during flight and then trying to recover, when a combination of tibiofemoral compression and anterior drawer of the tibia in relation to the femur acts on the athlete's knee (Meyer and Haut, 2008; Bere et al., 2011). Dynamic snowplowing starts in a back-weighted out-of-balance situation, leading to a split position and unloaded outer ski, and the loaded ski grips on the inner edge, subsequently leading to internal rotation and valgus (Bere et al., 2011).

Considering the aforementioned sport-specific mechanisms of ACL injuries and concomitant lesions, it is reasonable to consider poor leg axis stability (i.e., extensive dynamic knee valgus) a modifiable risk factor (Hewett et al., 2006) that plays a key role in injury mechanisms (Bere et al., 2011). Medial knee displacement (*MKD*) can be reliably quantified during drop jump (DJ) landing (Paterno et al., 2010; Krosshaug et al., 2016; Leppanen et al., 2016; Ellenberger et al., 2020b). Furthermore, core stability may be preventative in the context of out-of-balance mechanisms in ACL injuries (Hewett et al., 2005; Zazulak et al., 2007). However, an objective, reliable, and valid quantification of core stability is challenging (Hibbs et al., 2008). A more holistic approach that has been proven to be suitable in the context of injury prevention is the quantification of the rear chain stabilization capacity (Ellenberger et al., 2020a). In this regard, the anti-torsional stabilization capacity is assessed through the hip axis tilt in the frontal plane during deadbug bridging ($DBB_{displacement}$) (Ellenberger et al., 2020a). Both the *MKD* during DJ landings and $DBB_{displacement}$ are preferably quantified with a motion capture system, such as the Vicon Nexus.

To what extent does high degrees of laterality influence athletic performance and the risk of injury in different sports has not yet been conclusively clarified (Knapik et al., 1991; Bourne et al., 2015;

Bishop et al., 2018b; Dos'Santos et al., 2019; Maloney, 2019; Bishop et al., 2022; Westin et al., 2022a). Traditionally, subjects with interlimb asymmetries of >10%–15% have been associated with higher injury incidences than those with such asymmetries below this threshold (Barber et al., 1990; Impellizzeri et al., 2007; Grindem et al., 2011). However, it is not *a priori* clear whether, especially in highly asymmetrical sports, a high degree of laterality is adverse and must be prevented or whether, on the contrary, it is actually the key in enhancing performance or protecting athletes. Accordingly, recent research have proposed a more sophisticated approach for laterality analysis, which include cohort- and task-specific thresholds to account for the task- and metric-dependent nature of asymmetries (Bishop et al., 2018a; Bishop et al., 2021; Dos'Santos et al., 2021). Moreover, Exell et al. (2012) have stated that the asymmetry percentage must be larger than the coefficient of variation and suggested the application of an individual approach in the context of interlimb asymmetry considerations.

Accordingly, the aims of this study were threefold: 1) to determine whether there are distinct differences in leg axis and core stability between soccer players and skiers, 2) to investigate whether youth soccer players and alpine skiers exhibit leg axis and core stability differences between the dominant and non-dominant sides, and 3) to explore the outcomes of applying common sport-specific asymmetry thresholds to these two distinct cohorts. Considering the literature and the great importance of core and leg axis stability in both alpine skiing and soccer, similar absolute values have been hypothesized for both cohorts in their respective exercise tests. However, due to the asymmetric nature of the demands in soccer, which are in contrast to alpine skiing, it was been hypothesized that there would be greater differences between the dominant and non-dominant sides than it is for alpine skiers. Accordingly, a higher percentage of individuals in the soccer cohort were expected to be classified as asymmetric.

2 Materials and methods

2.1 Participants and study design

Twenty-one male youth soccer players and 61 youth alpine skiers participated in a cross-sectional study and were assessed with respect to leg axis and core stability as further defined below. All data were collected at a single point in time [i.e., before the competitive season in October (alpine skiers) and in January (soccer players)] and were analyzed without any interventional influence. Data collection took place on dedicated test days directly at the athletes' training facilities using a standardized mobile measurement setup and operated by the same experienced team of evaluators. Standard pretest preparation advice included no intense training or competition 24 h prior to testing and only healthy athletes participated.

Alpine skiers were recruited through their membership in a youth development structure of a national skiing association. The recruitment of the soccer players was based on their membership in a professional youth soccer academy and playing in the corresponding U16–U18 teams. Regarding training and performance classification, both cohorts met the criteria for *Tier 3*, which is defined as highly trained and competing at the national level (McKay et al., 2022). Further eligibility criteria were not being in a back-to-sports program after injury and not having systematic pathologies, diabetes mellitus, or inflammatory arthritis. The resulting sample size represents the full availability of healthy athletes within the cooperating associations at the time of assessment.

The selection of the two sports investigated was based, as outlined in the introduction, on the idea of comparing a group with highly symmetrical sport-specific requirements with a group that particularly has asymmetrical requirements. Alpine skiing and soccer are the two sports that fulfil this criterion and are also of high interest for injury prevention research due to their high risks.

All participants/participants' legal guardian/next of kin were informed about the study and provided written informed consent. The corresponding study protocols were approved by the local ethics committees (KEK-ZH-NR: 2017-01395 and EKNZ 2017-02148), and the procedures were in full accordance with the Declaration of Helsinki and national laws.

2.2 Data collection

Leg axis stability was quantified as medial knee displacement (*MKD*; in mm) during drop jump (DJ) landings (Ellenberger et al., 2020b). The *MKD* was specified as the maximal distance between the knee joint center during the ground contact phase and the predefined reference plane. The reference plane consisted of the hip, knee joint center, and ankle joint center and was set to one frame before ground contact. A threshold of 25 N was used to determine ground contact for both legs independently. The subjects were instructed to drop off from a 32-cm-high box in upright posture and subsequently perform a maximum height vertical jump with minimal ground contact time. Throughout the trial, both hands had to remain on the pelvis, and the subjects had to land with their feet on two adjacent force plates. A trial was considered invalid if the participants i) actively jumped off the box, ii) lost hand contact with the pelvis, iii) did not correctly hit the force plates, or iv) had hesitation in jumping off after landing. The subjects were asked to perform additional trials until two valid trials were recorded, with a minimum of 15 s of recovery time between the trials.

Core stability was quantified as the maximum amplitude of the vertical displacement (in mm) of the two pelvis markers during deadbug bridging exercise, with the marker of the stabilizing side representing the reference marker ($DBB_{displacement}$), as suggested previously (Ellenberger et al., 2020a). Thus, $DBB_{displacement}$ of the dominant side represents the displacement with the dominant side stabilizing while the non-dominant leg is lifted, and *vice versa*. In this regard, the subjects were asked to take a supine position on the floor with their arms abducted 90° from the body and their palms facing upward. Leg abduction was oriented such that the heels were in line with the elbows. To reach the starting position, the athletes were asked to lift their hip and keep ground contact only with their heels and shoulders. Subsequently, one heel had to be lifted to a position with knee and hip flexion angles of 90°. Holding this position for 3 s and returning to the starting position was one repetition. One trial consisted of three consecutive repetitions, without the hip touching the ground in between. The trial was repeated if i) the system could not detect the markers properly due to hip flexion, ii) the starting position was not taken properly, or iii) the hip touched the ground.

Biomechanical assessments were recorded with an optoelectronic 3D motion capture system with eight cameras (Vicon, Oxford Metrics) operating at 200 Hz. Additionally, two force plates were included in and synchronized with the measurement setup (SP Sportdiagnosegeräte GmbH) operating at 2,000 Hz. Participants were equipped with 31 reflective skin markers for DJ assessment, and placement was performed as defined by (Ellenberger et al., 2020b) in a slightly modified form of the plug-in-gait model (Vicon Nexus v2.6, Oxford Metrics). Prior to the dynamic assessment, four additional markers were placed on the medial femur epicondyles and the medial malleoli on both legs, and a static calibration was performed, allowing a more precise determination of knee and ankle joint centers. For the deadbug bridging performance assessments, four markers were bilaterally placed on the anterior superior iliac spine and the lateral malleoli. For both groups, the dominant leg was defined as the preferred leg to perform a soccer kick. All assessments were performed barefoot.

2.3 Data evaluation

Marker trajectories were identified using the Vicon Nexus software (Vicon Nexus v2.6, Oxford Metrics). Subsequently, the data were transferred to MATLAB (MATLAB R2016b, MathWorks, Inc.), and a customized MATLAB script was used for post-processing and parameter calculation. Interpolation of gaps in the marker trajectory was performed for a maximum of 10 frames (0.05 s). For DJ data processing, the reference plane was set one frame before ground contact for each leg separately and remained fixed at the hip joint center throughout the contact phase. The rectangular distance between the reference plane and the knee joint center throughout the trial was considered in *MKD* [mm]. Deadbug bridging trials were cut into three repetitions, identified through the minimal vertical height of the lateral malleolus marker of the lifted leg. For the three repetitions, the maximal amplitude in millimeters of the vertical displacement of the anterior superior iliac spine markers was averaged and then considered $DBB_{displacement}$, with the height of the stabilizing side as the reference. Such protocols for assessing *MKD* and $DBB_{displacement}$ have been shown to be reliable in previous studies (Ellenberger et al., 2020a; Ellenberger et al., 2020b). Individual laterality assessments were performed following the suggestions of Impellizzeri et al. (2007); asymmetry was thus calculated as the difference between the larger and smaller values divided by the larger value and represented in percent (Impellizzeri et al., 2007). To make visible which side had larger displacement, all asymmetry values where the non-dominant side represented the larger displacement value were multiplied by −1.

$$\textbf{Asymmetry}\,(\%) = \frac{\textbf{larger displacement value} - \textbf{smaller displacement value}}{\textbf{larger displacement value}} \times \mathbf{100}$$

2.4 Statistical analysis

The IBM SPSS statistics software version 28 was used for statistical analysis. The assumption of normality was checked for all metric data using the Shapiro–Wilk test. All baseline characteristics are expressed as the group mean with 95% confidence interval in brackets. Repeated-measures multivariate analysis of variance (MANOVA) with Bonferroni correction for pairwise comparisons was used for the analysis of potential *MKD* and $DBB_{displacement}$ differences. The within-subject factor was the side (dominant *vs.* non-dominant), and the between-subject factor was sports (soccer *vs.* alpine skiing). For the interpretation of laterality, coefficients of variation (CVs) and common asymmetry thresholds were used (Impellizzeri et al., 2007; Exell et al., 2012; Bishop et al., 2018a; Dos'Santos et al., 2021). In brief, the CV was calculated for each subject and exercised individually as a measure of reliability, and asymmetry thresholds were calculated for both cohorts and exercises as the classification criteria for the distinctiveness of laterality. Small to moderate asymmetry was assumed when athletes were above a threshold calculated as population mean + smallest worthwhile change (SWC; defined as 0.2 * SD between subjects) (Dos'Santos et al., 2021). The high asymmetry threshold

TABLE 1 Baseline characteristics.

	Soccer players (*n* = 21)	Alpine skiers (*n* = 61)
Age [years]	16.1 (15.6, 16.5)	15.7 (15.6, 15.8)
Body height [cm]	175.5 (173.2, 177.9)	172.4 (170.6, 174.3)
Body weight [kg]	66.0 (62.5, 69.4)	62.8 (60.3, 65.3)

Data are expressed as the group mean with 95% confidence intervals (CIs) in brackets.

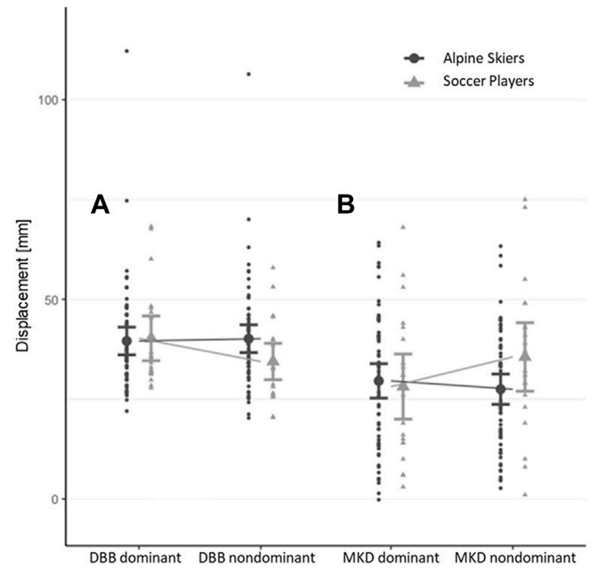

FIGURE 1
(A,B) Diagram with population mean, 95% CI, and individual values for deadbug bridging (DBB) and medial knee displacement (MKD). **(A)** Profile diagram for the interaction effect side*sports with respect to the maximum amplitude of the vertical displacement of the two pelvis markers during DBB exercise, with the marker of the stabilizing side representing the reference marker ($DBB_{displacement}$). **(B)** Profile diagram for the interaction effect side*sports withrespect to MKD.

TABLE 2 Medial knee displacement (MKD) and deadbug bridging displacement (DBB) for soccer players and alpine skiers.

	Soccer players (n = 21)	Alpine skiers (n = 61)
DBB dominant [mm]	40 (35, 46)	40 (36, 43)
DBB non-dominant [mm]	34 (30, 39)	40 (37, 44)
MKD dominant [mm]	28 (20, 36)	30 (25, 34)
MKD non-dominant [mm]	36 (27, 44)	28 (24, 31)

Data are expressed as the group mean with 95% confidence intervals (CIs) in brackets.

was defined as laterality differences above the population mean + SD (Dos'Santos et al., 2021).

3 Results

3.1 Baseline characteristics

The baseline characteristics for all participating soccer players and alpine skiers, such as age, body height, and body weight, are presented in Table 1.

3.2 Repeated-measures multivariate analysis of variance

On a multivariate level, there were no significant differences between the sports (soccer player *vs.* skiers; $p = 0.459$, $\eta^2p = 0.020$) and the side (dominant *vs.* non-dominant; $p = 0.107$, $\eta^2p = 0.055$), but there was an interaction effect side*sports ($p = 0.014$, $\eta^2p = 0.102$). As presented in Figures 1A, B, univariate tests did not reveal any significant differences in *MKD* ($p = 0.345$, $\eta^2p = 0.011$) or $DBB_{displacement}$ ($p = 0.398$, $\eta^2p = 0.009$) between the sports or between sides (*MKD*: $p = 0.244$, $\eta^2p = 0.017$; $DBB_{displacement}$: $p = 0.065$, $\eta^2p = 0.042$), but an interaction effect side*sports was observed for both variables (*MKD*: $p = 0.040$, $\eta^2p = 0.052$; $DBB_{displacement}$: $p = 0.025$, $\eta^2p = 0.061$) (Table 2).

A detailed overview of the *MKD* and $DBB_{displacement}$ values for each side and sport is given in Figure 1. On average, *MKD* laterality was directed to the non-dominant side and $DBB_{displacement}$ laterality to the dominant side in soccer players, whereas this pattern was reversed in alpine skiers, even though it was much less pronounced. Thus, despite similar absolute values and asymmetry magnitudes of dynamic knee valgus and deadbug bridging performance in youth soccer players and alpine skiers, the effect on the direction of laterality was opposite.

3.3 CV values and derivation of sport-specific asymmetry thresholds

Overall, the asymmetry CV values observed were relatively high: 0.1%–178.3% and 2.2%–94.2% for *MKD* and $DBB_{displacement}$, respectively. The sport-specific small to moderate and high asymmetry thresholds for *MKD* were 48.28% and 66.44% for soccer players (Figure 2B) and 45.10% and 65.25% for the skier group, respectively (Figure 2A). Small to moderate *MKD* asymmetries were detected in three soccer players (14.3%) and eight skiers (13.1%). High asymmetry values regarding *MKD* were found only in one soccer player (i.e., 4.8%) and in five skiers (i.e., 8.2%). For $DBB_{displacement}$, the sport-specific thresholds for small to moderate and high asymmetries were 21.0% and 34.3% for soccer players (Figure 3B) and 20.8% and 29.6% for skiers (Figure 3A), respectively. One soccer player (i.e., 4.8%) and seven skiers (i.e., 11.5%) had small to moderate asymmetries, and three soccer players (i.e., 14.3%) and six skiers (i.e., 9.8%) had high asymmetries.

4 Discussion

4.1 Similar absolute values and asymmetry magnitudes of dynamic knee valgus and deadbug bridging performance in youth soccer players and alpine skiers

Overall, the current study revealed no significant differences in *MKD* and $DBB_{displacement}$ between soccer players and skiers or between their dominant and non-dominant sides, underpinning the comparability of the two distinct cohorts examined in terms of their absolute values and asymmetry magnitudes of dynamic knee valgus and deadbug bridging performance. This is, on the one hand, certainly surprising, as soccer is, when compared to alpine skiing, a sport of a rather asymmetric nature (Rouissi et al., 2016; Bishop et al., 2021). However, on the other hand, a previous study in alpine skiing has reported a clear side dominance in the occurrence of ACL injuries (Westin et al., 2018), which is why the presence of lateralities in terms of functional performance factors also appears quite plausible. A potential relationship between these factors has been demonstrated, for example, for side-to-side differences in the side hop test and knee joint laxity, which have been shown to be factors that predispose skiers to ACL re-injury (Westin et al., 2022a).

4.2 Opposite laterality directions in soccer players compared with alpine skiers and their implications for dealing with asymmetric athletes

Despite a lack of main effects, the MANOVA revealed a crossover interaction between side* and sports for both *MKD* and $DBB_{displacement}$. This means that there is a distinct effect of the specific sport on comparisons between the dominant and non-dominant sides.

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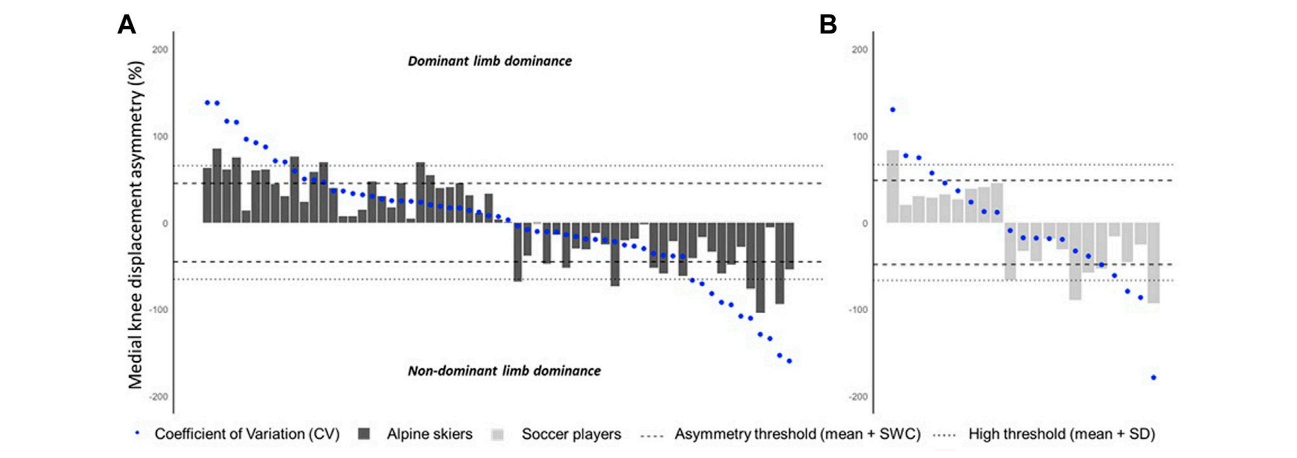

FIGURE 2
(A,B) Individual medial knee displacement (MKD) asymmetry data (bars) with the respective coefficient of variation (blue bullet points), threshold for small to moderate asymmetry [population mean + smallest worthwhile change (SWC), dashed lines], and threshold for high asymmetry (population mean + SD, dotted lines). **(A)** Alpine skiers; **(B)** soccer players.

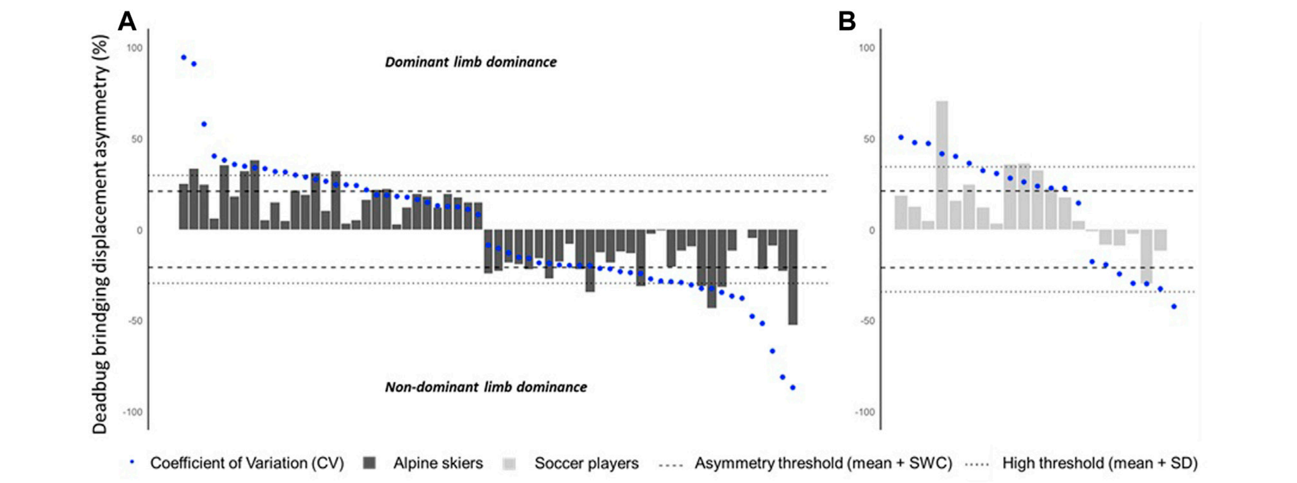

FIGURE 3
(A,B) Individual deadbug bridging displacement ($DBB_{displacement}$) asymmetry data (bars) with respective coefficients of variation (blue bullet points), thresholds for small to moderate asymmetry [population mean + smallest worthwhile change (SWC), dashed lines], and thresholds for high asymmetry (population mean + SD, dotted lines). **(A)** Alpine skiers; **(B)** soccer players.

In soccer players, *MKD* laterality was directed to the non-dominant side and $DBB_{displacement}$ laterality to the dominant side, whereas this pattern was reversed in alpine skiers, even though it was much less pronounced. For soccer players, this implies that while DJ landing the non-dominant leg (i.e., the standing leg) expressed higher magnitudes of dynamic knee valgus than the dominant leg (i.e., the kicking leg), and during the execution of the deadbug bridging exercise, the dominant side (i.e., the side ipsilateral to the kicking leg) had poorer stabilization performance than the contralateral side. From a functional perspective, such laterality makes absolute sense, since during cutting maneuvers, high dynamic valgus loads are evoked (McLean et al., 1998; Besier et al., 2001) and soccer players can typically perform faster cutting with the dominant leg (Rouissi et al., 2016). Thus, the dominant leg is the one that has to sustain the highest valgus stress and is therefore plausible to develop higher leg axis stability over time. This also reflects muscle strength assessments, where knee flexors and extensors of the dominant leg shows superior strength capacity when compared to the non-dominant leg (Rouissi et al., 2016; Rouissi et al., 2018). Moreover, higher strength in valgus antagonistic hip abductor muscles (i.e., M. gluteus medius and minimus) was found for the dominant legs of soccer players than for the non-dominant leg (Rouissi et al., 2016; Rouissi et al., 2018). Then, while kicking, when similarly executing a deadbug bridging exercise, the dominant side (i.e., the side ipsilateral to the kicking leg) rotates around the non-dominant side (with the fixed standing leg) (Kellis and Katis, 2007; Lees et al., 2010). The corresponding rotational acceleration of the pelvis on the dominant side by the diagonal concentric activation of the obliquus internus abdominis and obliquus externus abdominis muscles represents the same activation pattern as eccentrically breaking the hip axis drop on the non-dominant side with the punctum fixum on the dominant side. Accordingly, the finding of a better deadbug bridging stabilization performance on the non-dominant side is also a plausible functional adaptation to typical loading patterns in soccer.

By contrast, *MKD* in alpine skiers again shows less pronounced but oppositely directed laterality. This may represent a slightly more symmetric stabilization capacity but with slightly higher medial displacement within the dominant leg. Likewise, $DBB_{displacement}$ laterality was smaller than that in soccer players and oppositely directed to the non-dominant side. Another interesting observation, however, is the observation that at the individual level, a slightly higher percentage of alpine skiers were classified as asymmetric when compared to soccer players. This may be explained by the slightly lower professionalization of youth development programs at the U16 level in alpine skiing and lower financial resources that can be invested in systematically testing and addressing functional asymmetries, a difference that gradually disappears at higher levels.

In summary, despite similar absolute values and asymmetry magnitudes of dynamic knee valgus and deadbug bridging performance in youth soccer players and alpine skiers, the effect on the direction of laterality was opposite. It appears that sport-specific demands influence the direction rather than the presence and magnitude of asymmetries.

4.3 Study limitations

The first limitation of this study is that the coefficient of variance calculations for the *MKD* measures consisted of only two measurements, potentially limiting the representativeness for the corresponding asymmetry threshold derivation. Worth noting in this context are the rather large within-subject CV values observed in the current study. To some degree, this might be favored by the highly dynamic nature of the assessed movement tasks and also by the limited number of measurement repetitions underlying these calculations. The second limitation is differences in the number of participants within the groups, which was caused by the availability of the corresponding athletes.

5 Conclusion

As shown in this study, a certain degree of laterality is present in both youth soccer players and alpine skiers, and this is of a similar magnitude. However, despite similar absolute values and asymmetry magnitudes of dynamic knee valgus and deadbug bridging performance in youth soccer players and alpine skiers, the effect on the direction of laterality was opposite. This implies that the corresponding sports had a significant impact on the comparison between the dominant and non-dominant sides. Accordingly, our results underline the evident need to analyze lateralities on the basis of sport- or population-specific thresholds. Depending on the sport, laterality is not "unfavorable" *per se*, and potential functional advantages and disadvantages should be considered when addressing individual asymmetries in athletes.

Data availability statement

The datasets presented in this article are not readily available because their access is restricted to protect the interests of the project partner FC Basel and Swiss-Ski and their athletes. Requests to access the datasets should be directed to joerg.spoerri@balgrist.ch.

Ethics statement

The studies involving human participants were reviewed and approved by KEK-ZH-NR: 2017-01395 EKNZ 2017-02148. Written informed consent to participate in this study was provided by the participants/participants' legal guardian/next of kin.

Author contributions

JS and OF conceptualized and designed the study, recruited the participants, and organized the data collection. JS and LE collected the data. JH and LE processed the data and performed the statistical analysis. JH and JS interpreted the data and drafted the current manuscript, and all authors revised it critically and approved the final version of the manuscript.

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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 effect of 8-weeks of combined resistance training and chocolate milk consumption on maximal strength, muscle thickness, peak power and lean mass, untrained, university-aged males

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The overarching aim of this study was to investigate the combined effects of chocolate milk consumption (500 mL) with 8-week of resistance training on muscle hypertrophy, body composition, and maximal strength in untrained healthy men. A total of 22 Participants were randomly divided into two experimental groups: combined resistance training (3 sessions per week for 8 weeks) and chocolate milk consumptions (include 30 g protein) Resistance Training Chocolate Milk (RTCM) (Age: 20.9 ± 0.9 years old) and resistance training (RT) only (Age: 19.8 ± 0.7 years old). Muscle thickness (MT), using a portable ultrasound, body composition, body mass, maximal strength (one repetition maximum (1 RM), counter movement jump (CMJ) and peak power (PP) were determined at baseline and 8 weeks later. In the RTCM, finding showed a significant improvement in the outcomes compared to the RT group, besides the main effect of time (pre and post). The 1 RM total increased by 36.7% in RTCM group compared to 17.6% increased in the RT group ($p < 0.001$). Muscle thickness increased by 20.8% in the RTCM group and 9.1% in the RT group ($p < 0.001$). In the RTCM group, the PP increased by 37.8% compared to only 13.8% increase in the RT group ($p = 0.001$). The group*time interaction effect was significant for MT, 1RM, CMJ, and PP ($p < 0.05$), and it was observed that the RTCM and the 8-week resistance training protocol maximized performance. Body fat percentage (%) decreased more in the RTCM (18.9%) group than in the RT (6.7%) group ($p = 0.002$). In conclusion, chocolate milk (500 mL) with high protein content consumed in addition to resistance training provided superior gains in terms of MT, 1 RM, body composition, CMJ, and PP. The finding of the study demonstrated the positive effect of casein-based protein (chocolate milk) and resistance training on the muscle performance. Chocolate milk consumption has a more positive effect on muscle strength when combined with RT and should be considered as a suitable post-exercise nutritional supplement. Future research could be conducted with a larger number of participants of different ages and longer study durations.

KEYWORDS

supplementation, exercise, strength training, ultrasound, muscle hypertrophy

1 Introduction

Muscle strength is one of the most important biomotor skills in promoting physical fitness, health and performance (Phillips and Winett, 2010; Sugaono and Tecchio, 2020). Resistance training (RT) is the primary way to significantly increase muscle strength and induced hypertrophy (Schoenfeld, 2010). It is well known that repeated exposure to RT has a positive effect on muscle mass and strength (Burke et al., 2001; Candow et al., 2001; Burke et al., 2003). An individuals' resistance training history may influence their adaptive responses (Buckner et al., 2017). The magnitude of hypertrophic response is greater in untrained individuals compared to resistance trained (Ahtiainen et al., 2003). American College of Sports Medicine (ACSM) prescribes a minimum of two non-consecutive days per week for strength training, with 8–10 multi-joint exercises that stress the major muscle groups and perform two to three sets of 8–12 repetitions with good form (ACSM, 2009).

It is a consensus that RT has positive effects on many health-related mechanisms (Phillips and Winett, 2010). RT are safe and effective for various patient populations in preventing or treating health problems such as osteopathy, diabetes, and sarcopenia (Pescatello et al., 2004; Jones et al., 2009; Aronow et al., 2011; Westcott, 2012). Oppert et al. (2018) suggested that supervised resistance training for 18 weeks with additional whey protein intake (48 g/day) was superior to solely resistance training by means of strength gain. Further, a meta-analysis by Wirth et al. (2020) concluded that casein or whey protein taken whether before and after resistance training potentiate the lean body mass substantially. RT combined with additional casein protein consumption results in greater strength and muscle mass gain than RT alone (Snijders et al., 2015). It has been shown that 20 g of protein is sufficient for maximum stimulation of muscle protein synthesis (MPS) (Cuthbertson et al., 2005). Milk protein has a full profile of essential amino acids (AA) consisting of casein and whey are a muscle-building protein with adequate amounts of leucine responsible for MPS (Anthony et al., 2001; Norton and Layman, 2006; Layman et al., 2015). Anthony et al. (2000a) showed that orally administered leucine stimulated muscle protein synthesis (Anthony et al., 2000a; Anthony et al., 2000b). Milk protein contains essential amino acids, 80% casein and 20% whey protein (Phillips et al., 2009). In addition, casein protein consumption after RT is highly effective in increasing MPS compared to soy protein (Pasiakos and McClung, 2011). Whey is defined as "fast" protein and casein as "slow" protein (Boirie et al., 1997). Casein protein is slowly absorbed and may prolong high plasma-amino acid levels, thereby increasing whole-body protein conversion (Boirie et al., 1997). On the other hand, because whey protein is quickly absorbed, it gives the muscles the amino acids they need for MPS right after they eat it (Devries and Phillips, 2015). Chocolate milk also contains water, electrolytes, protein and carbohydrates. It is al-so very important in glycogen synthesis, repairing tissues and increasing performance. Milk consists of the desired 4:1 ratio of protein and carbohydrates (Ivy et al., 2003).

Studies have shown that milk protein is an effective beverage to facilitate adaptation to resistance training (Hartman et al., 2007; Josse et al., 2010). But according to one study, supplementing with 500 mL of chocolate milk daily in addition to 12 weeks of resistance exercise did not find significant increases in muscle strength and muscle fiber in both younger and older men. In addition, lower body exercise 2 days a week for 12 weeks was found to induce type II muscle fiber hypertrophy in older men (Mitchell et al., 2015). This may be due to the age of the study group. Indeed, the insufficient of hypertrophy of type II muscle fibers in older men may be due to anabolic resistance (Yang et al., 2012). In addition, the amount of protein consumed in the study may have been insufficient (Moore et al., 2015). It has been found that 40 g of high-quality protein consumed after RT in the elderly provides higher muscle protein synthesis compared to 20 g of protein (Yang et al., 2012). For this reason, it is necessary to increase muscle protein synthesis after RT and to consume more milk (protein) as an ergogenic support

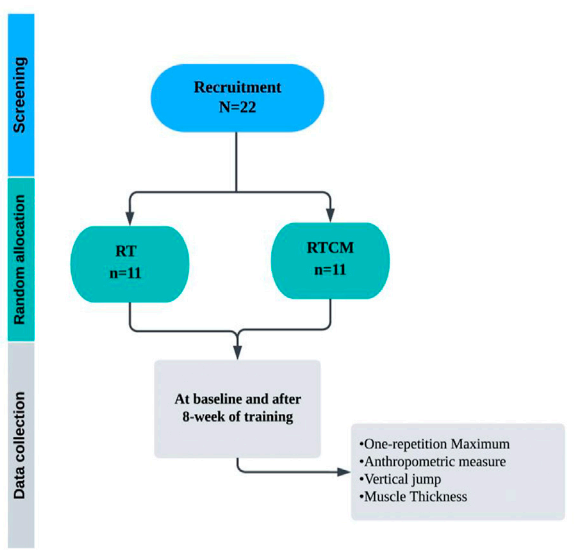

FIGURE 1
Study design.

TABLE 1 Total daily nutrient intakes from food diaries for all group.

	RTCM (*n* = 11)	RT (*n* = 11)
Energy (kcal)	2521 ± 322	2692 ± 381
Protein (g/day)	127.7 ± 48.1	97.3 ± 13.2
Protein (g/kg)	1.9 ± 0.7	1.6 ± 0.8
CHO (g/day)	360.2 ± 47.0	397.3 ± 47.7
CHO (g/kg)	6.6 ± 3.1	4.5 ± 1.2
Fat (g/day)	63.2 ± 10.8	79.3 ± 19.7
Fat (g/kg)	0.8 ± 0.1	0.9 ± 0.4
Calcium (mg)	1076.7 ± 97.9	1052.3 ± 87.0

CHO: carbohydrate; Kcal: kilocalories; g: Gram.

(Hartman et al., 2007). In addition, participants with previous RT experience and participants without training experience also provide different adaptations (Lopez et al., 2021). A review shows that when training stimuli are optimal (e.g., frequency, volume, duration), additional protein supplementation can improve muscle hypertrophy and performance (Pasiakos et al., 2015). According to the ACSM position stand study, the recommended frequency for training is 2–3 days per week (d.w-1) for beginner level, 3–4 d. w-1 for secondary education, and 4–5 d. w-1 for advanced training. For training load, 6–12 RM loads are recommended using loads corresponding to 1–12 RM, 1-2-min rest periods between sets at moderate speed (ACSM, 2009). Studies report that 8 weeks of strength training is sufficient to produce significant increases in muscle hypertrophy (Coburn et al., 2006) and muscle strength in different body parts in men and women (Dias et al., 2005). Studies in the literature report that protein supplementation is effective in increasing muscle hypertrophy. In the basis of the current literature, it has been revealed that consumption of whey protein as an additional to resistance exercise or as part of a weight loss or weight maintenance diet contributed to improve body composition parameters. However, not all studies found a significant protein effect. Research has focused on the effects of chocolate milk on recovery (Pritchett and Pritchett, 2012; Potter and Fuller, 2015). However, there has been limited re-search examining the potential changes in muscle thickness (MT), body composition, and performance of casein protein consumption in addition to resistance training. In addition, research about the efficacy of high protein chocolate milk ingestion during a resistance training program in young adults is limited. The aim of this study was to explore the effects of chocolate milk consumption (500 mL) with 8 weeks of resistance training on muscle hypertrophy, body composition, maximal strength and peak power (PP) in un-trained healthy men.

2 Methods

2.1 Participants

The study included healthy, untrained male university students 22 participants completed the exercises. G* power software (version 3.0.1) was used to calculate the sample size, with a target effect size 0.70, alpha 0.05 and power 0.80, yielding an estimated sample size of at least 19 participants for the two dependent groups (Faul et al., 2007). The mean ages of the participants in the RTCM ($n = 11$) and RT ($n = 11$) included in the study were 20.9 ± 0.9 years, 19.8 ± 0.7 years, and mean heights were 183 ± 6 cm, 178 ± 5 cm, respectively. Mean body weights were measured as RTCM: 73.0 ± 4.9, RT: 75.7 ± 3.9 kg, BMI values were determined as RTCM: 21.7 ± 1.4 kg/m^2, RT: 23.8 ± 1.1 kg/m^2. The exclusion criteria were as follows: Individuals without 1 year of resistance training experience, those taking performance-enhancing drugs, and those with health disabilities were excluded due to the possibility of impairing their ability to perform the physical tests. Participants were given detailed information about the potential risks and benefits of the study and signed a formulated consent form. The study was approved by the Kırıkkale University Non-Invasive Research Ethics Committee (2021.11.09). All study procedures were performed in accordance with the ethical standards outlined in the Declaration of Helsinki.2.2. Study Design.

A non-probability convenience sampling method was conducted in which healthy male volunteers who agreed to participate in the study were randomly assigned into two groups (The Resistance Training Chocolate Milk [RTCM] group, $n = 11$; The Resistance Training [RT] group, $n = 11$) (Figure 1).

TABLE 2 MT measurements analyzed using ultrasonography of the vastus lateral is muscles pre and post-test.

$n = 22$	Pre	Post	Δ	%	Time main effect	Group main effect	Interaction
					F Value	F Value	
					p_1-value	p_2-value	
Variable	M±SD	M±SD	TB-Tend		η^2_p	η^2_p	
MT (cm)							
RTCM ($n = 11$)	2.40 ± 0.3	2.90 ± 0.3	0.50 ± 0.2	20.8	F = 151.94 $p_1 < 0.001$*$\eta^2_p = 0.88$	F = 55.75 $p_2 < 0.001$*$\eta^2_p = 0.74$	F = 13.89 $p = 0.001$*$\eta^2_p = 0.41$
RT ($n = 11$)	2.20 ± 0.1	2.40 ± 0.1	0.13 ± 0.1	9.1			

MT: muscle thickness; M: mean values; SD: standard deviation; Δ: difference; Time Main Effect [Pre vs. Post]; Group Main Effect: [RTCM, vs. RT]; p1-value: significance test result between pre and post-test; p_2-value: significance test result between RTCM, and RT; *statistically significant p-value <0.05.

TABLE 3 Anthropometric measurements baseline and after 8-week resistance training.

n = 22	Pre	Post	Δ	%	Time main effect	Group main effect	Interaction
					F Value	F Value	
					p_1-value	p_2-value	
Variable	M±SD	M±SD	T_B-T_{end}		η^2_p	η^2_p	
Weight (Kg)							
RTCM	73.0 ± 4.9	68.6 ± 4.9	4.4 ± 1.3	6.4	F = 141.95 p_1 < 0.001*η^2_p = 0.87	F = 5.55 p_2 = 0.03*η^2_p = 0.22	F = 49.21 p < 0.001*η^2_p = 0.71
RT	75.7 ± 3.9	74.6 ± 3.4	1.1 ± 0.8	1.5			
BMI (Kg/m²)							
RTCM	21.7 ± 1.4	20.4 ± 1.1	1.3 ± 0.5	6.4	F = 11.59 p_1 < 0.001*η^2_p = 0.85	F = 28.22 p_2 < 0.001*η^2_p = 0.58	F = 36.88 p < 0.001*η^2_p = 0.65
RT	23.8 ± 1.1	23.5 ± 0.9	0.4 ± 0.2	1.3			
Fat (%)							
RTCM	13.2 ± 1.5	11.1 ± 1.5	2.0 ± 0.8	18.9	F = 39.70 p_1 < 0.001*η^2_p = 0.66	F = 12.05 p_2 = 0.002*η^2_p = 0.38	F = 6.92 p = 0.02*η^2_p = 0.26
RT	16.0 ± 3.4	15.0 ± 2.6	0.8 ± 1.2	6.7			
Fat free (Kg)							
RTCM	9.6 ± 1.6	12.2 ± 2.9	1.9 ± 0.6	27.1	F = 63.11 p_1 < 0.001 η^2_p = 0.76	F = 12.24 p_2 = 0.002*η^2_p = 0.38	F = 10.22 p = 0.005*η^2_p = 0.34
RT	7.7 ± 1.6	11.4 ± 2.1	0.8 ± 1.0	48.1			

BMI: body mass index; M: mean values; SD: standard deviation; Δ: difference; Time Main Effect [Pre vs. Post]; Group Main Effect: [RTCM, vs. RT]; p_1-value: significance test result between pre and post-test; p_2-value: significance test result between RTCM, and RT; *statistically significant p-value <0.05.

Randomization was based on computer-generated numbers, and revealed in the order in which participants completed baseline testing. Both intervention groups performed 8 weeks of RT for 3 days a week at the fitness center. The Resistance Training Chocolate Milk (RTCM) group consumed high-protein chocolate milk within half an hour after strength training. RT group performed only strength training at the same intensity as the RTCM group. Two weeks before the training started; the participants were given detailed information about the tests by visiting the laboratory. A week prior to the training sessions, all testing was conducted in research laboratories at Kirikkale University.

2.3 Training and supplementation protocol

Certified trainers checked all workouts to ensure they performed in the correct training form. After warm-up and familiarization, all the testing procedures were conducted at the same time of day and under control environmental conditions (24°C, 58%–64% relative humidity) and were performed by the same expert. After the 1RM maximum values of the participants were determined, the training loads were calculated separately for each participant. Each training session lasted approximately (55 min). Each training session consist of 8 exercises performed at volume of 3 sets of 8 repetitions with a 120-s resting interval between sets. The weekly training loads of all participants were increased by 5%.

While the RT group received only high-carbohydrate pudding in addition to the training, In the RTCM group, Energy; 191 kJ/45 kcal; saturated fat 01 g (0.1); carbohydrate 5.0 g; sugar 5.0 g; protein 6.0 g; salt 0.5 g; calcium 150 mg; (per 100 g) consumed 500 mL of chocolate milk half an hour after training. To ensure the energy balance of both groups, the participants in the RT group consumed 50 g pudding without protein (Table 1). Pudding include; Energy; 2100 kJ/502 kcal; fat 2.5 g; saturated fat 1.6 g; carbohydrate 21.7 g; sugar 4.7 g; (per 100 g).

2.4 One-repetition maximum measurements

The participants applied two different warm-up protocols before the 1 repetition maximal values were determined. Participants cycled in the protocol for 20 min and then performed the specific warm-up (SWU protocol. They performed only the SWU before the 1RM test. In the SWU protocol, participants performed one set of 8 repetitions at approximately 50% of the estimated 1RM, followed by another set of 3 repetitions at 70% of the estimated 1RM (Brown and Weir, 2001). The test protocol was previously described by Kraemer et al. (Kraemer et al., 1991). One Repetition Maximum (1-RM) lift for Bench press (BP), Chest press (CP), Seated row (SR), Leg extension (LE), Leg curl (LC), Leg press (LP), and Squat (SQ) strength was determined, and the test consisted of two warm-up sets using three to five repetitions at 60% and 80% of the predicted 1-RM, followed by three to five subsequent trials to determine the 1-RM load. The highest mass (kg) lifted with proper form was used as the 1-RM test score.

2.5 Diet analysis

Participants were asked not to change their diet or restrict calories to control dietary effects. Participants recorded their food and beverage intake using a 3-day eating log be-fore and after the exercises began. Meal diaries consisted of 2 weekdays and 1 weekend day. Necessary information on how to fill in the food diary was explained to the partici-pants in detail before the research. Subsequently, the researchers noted the food diaries and clarified any misunderstandings. BeBis nutrition analysis computer application was used to examine the food diaries (BeBiS software program; Bebispro for Windows, Stuttgart, Germany; Turkish Version (Bebis 4)). The same researcher (blinded to the inter-ventions) assessed all the food diaries.

2.6 Peak power, vertical jump

The muscle peak power of the participants was measured in watts (W) and CMJ (cm) during vertical jump test using the Accupower 2.0 portable force platform system (Accupower 2.0, United States). Participants' CMJ values were measured using the previously described procedure (Gülü and Akalan, 2021). The device was calibrated before the measurements were made and the measurement frequency was set to 500 Hz (Gülü and Akalan, 2021). The CMJ protocol was explained to the participants in detail. The participant was instructed to jump hands-free during the jump. Participants did a 5-min warm-up before a jump. After warming up, participants performed 3 different jumps on the strength plat-form, with 5 min' rest between each jump. The best CMJ values and peak power values were recorded.

2.7 Anthropometric measurements

The height of the participants was measured without shoes, with the heels together and standing, with a height meter (Seca 217, Seca, Hamburg, Germany). Pre- and post-test Body mass was measured using a portable body analysis system accurate to 0.1 kg for the participant (Tanita Corp, Tokyo, Japan). Various methods are used to evaluate body composition. Measured components of body composition (total body fat, lean body mass, BMI, % fat) in Tanita with the BIA method. Bioimpedance analysis (BIA) which can measure several important body com-position components (Heymsfield et al., 2009). BIA measurements are based on the conduction principle of water in skeletal muscle and electrical activity in adipose tissue (Esco et al., 2011). The presence of more adipose tissue prevents the flow of electrical activity, resulting in lower electrical activity (Wagner and Heyward, 1999). By using this electric flow principle, the body fat percentage can be calculated with the BIA technique.

2.8 Muscle thickness measurements

MT was measured by portable ultrasonography (GE Healthcare VScan, Ultrason, General Electric Company, United States). Measurements were carried out according to the previously described procedure (Ticinesi et al., 2018). At the beginning of the measurements, each participant was asked to lie supine on a hospital bed with the knee fully extended. In addition, they were asked not to change their positions during the measurements and to maintain their resting conditions. The operator then palpated the right greater trochanter and the right intercondylar notch as landmarks of the upper and lower borders of the Vastus Lateralis muscle. Once identified, landmarks are marked on the skin with a demographic pen, and the subject is then asked to regain the resting position with the knee fully extended. The proximal-distal length between the determined points should be measured with a flexible tape measure and was accepted as the Vastus Lateralis length. MT was measured from one area: Quadriceps femoris (vastus lateralis) MT was measured as 50% between the greater trochanter and lateral epicondyle of the femur (Bridge et al., 2019). This region corresponds to where the muscle core is thickest. Participants were placed comfortably on their backs with their palms facing their bodies. A thin layer of gel was applied to the muscle area, and the ultrasound probe was placed on the area without putting pressure on the skin. The measurement was obtained by gently pressing the probe against the skin and moving it over the muscle. The MT was measured from bone to external/superficial sarcolemma. Three images were acquired from the quadriceps region and then averaged to obtain a final value. Ultrasound tests were completed at baseline and 8 weeks after training program. All tests were performed in the morning, when the participants were fasting.

2.9 Data analysis

In this study, the assumption of normal distribution for quantitative data was checked with the "Shapiro-Wilk" test. Quantitative data were expressed as mean and standard deviation since they showed a normal distribution. The effect of different protocols (RT and RTCM) on measurement times (Pre and Post) was determined using the Repeated Measurements two-way ANOVA test. Mauchly's test of sphericity was used to test the homogeneity of variances and Greenhouse-Geisser correction was applied when necessary. Effect sizes for within-group, between-group and interaction effect were analyzed with partial eta-squares ($\eta^2 p$). The magnitude of differences was tested using the standardized effect size (ES) of, following the thresholds: 00.00–0.059 (small effect), 0.06–0.14 (medium effect), and ≥ 0.15 (large effect) (Cohen, 1973). The Pearson correlation coefficient was calculated to determine the relationship between muscle strength and protein intake. The following ranges were considered for the correlation coefficient sizes: 0.3–0.5 = moderate; >0.5–0.7 = large; >0.7–0.9 = very large; and >0.9 = nearly perfect (Hopkins et al., 1987). The American Psychological Association (APA) 6.0 style was used to report statistical differences (Yağin et al., 2021). Statistical data were analyzed using SPSS version 26 for Windows (IBM Corp, Armonk, NY, United States) and Python version 3.9 software. Statistical significance was set at $p \leq 0.05$.

TABLE 4 Baseline and post-test results of 1 RM values.

n = 22	Pre	Post	Δ	%	Time main effect	Group main effect	Interaction
					F Value	F Value	
					p_1-value	p_2-value	
Variable	M±SD	M±SD	T_B-T_{end}		η^2_p	η^2_p	
BP (Kg)							
RTCM	53.20 ± 9.0	80.50 ± 6.5	27.3 ± 4.1	51.3	F = 492.10 p_1 < 0.001*η^2_p = 0.96	F = 3.25 p_2 = 0.08 η^2_p = 0.14	F = 45.58 p < 0.001*η^2_p = 0.69
RT	51.40 ± 13.4	65.90 ± 13.0	14.6 ± 4.7	28.2			
CP (Kg)							
RTCM	65.9 ± 11.4	86.40 ± 7.8	20.5 ± 4.2	31.1	F = 335.74 p_1 < 0.001*η^2_p = 0.94	F = 3.50 p_2 = 0.07 η^2_p = 0.15	F = 55.41 p < 0.001*η^2_p = 0.73
RT	61.8 ± 15.8	70.5 ± 14.2	8.6 ± 3.2	14.1			
SR (Kg)							
RTCM	64.1 ± 6.6	90.5 ± 4.7	26.4 ± 5.5	41.2	F = 359.55 p_1 < 0.001*η^2_p = 0.95	F = 0.80 p_2 = 0.38 η^2_p = 0.04	F = 72.81 p < 0.001*η^2_p = 0.78
RT	69.4 ± 9.3	79.5 ± 8.5	10.0 ± 3.2	14.6			
LE (Kg)							
RTCM	72.3 ± 4.1	80.6 ± 7.4	17.0 ± 4.9	11.5	F = 193.40 p_1 < 0.001*η^2_p = 0.91	F = 4.54 p_2 = 0.04*η^2_p = 0.18	F = 14.10 p = 0.001*η^2_p = 0.41
RT	70.8 ± 5.4	80.6 ± 7.4	9.7 ± 4.1	13.8			
LC (kg)							
RTCM	60.2 ± 11.4	83.6 ± 7.1	23.4 ± 10	38.9	F = 92.15 p_1 η^2_p = 0.82	F = 6.16 p_2 = 0.02*η^2_p = 0.23	F = 17.10 p = 0.001*η^2_p = 0.46
RT	57.7 ± 11.6	67.0 ± 8.8	9.3 ± 3.6	16.1			
LP (Kg)							
RTCM	72.9 ± 15.1	94.1 ± 10.3	21.2 ± 12	29.1	F = 52.30 p_1 < 0.001*η^2_p = 0.72	F = 14.78 p_2 = 0.001*η^2_p = 0.42	F = 15.72 p = 0.001*η^2_p = 0.44
RT	64.6 ± 8.1	70.1 ± 7.3	6.2 ± 3.4	8.5			
SQ (Kg)							
RTCM	60.5 ± 9.6	90.5 ± 8.5	30.0 ± 5.0	49.6	F = 632.81 p_1 < 0.001*η^2_p = 0.97	F = 0.07 p_2 = 0.80 η^2_p = 0.003	F = 137.81 p < 0.001*η^2_p = 0.87
RT	69.1 ± 8.3	80.0 ± 7.1	10.9 ± 2.0	15.8			
1RM total (Kg)							
RTCM	449.1 ± 44.0	614.7 ± 30.1	165 ± 19.4	36.7	F = 1398.01 p_1 < 0.001*η^2_p = 0.99	F = 10.92 p_2 = 0.004*η^2_p = 0.35	F = 182.54 p < 0.001*η^2_p = 0.90
RT	444.8 ± 32.3	522.6 ± 319.1	78 ± 9.5	17.6			

BP: bench press; CP: chest press; SR: seated row; LE: leg extension; LC: leg curl; LP: leg press; SQ: squat; RM: repetition maximum; M: mean values; SD: standard deviation; Δ: difference; Time Main Effect [Pre vs. Post]; Group Main Effect: [RTCM, vs. RT]; p_1-value: significance test result between pre and post-test; p_2-value: significance test result between RTCM, and RT; *statistically significant p-value <0.05.

3 Results

The findings of the study showed a significant improvement in the RTCM compared to the RT group for all outcome of interest, and results were significantly higher in the post-test.

MT responses for pre and posttests following both RT and RTCM protocol are evaluated in Table 2. MT responses were different for RT and RTCM (ANOVA: group (RT vs. RTCM), F = 55.75; p < 0.001; $\eta^2 p$ = 0.74; group × time, F = 13.89; p < 0.001; $\eta^2 p$ = 0.41), moreover MT Increased with 8-week resistance training (ANOVA: time (Pre vs. Post), F = 151.94; p < 0.001; $\eta^2 p$ = 0.88).

In Table 3, the results anthropometric measurements of the participants' within group, between group and interaction effect were evaluated. Weight (kg) (ANOVA: time, F = 141.95; p1 < 0.001; $\eta^2 p$ = 0.87; group (RT vs. RTCM), F = 5.55; p_2 = 0.03; $\eta^2 p$ = 0.22; group × time, F = 13.89; p < 0.001; $\eta^2 p$ = 0.41), BMI (kg/m^2) (ANOVA: time, F = 11.59; p1 < 0.001; $\eta^2 p$ = 0.85; group (RT vs. RTCM), F = 28.22; p_2 < 0.001; $\eta^2 p$ = 0.58; group × time, F = 36.88; p < 0.001; $\eta^2 p$ = 0.65), and Fat (%) (ANOVA: time, F = 39.70; p1 < 0.001; $\eta^2 p$ = 0.66; group (RT vs. RTCM), F = 12.05; p_2 = 0.002; $\eta^2 p$ = 0.38; group × time, F = 6.92; p = 0.02; $\eta^2 p$ = 0.26) decreased with 8-week resistance training and RTCM.

However, Fat free (kg) (ANOVA: time, F = 63.11; p1 < 0.001; η^2p = 0.76; group (RT vs. RTCM), F = 12.24; p_2 = 0.002; η^2p = 0.38; group × time, F = 10.22; p = 0.005; η^2p = 0.34) showed maximum increase with 8-week resistance training and RTCM. When the ES (η^2p) results are examined, the larger effect between groups (RTCM vs. RT) (η^2p = 0.58) is BMI (kg/m^2), and within-group (pre vs. post) the larger effect (η^2p = 0.87) is weight (kg) was observed.

In Table 4, the changes in the 1RM values of the participants were evaluated. For BP (kg) responses, time (Pre vs. Post) had a main effect and the group*time interaction effect was significant (ANOVA: time (Pre vs. Post), F = 492.10; p_1 < 0.001; η^2_p = 0.96; group × time, F = 45.58; p < 0.001; η^2_p = 0.69), while RTCM and RT results were similar (ANOVA: group (RTCM vs. RT), F = 3.25; p_2 = 0.08; η^2_p = 0.14). It was observed that the RTCM protocol with 8-week resistance training increased BP (kg) results. Similarly, there was no significant main effect for group in CP (kg) (ANOVA: group (RTCM vs. RT), F = 3.50; p_2 = 0.07; η^2_p = 0.15), while these increased with time, and the interaction effect was significant (ANOVA: time (Pre vs. Post), F = 335.74; p_1 < 0.001; η^2_p = 0.94; group × time, F = 55.41; p < 0.001; η^2_p = 0.73). CP (kg) results increased significantly with 8-week resistance training and RTCM protocol. The interaction effect was significant in SR (kg) and was highest in post-test after RTCM protocol (ANOVA: time (Pre vs. Post), F = 359.55; p_1 < 0.001; η^2_p = 0.95; group × time, F = 72.81; p < 0.001; η^2_p = 0.78). The SR (kg) response were also similar between RTCM and RT protocols (ANOVA: group (RTCM vs. RT), F = 0.80; p_2 = 0.38; η^2_p = 0.04).

After the RTCM protocol, there was a significant increase in LE (kg) with 8-week resistance training (ANOVA: time (Pre vs. Post), F = 193.40; p_1 < 0.001; η^2_p = 0.91; group, F = 4.54; p_2 = 0.04; η^2_p = 0.18; group × time, F = 14.10; p < 0.001; η^2_p = 0.41) During the RTCM protocol, LC (kg) increased and this increase was higher in the post-test compared to the pretest (ANOVA: time (Pre vs. Post), F = 92.15; p_1 < 0.001; η^2_p = 0.82; group (RTCM vs. RT), F = 6.16; p_2 = 0.02; η^2_p = 0.23), furthermore the group*time interaction effect for LC (kg) was significant (ANOVA: group × time, F = 17.10; p < 0.001; η^2_p = 0.46). The main effect of time and the interaction effect of group*time were significant in LP (kg) (ANOVA: time (Pre vs. Post), F = 359.55; p_1 < 0.001; η^2_p = 0.95; group × time, F = 72.81; p < 0.001; η^2_p = 0.78). RTCM significantly affected LP (kg) performance (ANOVA: group (RTCM vs. RT), F = 14.78; p_2 = 0.001; η^2_p = 0.42) and LP (kg) was higher in RTCM compared to RT.

SQ (kg) increased after 8-week resistance training (post-test) and had a higher effect (interaction effect) with RTCM (ANOVA: time (Pre vs. Post), F = 632.81; p_1 < 0.001; η^2_p = 0.97; group × time, F = 137.81; p < 0.001; η^2_p = 0.87), while there was no significantly different between RTCM and RT protocols (ANOVA: group (RTCM vs. RT), F = 0.07; p_2 = 0.80; η^2_p = 0.003). Although the group main effect (RTCM or RT) was not significant for SQ (kg) performance, the group*time effect was observed to have a large effect (η^2_p = 0.87) and SQ (kg) showed the highest performance in the post-test after RTCM protocol. Similarly, for 1RM total (kg) results, the group*time interaction effect, time, and group main effect was significant (ANOVA: time (Pre vs. Post), F = 1398.01; p_1 < 0.001; η^2_p = 0.99; group (RTCM vs. RT), F = 10.92; p_2 = 0.004; η^2_p = 0.35; group × time, F = 182.54; p < 0.001; η^2_p = 0.90). Moreover, the 8-week resistance training protocol with RTCM showed the larger ES in 1RM total (kg) performance.

The group*time interaction effect was significant in CMJ (cm) performance (ANOVA: group*time, F = 14.10; p = 0.001; η^2p = 0.41) and increased after RTCM compared to RT (ANOVA: group (RTCM vs. RT), F = 12.27; p2 = 0.002; η^2p = 0.38). Furthermore the main effect of time was significant in CMJ (cm) (ANOVA: time (Pre vs. Post), F = 72.64; p1 < 0.001; η^2p = 0.78). Similarly, PP (watts) performance was 8-week resistance training protocol with RTCM increased significantly after *postpartum* period, that is, the group*time interaction effect was significant (ANOVA: group*time, F = 19.63; p < 0.001; η^2p = 0.49). There was also main effect of group and time for PP (watts) (ANOVA: time (Pre vs. Post), F = 40.71; p1 < 0.001; η^2p = 0.67; group (RTCM vs. RT), F = 13.69; p_2 = 0.001; η^2p = 0.41) (Table 5).

Table 6 shows the results of correlation analysis between protein intake and lean, MT, PP, and IRM results. The results showed moderate, large and very large positive correlation between PP, MT and IRM with protein intake, respectively.

4 Discussion

The aim of this study was to examine the effects of chocolate milk consumption (500 mL) and 8-week of RT in young healthy men on muscle performance profile, including muscle hypertrophy, body composition, peak power and maximal strength. The main finding of this study emphasis our hypothesis which showed evidence of statistical significant and greater improvement in the muscle strength in the RTCM compared to RT group. The most improvement in 1RM, CMJ, MT, and body composition values were found in the interaction of 8-week resistance training with RTCM protocol. Findings high-lighted the effectiveness of combined RT and consumption of chocolate milk after training.

A study in parallel with our findings reported that casein protein (35 g) consumption effectively increases muscle strength and induced hypertrophy after 12 weeks of resistance training (+0.4 cm in vastus lateralis and vastus medialis) (Joy et al., 2018). In another study, in which a 12-week of resistance training and additional casein protein (27.5 g) consumption were found to provide greater strength and muscle mass gain (+11% increase in type II fiber) than resistance training without additional protein support (Snijders et al., 2015). Milk (17.5 g of protein) consumption after strength training induces greater hypertrophy in beginners compared to isoenergetic soy or carbohydrate consumption in the early stages of resistance training (p = 0.006) (Hartman et al., 2007). In study by Coburn et al. (Coburn et al., 2006) found that greater improvement in muscle strength and cross-sectional area (+7.31%) in those who consumed leucine (6.2 g)/whey (20 g) protein after resistance exercise compared to the group that consumed energy-compatible carbohydrate supplements. Additionally, another study reported that milk consumption promotes a positive muscle protein balance (Elliot et al., 2006). In this context, our findings support the studies in the literature, as in this study, significant improvements were found in MT in the RTCM group consuming chocolate milk compared to the RT group. In a study, the group consuming chocolate milk after resistance exercise provided significant (p = 0.04; ŋp2 = .08) composite muscle strength compared to the group consuming carbohydrates (Born et al., 2019). One of the main reasons for the superior gain in the RTCM group may be that it

TABLE 5 Baseline and posttest CMJ and PP results.

n = 22	Pre	Post	Δ	%	Time main effect	Group main effect	Interaction
					F Value	F Value	
					p_1-value	p_2-value	
Variable	M±SD	M±SD	T_B-T_{end}		η^2_p	η^2_p	
CMJ (cm)							
RTCM	26.80 ± 5.80	34.50 ± 3.70	7.72 ± 3.7	28.7	F = 72.64 $p_1 < 0.001^*\eta^2_p = 0.78$	F = 12.27 $p_2 = 0.002^*\eta^2_p = 0.38$	F = 14.10 $p = 0.001^*\eta^2_p = 0.41$
RT	23.90 ± 2.40	26.90 ± 2.00	3.00 ± 1.8	12.6			
PP (watts)							
RTCM	2964 ± 398	4085 ± 653	1139 ± 565	37.8	F = 40.71 $p_1 < 0.001^*\eta^2_p = 0.67$	F = 13.69 $p_2 = 0.001^*\eta^2_p = 0.41$	F = 19.63 $p < 0.001^*\eta^2_p = 0.49$
RT	2740 ± 546	2946 ± 294	205 ± 410	13.8			

CMJ: counter movement jump; PP: peak power; M: mean values; SD: standard deviation; Δ: difference; Time Main Effect [Pre vs. Post]; Group Main Effect: [RTCM, vs. RT]; p_1-value: significance test result between pre and post-test; p_2-value: significance test result between RTCM, and RT; *statistically significant *p*-value <0.05.

TABLE 6 Correlation analysis results between protein, fat free, MT and PP.

Variables	Statistics	MT (cm)	PP (watts)	IRM (total)	Protein intake
MT (cm)	**r**	1	0.630	0.859	0.521
	***p*-value**		0.002*	<0.001*	0.013*
PP (watts)	**r**		1	0.683	0.473
	***p*-value**			<0.001*	0.026*
IRM (total)	**r**			1	0.705
	***p*-value**				<0.001*
Protein intake	**r**				1
	***p*-value**				

MT: muscle thickness; PP: peak power; RM: repetition maximum; *statistically significant *p*-value <0.05.

stimulated the net intake of phenylalanine and threonine, which represent net muscle protein synthesis, following resistance exercise. Studies have reported that the improvement in protein net balance of fat-free milk consumption is due to the increase in muscle protein synthesis after resistance training (Wilkinson et al., 2007). Contrary to our findings, one study reported that chocolate milk consumption after RT did not increase skeletal muscle hypertrophy ($p = 0.52$) (J. et al., 2015). Another study reported that chocolate milk or protein supplementation did not affect strength gains in the first 7 weeks of resistance training (Kuehn et al., 2015). Contrary to our findings, in studies by Kuehn et al. and Cameron et al., 2015 found that supplementing with chocolate milk did not significantly affect strength gains during the first 7 weeks of resistance training. The reason of this possibly due to insufficient training load, short training duration, or a relationship with the protein value of the milk consumed. Studies have shown that post-exercise chocolate milk consumption can provide a large intracellular signal stimulus as well as improve subsequent exercise performance (Ferguson-Stegall et al., 2011). For untrained individuals, consuming additional protein probably had no effect on lean mass and muscle strength during the first weeks of resistance training. However, as the duration, frequency, and volume of resistance training increases, protein supplementation can increase muscle hypertrophy and improve gains in muscle strength. Moreover, increased muscle mass may be associated with increased IGF-1 production with high-intensity training (Brahm et al., 1997; Goldspink, 2005).

In this study, significant increases in 1 RM as proxy of the strength were found in the RTCM group compared to the RT group, furthermore, the interaction results were observed that the 8-week resistance training protocol with chocolate milk significantly in-creased 1RM. Consistent with our findings, in study by Sharp et al. (2018) found that protein supplementation to resistance exercise resulted in improvements (+11–19%) in all groups for both deadlift and bench press compared to the 1 RM baseline. In another study, the group that consumed high-protein milk in addition to resistance exercise had superior gains compared to the control group ($p < 0.0001$) (Pourabbas et al., 2021). In untrained young men, consumption of dairy milk combined with 12 weeks of resistance exercise resulted in significant increase in type I and type II muscle fiber area (Hartman et al., 2007). In another study, chocolate milk consumption as an additional supplement to resistance training increased the muscle maximum strength (Cohen's $d = 0.7$) (Forsyth, 2010).

Consumption of high-protein chocolate milk after exercise resulted in greater in-creases in lean mass in untrained young men compared to the RT group, these results support previous findings. A study proved that protein (46 g) consumed after RT improves body composition (Sharp et al., 2018). In the same study, protein supplement groups had a significant increase in Lean Body Mass and decrease in Fat Mass, while none of these effects were found in the control group (Sharp et al., 2018). In one study, participants consumed milk after resistance training, and a significant improvement in lean body mass was found in the milk-consuming group (Rankin et al., 2004; Pourabbas et al., 2021). In untrained young men, consuming dairy milk combined with 12 weeks of resistance exercise significantly improved lean body mass (Hartman et al., 2007). In another study, consuming chocolate milk as an additional supplement to 8 weeks of resistance training improved body fat percentage and lean body mass (Forsyth, 2010).

This study found a significant improvement in PP and CMJ values in the group that consumed high protein chocolate milk in addition to training compared to the RT group. A study by Sharp et al., shows that protein choice did not affect muscle strength outcomes, as all quality protein sources (beef protein isolate, whey protein concentrates and hydrolyzed chicken) protein showed significant improvements in maximum strength, but not significantly greater than control (Sharp et al., 2018). But only whey protein concentrates increased muscle power (Sharp et al., 2018). High protein daily milk consumption in addition to 6 weeks of resistance exercise significantly improved power compared to the control group (Pourabbas et al., 2021). Our findings support the results in the literature. The greater improvement in the group that consumed milk in addition to RT may be due to the effect of milk increasing MPS.

The results showed large level of negative correlation between Fat Free (kg) and protein measurements, while moderate, large and very large positive correlation between PP, MT and IRM with protein intake, respectively. In parallel with our findings, early intake of oral protein supplementation after RT is highly important for skeletal muscle hypertrophy in older men in response to resistance exercise (Esmarck et al., 2001). A study has found that high protein consumption is associated with muscle strength (Mangano et al., 2017). In another study, higher consumption of total, white, red and fish meat was associated with an increased index of muscle strength in young adults. Total protein intake and per-cent lean muscle mass mediated this association (Bizzozero-Peroni et al., 2022). However, another study found no association between a difference in protein intake and muscle mass in postmenopausal women (Lemieux et al., 2014). The main reason for the difference between the results of the studies may be due to the peculiarities of the methodology adopted to analyze the dietary data. In addition, the characteristics of the participant group in the research may be caused by various factors such as the amount and quality of the protein consumed, the frequency and volume of the training performed by the participants.

Although gains were obtained in MT, strength and performance with protein supplementation combined with training, yet some limitations should be acknowledged. The study was conducted among untrained male students which limit the generalizability of our finding to other subset of population because skeletal muscle responses to exercise and protein supplementation differ between trained and untrained individuals. Furthermore, findings of this study cannot be extrapolated to female due to gender disparity in the physiological profile. From physiological perspective, gender-based difference in the muscle mass and power required further investigation in future work. Another limitation of this research, that we did not assess physiological mechanism underlying the improvement in the RTCM as we did not measure the biomarkers of muscle bioenergetics system. As a another limitation that there was no control of the external activities that the participants of the sample did outside of the training or the consumption of some other ergogenic substance. Future research is required to investigate the long-term effect and the mechanisms underlying these changes in the muscle capacity and power.

5 Conclusion

The main findings of this study were: (i) all groups improved in body composition measurements except fat mass with improvements between groups being greater in the RTCM group; (ii) All groups had superior improvements in triceps skinfold thickness and abdominal skinfold thickness measurements in the RTCM group than in the RT group; (iii) Significant improvements were seen in all groups in MT measurements, while the most improvement was found in the RTCM group (iv) all groups showed improvements in vertical jump and peak power values, the RTCM group showed more improvement than the RT group (v) all groups were at 1 RM values showed improvement, more improvement was found in the RTCM group. In general, adaptations to strength training were found in both groups. However, in addition to strength training, consumption of high-protein chocolate milk significantly increased muscle growth compared to the RT group. Our findings can be used as a guide in training planning for mid- and long-term program design for participants with no previous resistance training experience. Future research may examine the effects on different populations of athletes, the elderly, obese individuals, and individuals with osteoporosis.

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 human participants were reviewed and approved by The study was approved by Kirikkale University Non-Interventional Research Ethics Committee (Date: 2021-11-09, No: 2021/16) and was conducted according to the principles stated in the Declaration of Helsinki. . The patients/participants provided their written informed consent to participate in this study.

Author contributions

Conceptualization, MG; methodology, MG; formal analysis, HY, MK, and FY; investigation, MG, HY; data curation, HY, DU, EC, and OE; writing—original draft preparation, MG and SB; MA; writing—review and editing, MG, FY, RK, MA, and SB; visualization, MG; supervision, MG; Funding acquisition, MA All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

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

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Effects of single session transcranial direct current stimulation on aerobic performance and one arm pull-down explosive force of professional rock climbers

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Objective: To explore the effects of single-session transcranial direct current stimulation (tDCS) on aerobic performance and explosive force in the one-arm pull-down of long-term trained rock climbers.

Method: Twenty athletes (twelve male and eight female) from the Rock Climbing Team of Hunan province (Hunan, China) were selected for a randomized double-blind crossover study. After baseline tests, All subjects visited laboratories twice to randomly receive either sham or a-tDCS at a current intensity of 2 mA for 20 min. The two visits were more than 72 h apart. Immediately after each stimulation, subjects completed a 9-min 3-level-load aerobic test and a one-arm pull-down test.

Results: Differences in the heart rate immediately after 9-min incremental aerobic exercises revealed no statistical significance between each group ($p > 0.05$). However, the decrease in heart rate per unit time after exercise after real stimulation was significantly better than before stimulation ($p < 0.05$), and no statistical significance was observed between after sham stimulation and before stimulation ($p > 0.05$). One-arm pull-down explosive force on both sides after real stimulation was improved by a-tDCS compared with before stimulation, but with no significant difference ($p > 0.05$). Real stimulation was significantly improved, compared with sham stimulation on the right side ($p < 0.05$).

Conclusion: Single-session tDCS could potentially benefit sports performance in professional athletes.

KEYWORDS

transcranial direct current stimulation, rock climbing, athletes, sports performance, aerobic performance, explosive force

1 Introduction

As a new non-invasive nerve regulation technology, transcranial direct current stimulation (tDCS) applies a weak direct current (1–2 mA) on the scalp in the form of electrodes, lasting for 5–20 min (Nitsche et al., 2008). Its earliest introduction is for the treatment of clinical diseases, mainly involving psychiatric diseases such as pain, Parkinson's disease, stroke, Alzheimer's disease, depression, schizophrenia, and craving/addiction, and it has proved a significant therapeutic effect (Lefaucheur et al., 2017). Some studies have shown that tDCS can regulate the subthreshold of neuron membrane potential, changing cortex excitability and activity according to the direction of current passing through the target neuron (Purpura and McMurtry, 1965). In addition, it may also relate to neurotransmitter variation caused by current changes, effects of glial cells and microvessels, and inflammatory process regulation (Woods et al., 2016). However, the effects of tDCS depend on current intensity, polarity, relative position of electrode and intervention duration (Paulus, 2011; Angius et al., 2019a; Borges et al., 2020). Marom et al. (Bikson et al., 2016) have summarized more than 33,200 courses of treatment and 1,000 repeated courses of treatment on human subjects and discovered no reports of serious adverse effects or irreversible injuries. With advantages of safety, low cost, portability and ease of operation, this technology enjoys a broad application prospect in the field of brain science. In recent years, numerous studies have revealed that tDCS can help improve sports performance, including enhancement in motor learning (Debarnot et al., 2019), cognitive execution (Yu et al., 2018), muscle strength (Alix-Fages et al., 2020; Kenville et al., 2020), muscle endurance and fatigue perception (Park et al., 2010; Angius et al., 2019b). Due to its potentiality in improving the above sports performance, the current research on the potential application of tDCS in sports related skills has come to the foreground. So far, the research on the neurophysiological mechanism underlying tDCS's regulation of motor performance is relatively weak. It has been speculated that possible mechanisms of tDCS improving motor performance include: 1) increasing or decreasing the resting membrane potential leads to an increase or decrease of nerve excitability (Gandiga et al., 2006); 2) Regulating and altering synaptic activity (Stagg and Nitsche, 2011); 3) Improving functional connectivity of various brain regions (Meinzer et al., 2012).

An exploration of safe and effective improvement of athletes' competitive level and performance is a core part in science and technology' support in competitive sports. The neural plasticity of the human brain is that the neural circuit can be affected by external or internal factors and possess features of reorganization and reconstruction. Also, both disease and stress can cause changes in the synaptic function of the brain (Steinberg et al., 2018). As a stress event, sports training has a great impact on the structure and function of human brain. Research indicates that after long-term sports training, professional athletes are significantly different from ordinary people in brain structure, neural activation, fine regulation and other aspects. Transcranial direct current stimulation (tDCS) may further improve training results by regulating the brain regions that display the training-induced neural plasticity (Seidel-Marzi and Ragert, 2020). However, there are still controversies on the research results of professional athletes. Some studies have discovered that the utilization of tDCS has no (Valenzuela et al., 2019; Mesquita et al., 2020) or even deteriorating (Mesquita et al., 2019) effect on sports performance after an intervention on professional athletes. Other studies have proved that tDCS can significantly improve athletes' performance (Kamali et al., 2019; Machado et al., 2019). At present, the relevant research is still rare, and causes for the different results are to be further studied. More evidence is needed to see whether tDCS can help to further improve the exercise ability at a high level of exercise.

Currently, most intervention methods used in scientific studies are single acute stimulation. Some results show that single acute tDCS stimulation can improve the body's performance, such as muscle strength and endurance. Xiao (Xiao et al., 2020) et al. studied acute effects of a single high definition transcranial direct current stimulation (HD-tDCS) on foot muscle strength and static balance, and found that it has improved the toe flexor strength and static standing balance performance. Angius (Angius et al., 2019b)'s acute tDCS stimulation program enhanced the individual's inhibitory control and endurance cycle performance. Halo Sport headset is a commercial device based on tDCS technology. Huang et al. (Huang et al., 2019) applied Halo Sport to the motor cortex of healthy adult men and found that it has a significant promoting effect on cycling power output and cognitive executive function. Currently, few studies have explored the effects of tDCS on professional rock climbers. Hence, this experiment takes professional rock climbers as subjects and uses Halo Sport transcranial DC headset to observe the effect of an acute intervention on their aerobic performance and one-arm pull-down explosive force, so as to further enrich the experimental research in this field.

2 Methods

2.1 Subjects

Twenty athletes (twelve male and eight female) from the Rock Climbing Team of Hunan province (Hunan, China) were chosen for this study. Subjects were recruited from filling questionnaires with basic information like age, years of training, etc., Their ages were 17.11 ± 2.38 years old, with a training duration of 5.80 ± 2.78 years, height of 166.82 ± 7.62 cm and weight of 58.18 ± 7.82 kg. The inclusion criteria are as follows: 1) between 15 and 20 years old; 2) healthy with normal muscle function; 3) at least 3 years of rock climbing training; 4) all athletes are from the same team to ensure that the training time and frequency are exactly the same. The exclusion criteria are as follows: 1) athletes with poor sleep, drinking or coffee habits, and chronic mental stress. 2) with a history of head injuries. Participants who fell into the exclusion criteria were excluded. Health conditions of participants were self-reported. The laboratory environment was quiet and stable during treatment (temperature 22° ± 0.5°C, humidity 47% ± 4%).

All subjects provided informed consent prior to the experiment, and were aware of the test content and experimental process prior to treatment. This research was approved by the Hunan Institute of Sports Science Committee (Agreement No. 2022112201).

2.2 Experimental procedure

We utilized randomized, double-blind and crossover experiments, Written informed consent was obtained from all participants. Participants were asked to wear sports clothes during test. Two or three simulation tests were conducted before formal testing to help athletes familiarize themselves with the test methods. 3 min warm-up exercise before formal test. Each subject received three tests, namely, a baseline test, a real stimulation, and a sham stimulation, and the interval between two tests was 72 h. All of the tests were conducted in the morning. In the formal experiments, the first time was the baseline test of motor ability, include Aerobic Performance Test and One-arm Pull-down Explosive Force Test, the second and third assessments were the true or sham stimulation, each with a motor ability test afterwards.

These two test procedures were the same as the first baseline test. During the intervention experiment, the subjects sat in a chair and wore Halo Sport transcranial DC earphones (Halo Neuroscience, United States). The current-stimulated portions of the brain were the left and right primary motor cortex, in accordance with the 10–20 international electrode positioning system. The Halo Sport was placed on the subjects' head after the device's integrated electrodes were saturated with water. The associated mobile application was used to confirm a strong connection. In the real stimulation group, the current gradually increased from 0 mA to 2 mA within 30 s, and the whole testing lasted for 20 min; in the sham stimulation-controlled group, the current gradually increased from 0 mA to 2 mA within 30 s, then dropped to 0 mA within 30 s, and subjects continued to wear their headphone until 20 min of testing concluded. In testing, only one athlete and one tester were left in the quiet laboratory. In the real stimulation testing, some athletes felt itchy and slight tingling on the head, with no other adverse reactions (Figure 1 and Figure 2).

2.3 Aerobic performance test

A Monark powered bicycle (Monark 928E, Sweden) was used for aerobic tests. The experimental methods refer to Li et al. (Li et al., 2010), Three minute incremental exercise can be an effective way to test aerobic capacity. The subjects wore a Polar heart rate strap and received three-level load exercise tests of 50 w, 100 w, and 150 w, respectively. The exercise time of each level of load was 3 min, meaning 9 min in total. Heart rates at all three levels of load during exercise, immediately after exercise, and the first, third, and fifth minutes of the recovery period after exercise were recorded. The recovery heart rate per unit time was then calculated. This was plotted using the following equation: recovery heart rate per unit time (10 s) = (heart rate in the fifth minute of recovery period—heart rate immediately after the exercise)/30.

2.4 One-arm pull-down explosive force test

Keiser Pneumatic Resistance Training Machines (Keiser3025, United States) was used for this test. those machines seem credible for 1RM testing (Lu et al., 2021). During the first time period, the best resistance test was conducted. The subject grasped the pull strap with both hands, and first took a light resistance test three times, and then the heavy resistance test for three times. This way, the best resistance force that could produce the maximum explosive force was calculated. With this resistance value, a full standardized one-arm high pull-down test was conducted three times, and the interval between two tests was 1 min. The optimal value was then taken.

2.5 Data analysis

SPSS 22.0 was used data for statistical analysis. The data, expressed as the mean ± standard deviation (x ± s), were assessed by two-way ANOVA (stimulus mode × time). Stimulus modes of real stimulation and sham stimulation and test time points were used as independent variables, while the test results were used as dependent variables. Mauchly's test was used to test the sphericity hypothesis. When the sphericity test was met, a paired sample t-test was used to compare each group, and when it was not met, multivariate tests were used. LSD was utilized for pairwise comparisons to analyze the differences of indicators at different times and in different intervention modes. Cohen's d was used to express the effect size: 0.2 was a weak effect, 0.5 was a medium effect, and 0.8 was a strong effect. $p < 0.05$ indicated that a difference was significant.

3 Results

3.1 Aerobic performance test

Figure 3 displays the immediate heart rate after 9 min of aerobic activity. There was no interaction between stimulation and test time (F = 1.254, $p = 0.298$). T-test results for paired samples were used to assess the immediate heart rate after three-level load exercise, and no significant difference was observed between after real stimulation and before stimulation ($p = 0.281$, Cohen's d = 0.248), after sham stimulation and before stimulation ($p = 0.278$, Cohen's d = 0.249), or after real stimulation and after sham stimulation ($p = 0.882$, Cohen's d = 0.034). these results all show small effect sizes.

Figure 4 shows the drop rate in heart rate per unit time. There was no statistically significant interaction between stimulation and test time (F = 2.441, $p = 0.101$). The paired sample t-test results showed that after real stimulation was significantly higher than before stimulation ($p = 0.045$, Cohen's d = 0.480), and slightly higher than after sham stimulation with no significant difference ($p = 0.443$, Cohen's d = 0.175). After sham stimulation also showed no statistical difference compared with before stimulation ($p = 0.151$, Cohen's d = 0.335). these results all show small effect sizes.

3.2 One-arm pull-down explosive force test

Figures 5, 6 show that there was no interaction between the stimulation of left-arm pull-down explosive force and test time (F = 0.796, $p = 0.459$). No significant difference was detected between after real stimulation and before stimulation ($p = 0.334$, Cohen's d = 0.222). After sham stimulation improved slightly compared with before stimulation, but there was no statistically significant difference ($p = 0.443$, Cohen's d = 0.175). No

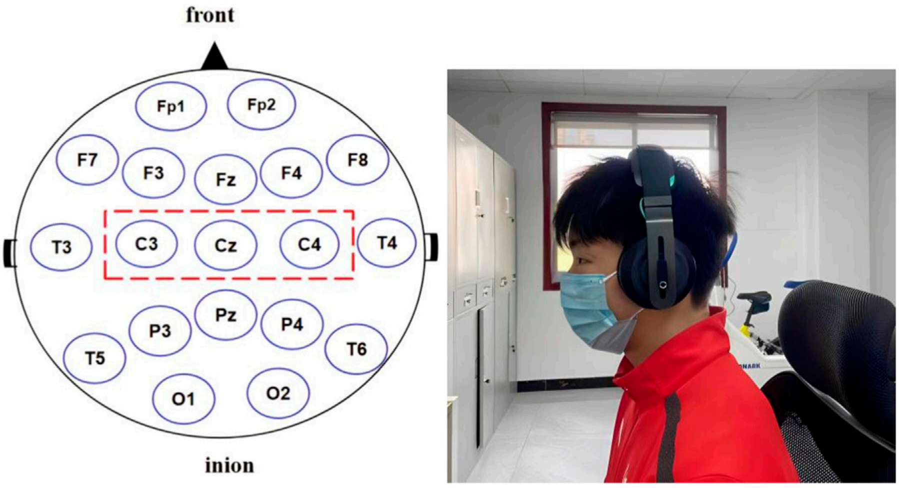

FIGURE 1
The red dotted box represents the stimulated areas in the picture on the left. The image on the right is an athlete undergoing treatment.

FIGURE 2
Study design. Pre-test and post-test indicate sports performance test, a-tDCS represents current gradually increasing from 0 mA to 2 mA within 30 s, and the whole test lasted for 20 min.

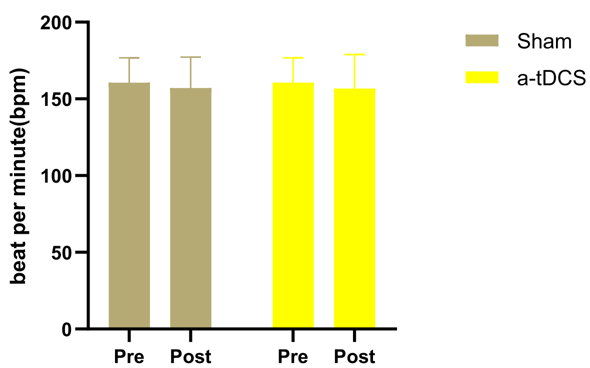

FIGURE 3
Immediate heart rate after 9-min aerobic activity. The white bars represent real stimulation compared to pre-stimulation, and the gray bars represent sham stimulation compared to pre-stimulation. “Pre” means before stimulation, and “post” means after stimulation.

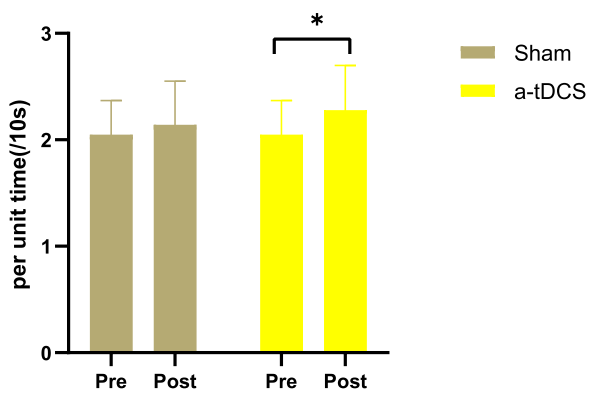

FIGURE 4
Drop in heart rate per unit time. The white bars represent real stimulation compared to pre-stimulation, and the gray bars represent sham stimulation compared to pre-stimulation. “Pre” means before stimulation, and “post” means after stimulation. Note: * indicates $p < 0.05$.

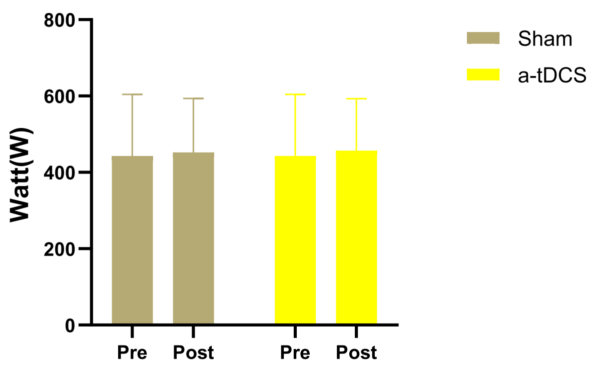

FIGURE 5
Left-arm pull-down explosive force. The white bars represent real stimulation compared to pre-stimulation, and the gray bars represent sham stimulation compared to pre-stimulation. "Pre" indicates before stimulation, while "post" represents after stimulation.

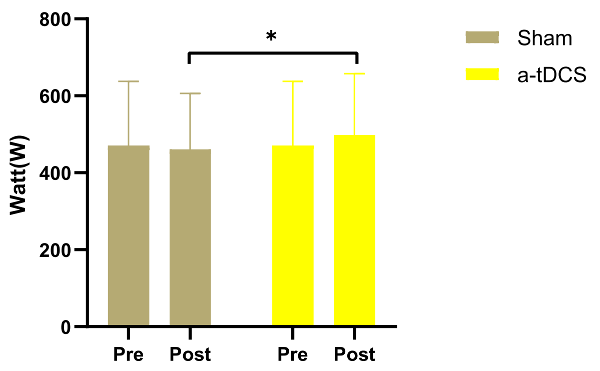

FIGURE 6
Right-arm pull-down explosive force. The white bars represent real stimulation compared to pre-stimulation, while the gray bars represent sham stimulation compared to pre-stimulation. "Pre" means before stimulation, and "post" means after stimulation. Note: * means $p < 0.05$.

significant difference was observed between the real and sham stimulation groups ($p = 0.736$, Cohen's d = 0.076). The right-arm pull-down explosive force stimulation showed no interaction with test time (F = 0.417, $p = 0.662$). Compared with before stimulation, the after real stimulation group was improved but without a significant difference ($p = 0.279$, Cohen's d = 0.249), and after real stimulation was significantly improved compared with after sham stimulation ($p = 0.046$, Cohen's d = 0.165), and there was no significant difference between after sham stimulation and before stimulation ($p = 0.469$, Cohen's d = 0.478). these results all show small effect sizes.

4 Discussion

Rock climbing has attracted much international attention after its inclusion as an official event in the next Olympic Games, and thus, improvement of its scientific training level has become a focus in sports research. Currently, tDCS, a new technology to assist athletic sports, is at the forefront of sports training, but reports on its application in professional athletes are rare and inconsistent. Thus, we sought to explore the effects of tDCS on the athletic ability of long-term professionally trained rock-climbing athletes. To this end, athletes' bilateral motor cortexes were stimulated using Halo Sport transcranial DC earphones at an intensity of 2 mA for 20 min. The experimental results showed that acute tDCS stimulation had no distinct effect on the heart rate immediately after intensity-incremental aerobic load testing. However, it did significantly improve the heart rate decline during the recovery period after aerobic exercise, and a single acute stimulation impacted the explosive force in one-arm pull-down tests of rock climbers.

4.1 Effects of tDCS on aerobic performance in rock climbers

Aerobic capacity is one of the key factors affecting the performance of elite rock climbers, improving whole-body aerobic capacity is a notable contribution to Rock climbing performance (Fryer et al., 2018). Research showed that a steady-heart rate or entrance into a stable state was observable approximately 3 min after moderate intensity uniform motion, and the heart rate at this moment reflects aerobic exercise intensity (Du et al., 1998). Therefore, this study adopted an aerobic exercise program with three level incremental loads, and each level lasted for 3 min. During true and sham stimulations, the heart rates immediately after exercise were slightly improved compared with before stimulation, but this was not statistically significant. This result was consistent with current results at home and abroad. Some research (Park et al., 2010; Holgado et al., 2019) has shown that tDCS has no effect on cardiorespiratory responses during exercise, such as heart rate (HR) and oxygen uptake (VO2). For example, Mesquita et al. (Mesquita et al., 2020) studied whether anode tDCS had a significant effect on aerobic performance in professional taekwondo athletes. Machado et al. (Da Silva Machado et al., 2021) also reported that the heart rate of 80% cycle endurance tests and other physiological indices of endurance athletes did not change after 20-min high-precision tDCS (HD tDCS) (2.4 mA) and traditional tDCS (2.0 mA). The reason may have been that the communication between the central nervous system and the exercise unit was only regulated by afferent responses or there was a ceiling effect. Previous studies have also revealed (Hilz et al., 2002; Tanaka et al., 2009) that the heart rate during exercise is controlled by the autonomic nervous system, thus increasing or decreasing parasympathetic and sympathetic functions can affect fatigue and sports performance. Meta analysis has shown that non-invasive brain stimulation (NIBS), including tDCS, can affect cardiovascular and autonomic nervous system activities (Makovac et al., 2017). Okano et al. (Okano et al., 2015) applied tDCS to the temporal lobe cortex (TC) of professional cyclists, using a 2-mA current for 20 min. They observed that the heart rate decreased under sub-maximum workload, suggesting that anode tDCS seemed to induce cardiac autonomic control and the improvement of cardiac efficiency during aerobic exercise. Another study (Kamali et al., 2019) also reported a decrease of heart rate of 4.9% in bodybuilders when they were doing 12 knee joint stretching exercises 13 min after a 2-mA current stimulation of the M1 and left TC area. However, the current evidence is still inconclusive about the effects of tDCS on heart rate during exercise, and no significant effect was observed in this study. It has been speculated that results can affected by factors like the setting of each exercise program, electrode stimulation parameters and brain positioning, and any slight improvement of aerobic capacity on athletes in this experiment may be attributable to some positive psychological implications of the intervention mode.

Our study highlighted that tDCS can promote the recovery of heart rate after exercise. Moreira et al. (Moreira et al., 2021) stimulated the left and right dorsolateral prefrontal cortex (F3 and F4) of professional football players with 2 mA for 20 min to test the heart rate recovery 1 min after exercise. They also found that tDCS had a significant effect on the rapid recovery of early heart rate. They suggested that tDCS intervention might lead to changes in brain regions related to autonomous control, and ultimately caused the activation of parasympathetic autonomic activities to optimize the recovery of players. In addition, Montenegro et al. (Montenegro et al., 2013), after a research on 11 healthy men, discovered the regulatory effect of tDCS on physiological function after exercise. They speculated that the effect of tDCS on the prefrontal cortex may have a beneficial impact on autonomic respiratory control by increasing VO2 and energy consumption after aerobic exercise. Although there is scant relevant research, the effect of tDCS on regulating autonomic nervous activity and promoting the recovery of athletes after sports is an important contribution to this field.

4.2 Influence of tDCS on the upper limb explosive force of rock climbers

Strong back muscle strength is crucial to rock-climbers. As a classic action in physical training, high pull-down tests reflects the muscle strength of the upper back, latissimus dorsi and trapezius. tDCS appeared to result in better enhancement of muscle strength than muscle endurance and other sports performance metrics, and this enhancement was consistent across different subjects, such as ordinary subjects and patients (Sun et al., 2021; Chinzara et al., 2022). Patel et al. (Patel et al., 2019) summarized reports on the effects of tDCS on the upper limb motor performance in healthy adults, and found that tDCS could significantly increase upper limb strength. Hazime et al. (Hazime et al., 2017) conducted tDCS on female handball players, participating in regional and national competitions, and discovered that it could increase their maximum isometric contraction strength of the internal and external rotation shoulder muscles. Lattari et al. (Lattari et al., 2016) carried out a tDCS program on bodybuilders who had received resistive exercise training for at least 3 months and noted increased strength in their elbow flexion. The results of this study also showed that tDCS applied to the primary motor cortex may enhance the explosive force of one-arm pull-down in rock climbers. The neurophysiological mechanism of tDCS's improvement of motor performance has been reported in a small number of reports. Hendy et al. (Hendy et al., 2014) found that the application of a 20-min current of 2 mA to the right motor cortex could significantly improve maximum autonomic strength of the untrained wrist, and along with corticospinal excitability, reduced inhibition in the short interval cortex and increased cross activation. In addition, Alix et al. (Alix-Fages et al., 2020) conducted a 15-min 2 mA tDCS stimulation of the dorsolateral prefrontal cortex in 14 healthy men, and discovered that with one repeat maximum, the force-velocity relationship parameters were not improved. This was because other factors such as effect size, stimulation parameters, genetics, gender, experience and even skull thickness may regulate tDCS effects (Zimerman and Hummel, 2010; Craig et al., 2020; Hunold et al., 2021).

There were some limitations in this study that need to be noted, such as the major limitation of the present study, which was that the sample size was too small In order to avoid sample differences caused by a large age span, the sample size needs to be further expanded in future studies.

5 Conclusion

tDCS as a new technology to assist athletic sports could potentially benefit the sports performance of professional athletes. Future studies should be conducted with larger samples to increase the statistical power of these findings.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by Hunan Institute of Sports Science Committee. The patients/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

Conceptualization, JL and SH; methodology, ZR, JL, and CF; Validation, JL and CF; investigation, JL and CF; resources, ZR; writing—original draft preparation, JL; writing—review and editing, JL, JW, WX, LB, JY, and ZR. All authors have read and agreed to the published version of the manuscript.

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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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Kinematic parameters and metabolic power in elite soccer players: A small sided a large sided games comparison

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Introduction: The goal of this paper is to determine what happens in one minute (on average) in kinematic parameters and metabolic power in small sided games (SSG) (3v3; 5v5) and large sided games (LSG) (10v10) and in which games kinematic parameters and metabolic power are best developed.

Methods: The participants of this study were 22 professional football players, height 182.95±6.52 cm, mass 77.17±8.21 kg, body mass index (BMI) 22.97±1.47 kg/m2, body fat 9.85±2.55 %, aged 27.1±5.4 yrs, who played in the Premier League of Bosnia and Herzegovina. Data total distance (TD), maximum speed (MS), number of accelerations (nAcc), number of decelerations (nDec), number of sprints (nS), high intensity distance (Z4≥19.8 km/h), sprint distance (Z5≥25.2 km/h) and movements requiring a certain metabolic power (Pmet), were collected using a 20 Hz Global positioning system (GPS) system Pro2 (GPEXE, Exelio srl, Udine, Italy), on a total of 307 individual observations.

Results: The results showed that the average total distance was significantly higher in the 5v5 (135.16±18.78 m) and 10v10 (133.43±20.06 m) games ($F=64.26$, $p<0.001$) compared to the 3v3 (108.24±11.26 m). Furthermore, the values of the variables Z4 (8.32±3.38 m, $F=97.59$), Z5 (1.84±1.53 m, $F=123.64$), nS (0.13±0.10 n, $F=96.14$) as well as Maxspeed (27.06±1.90 km/h, $F=139.33$), are statistically significantly higher ($p<0.001$) in the 10v10 game compared to the other two game formats. The average number of nAcc (0.40±0.32 n, $F=9.86$, $p<0.001$) and nDec (0.62±0.36 n, $F=6.42$, $p<0.001$) is statistically significantly higher in the 5v5 game. The results showed that the 5v5 game is significantly more metabolically demanding Pmet (2.76±0.67 W•kg^{-1}, $F=66.08$, $p<0.001$) compared to the other two game formats.

Discussion: The data presented in this paper can be used as a basis for the construction of specific exercises based on kinematic and physiological requirements, and for planning and programming microcycles in football.

KEYWORDS

soccer (football), global positing system (GPS), acceleration, small sided games, duration

Introduction

Sports with a ball, such as football, are complex adaptive systems that enable the emergence of rich patterns of player movement in a constantly dynamically changing environment (Silva et al., 2016). In elite football, coaches are constantly looking for drills and modified games, which can contribute to improved physical, technical and tactical performances of the football players. Although the football match is played with 11 players per team, the SSG often includes <4 players per team (with or without a goalkeeper) on reduced pitch areas (Dellal et al., 2011). The SSG is a training method for which coaches consider to optimize training time and allows trainers to repeat the requirements as in the football match (William et al., 2018). This is the reason football coaches constantly used SSG to improve and maintain physical fitness including technical and tactical performance in elite football. Internal and external loading in SSG characterize to collect values of heart rate, movement demands, blood lactate, and rate of perceived exertion (Hill-Haas et al., 2011). Research has confirmed that the size of the playing area, the rules of the game and number of players all influence the acute physiological response (Hill-Haas et al., 2011; Casamichana et al., 2012). Also, the validity and reliability of kinematic parameters has been the subject of extensive research in recent years. In the scientific literature, you can find a large number of scientific research that prove the validity and reliability of kinematic parameters (Scott et al., 2016; Bastida-Castillo et al., 2018). It is not well understood what impact SSGs may have in the hours and days that follow. A greater understanding of this would be of interest to those responsible for the design of football training programs, given the possible influence that this may have on additional training sessions performed within the week. The metabolic power (Pmet) presented as a tool to estimate the energetic demands of variable-speed and accelerated/decelerated locomotion activities typically seen in football games. While it is difficult to measure directly the exact energy cost of changing speed, a metabolic power calculation based on a theoretical model has been used to estimate the energy cost of locomotion in football games (Polglaze and Hoppe, 2019). However, this model was questioned since it may underestimate the actual net energy demand of football - specific exercises. Additionally, the traditional speed-threshold approach was shown to provide a similar external load compared to Pmet (Dubois et al., 2017). Nevertheless, the metabolic power approach could capture the high—demanding locomotor activities independently of the actual speed registered by GPS, and it was shown to be a useful tool for the classification of the locomotion intensity in team sports (Riboli et al., 2020). The study carried out by (Manzi et al., 2014) presented evidence of the validity of this approach by stating a positive correlation between Pmet and aerobic fitness during elite football matches. Moreover, Pmet can be sensitive to decrements in running performance during competition (Malone et al., 2016) and it could be used to account for positional differences. A combination of the Pmet approach and traditional speed—threshold measurement is used to understand assessment of the intermittent running demands typically occurring in football games (Riboli et al., 2020), because, may help to plan the training sessions to condition the locomotor activities typically required during the official match and to optimize performance goals (Martin-Garcia et al., 2018). The goal of this paper is to determine what happens in 1 min (on average) in kinematic parameters and metabolic power in SSG (3v3; 5v5; 10v10) and in which games kinematic parameters and metabolic power are best developed.

Materials and methods

Participants and drills observations

The research included a sample of 22 professional football players FK Borac, Banja Luka, height 182.95 ± 6.52 cm, body mass 77.17 ± 8.21 kg, BMI 22.97 ± 1.47 kg/m2, body fat 9.85% ± 2.55%, age 27.1 ± 5.4 years. A total of 307 individual drill observations were undertaken on outfield players (goalkeepers were excluded). The football players participated in this research are competing in the Premier league, highest ranked competition of Bosnia and Herzegovina. The testing was done in 2020/2021. To be qualified to participate in the research, the players should satisfy the following criteria: that the players have been on the first team for at least 6 months, that all players have gone through a preparatory period with the team, without injuries in the last 6 months, that they have played one half-season before testing. The footballers were excluded from the testing in case: football players in the recovery phase from some form of acute or chronic injuries, football players who did not complete the entire preparatory period. All the players were informed about the purpose and the goal of this research and the procedure was explained to them. The club president, main coach and all the players signed the paper accepting participation in the test. The research was approved by the Ethics Commission of the Faculty of Sports and Physical Education, University of Banja Luka in accordance with the Declaration of Helsinki. The players were instructed not to consume performance enhancing substances such as creatine, ribose, *etc.* (coffee was limited to 1 cup) prior to tests, not to engage in high intensity physical activity 24 h prior to the tests (Tatlicioglu et al., 2019).

Data collection

The players' physical activity during each training sessions were monitored using portable global 20 Hz GPS system Pro2 (GPEXE, Exelio srl, udinese, Italy). This version of the SPI Pro (6 g tri-axial accelerometer sampling at 20 Hz integrated; size = 48 × 20 × 87 mm; mass = 76 g) provides raw position, velocity and distance data at 20 Hz (20 samples per second). For the purpose of this study, every three raw data points were averaged to provide a sampling frequency of 5 Hz (Gaudino et al., 2013). A particular vest was tightly fitted to each player, placing the receiver between the scapulae. All devices were always activated 15-min before the data collection to allow acquisition of satellite signals (Maddison and Ni Mhurchu, 2009). The minimum acceptable number of available satellite signals was 8 (range 8–11) (Varley et al., 2012). Data was eliminated on days when the satellite signal was below this value. In addition, in order to avoid inter-unit error players wore the same GPS device for each training sessions (Buchheit et al., 2014). This type of system has previously been shown to provide valid and reliable estimates of instantaneous velocity during acceleration, deceleration, and constant velocity movements (Varley et al., 2012). This instrument has previously been used in order to quantify the number of accelerations during elite Australian football matches (Varley and Aughey, 2013). However, as 5 Hz GPS may slightly underestimates instantaneous velocity during acceleration or high speed movements any reported values in this investigation are the minimum of what a player would actually undertake during the analysed drill (Varley et al., 2012). Through the use of this instrument drill duration, total distance covered and distance covered in the different speed categories was calculated using a custom Excel spreadsheet from instantaneous raw data of time, speed and distance available from the GPEXE cloud (GPEXE, Exelio srl, Udine, Italy). In the same program instantaneous acceleration values were calculated by dividing the change in speed by time. Finally, the mathematical model proposed by di Prampero et al. (2005) were also integrated in the custom spreadsheet in order to calculate total estimated energy expenditure, average metabolic power, and distance covered in different metabolic power categories as reported in previously studies using GPS technology.

Study procedures

Kinematic parameters, total distance passed (TD), maximum speed (MS), acceleration numbers (nAcc), deceleration numbers (nDec), number of sprints (nS), number of jumps (nJumps), distance (Z4), sprint distance (Z5) and movements requiring a certain metabolic power (Pmet), were obtained using a 20 Hz GPS system Pro2 (GPEXE, Exelio srl, Udine, Italy). Studies, (Nagahara et al., 2017; Hoppe et al., 2018), confirmed the reliability and validity of the application of the GPS system in science and practice. The GPEXE unit determined acceleration as any change in speed of movement by 2.5 m/s for a duration of 0.5 s, while it determined deceleration as any change in speed of movement by −2.5 m/s for a duration of 0.5 s. Furthermore, (Z4) are registered as high-intensity running ≥19.8 km/h for a minimum duration of 0.5 s, (Z5) sprint distance ≥25.2 km/h for a minimum duration of 0.5 s and the number of sprints as all movements at a speed ≥25.2 km/h for a minimum duration of 1 s. Regarding predicted metabolic parameters, average metabolic power (Pmet) was calculated (di Prampero et al., 2005). Pmet categories were defined as: distance covered (m) at high power (HP; from 20 to 35 W kg^{-1}), elevated power (EP; from 35 to 55 W kg^{-1}) and maximal power (MP; >55 W kg^{-1}) (di Prampero et al., 2005; Gaudino et al., 2013). Total distance covered at high Pmet (TP; >20 W kg^{-1}) was also analyzed as an indicator of the high intensity distance covered (Gaudino et al., 2013; Gaudino et al., 2014a). Jump calculation was performed based on the movement of the gyroscope integrated inside the GPS unit. A jump is software-determined as any movement of the GPS unit in the vertical direction over 20 cm.

Small-sided games (SSG) and large sided games (LSG)

In this research (SSG) were analyzed in three different formats (small 3v3+GK, medium 5v5+GK and large 10v10 + GK) for the development of functional capacities in specific conditions during the training process in the 2020/21 season. It should be emphasized that the training units in which auxiliary games were conducted represented the most intense loads during the microcycle and were conducted 72 h after the competitive match. The training units consisted of: standard warm-up for 20 min, elementary technique exercises for 10 min, possession of the ball for 10 min, and after that SSG. All training units were realized in the afternoon hours on a surface with natural grass in optimal weather conditions. SSG and LSG were determined by the number of players, the duration of the game, the number of sets, the length of the break between sets and the dimensions of the playing field (Verheijen, 2014) which is shown in Table 1. All SSG and LSG were realized by playing between two standard-sized goals with goalkeepers (GK) in goal. Modified football rules were applied: the player was limited to a maximum of 3 touches with the ball, otherwise the ball went to the opposing team while the goalkeeper had a maximum of 3 s to put the ball into play. The ball going out or a goal-out was determined by throwing the ball into play by the goalkeeper in relation to which team the ball went. It is very important to emphasize that the assistant coaches stood around the field for playing with balls, they controlled the speed of putting the ball into the game in case the ball goes out or a goal out and verbally encouraged the players to high intensity of the game itself. All players were familiar with the experimental and training procedures and during training they always wore the same GPS unit to reduce measurement error. Also, only the data of players who were completely physically healthy and who performed all the scheduled series in a specific game format for the given training were included in the analysis.

Data analysis

The normality of the distributions was confirmed by the Kolmogorov-Smirnov test, and the data are presented as the means ± standard deviations. Differences among 3 different formations SSG by 1 min play were analyzed by one-way analysis of variance, while the consecutive LSD *post hoc* test was used to analyze the diffrences across variables. The statistical procedures were executed on SPSS software (version 26.0, IMB, United States) for $p < 0.05$.

Results

Table 2 present the descriptive parameters of the kinematic analysis of 3 different support game formats (small 3v3 + GK, medium 5v5 + GK and large 10v10 + GK) based on 1 min of play (average).

Anova shows a statistically significant difference ($p < 0.05$) in all compared variables for all three game formats (Table 3). The analysis showed that the average distance covered in 1 min is significantly higher in the medium 5v5 (135.16 ± 18.78 m) and large 10v10 (133.43 ± 20.06 m) game formats ($F = 64.26$, $p < 0.001$) compared to the small 3v3 (108.24 ± 11.26 m) game format. However, it is very interesting that the statistical analysis did not show a statistically significant difference between the medium and large format of the game when it comes to the average distance passed in 1 min. Furthermore, the results show that the values of the

TABLE 1 Small sided games and large sided games.

Game format	Game duration (min)	Pause between sets (min)	Field Dimensions (m)	Area of the playing Field (m^2)
3v3+GK	2 × 6 × 1 min	2	30 x 18	600
5v5+GK	4 x 5 min	2	50 x 30	1500
10v10+GK	3 x 12 min	2	100 x 60	6000

TABLE 2 Descriptive statistics of variables based on 1 min of play in three different game formats.

Variables	SSG and LSG	Mean ± Std.Dev	95% CI
	3v3	108.24 ± 11.26	105.65–110.84
TD	5v5	135.16 ± 18.78	132.27–138.04
(m)	10v10	133.43 ± 20.06	128.53–138.32
	3v3	2.71 ± 1.59	2.34–3.08
Z4 (m)	5v5	3.26 ± 2.84	2.82–3.69
	10v10	8.32 ± 3.38	7.49–9.14
	3v3	0.98 ± 0.26	0.03–0.16
Z5 (m)	5v5	0.109 ± 0.46	0.03–0.18
	10v10	1.84 ± 1.53	1.47–2.22
	3v3	0.38 ± 0.18	0.34–0.43
AccEvents	5v5	0.40 ± 0.32	0.35–0.46
(n)	10v10	0.23 ± 0.12	0.21–0.27
	3v3	0.55 ± 0.22	0.51–0.61
DecEvents	5v5	0.62 ± 0.36	0.56–0.68
(n)	10v10	0.46 ± 0.17	0.42–0.51
	3v3	1.88 ± 0.37	1.80–1.97
Metpower	5v5	2.76 ± 0.67	2.65–2.86
($W \cdot kg^{-1}$)	10v10	2.07 ± 0.62	1.92–2.23
	3v3	23.60 ± 1.84	23.17–24.03
Maxspeed	5v5	22.05 ± 2.22	21.71–22.39
(km/h)	10v10	27.06 ± 1.90	26.60–27.53
	3v3	0.53 ± 0.31	0.46–0.60
Jumps	5v5	0.34 ± 0.36	0.29–0.40
(n)	10v10	0.07 ± 0.09	0.05–0.10
	3v3	0.01 ± 0.04	0.00–0.02
Sprints	5v5	0.01 ± 0.46	0.00–0.02
(n)	10v10	0.13 ± 0.10	0.11–0.16

Legend: TD, total distance; Z4, distance 4 (≥19,8 km/h); Z5, distance 5 (≥25.2 km/h); AccEvents, acceleration; DecEvents, deceleration; Metpower, Metabolic power; MaxSpeed, maximal speed.

variable (Z4 ≥ 19.8 km/h) obtained in the 10v10 game (8.32 ± 3.38 m, F = 97.59, p=<0.001) are significantly different compared to the values obtained in the 3v3 format (2.71 ± 1.59 m) and 5v5 (3.26 ± 2.84 m), while no statistically significant difference was obtained between the 3v3 and 5v5 games. The greatest distance in the Z5 sprint (≥25.2 km/h) was also achieved by the players in the

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TABLE 3 Differences in kinematic parameters and metabolic power.

Variables	Mean ± Std.Dev			F	Sig
	3v3	5v5	10v10		
TD (m)	108.24 ± 11.26	135.16 ± 18.78†	133.43 ± 20.06†	64.268	**.001**
Z4 (m)	2.71 ± 1.59	3.26 ± 2.84	8.32 ± 3.38†‡	97.590	**.001**
Z5 (m)	0.98 ± 0.26	0.109 ± 0.46	1.84 ± 1.53†‡	123.64	**.001**
Accevents	0.38 ± 0.18†	0.40 ± 0.32‡	0.23 ± 0.12	9.868	**.001**
(n) Decevents	0.55 ± 0.22	0.62 ± 0.36†‡	0.46 ± 0.17	6.423	**.002**
(n) Metpower (W·kg-1) Maxspeed	1.88 ± 0.37 23.60 ± 1.84†	2.76 ± 0.67†‡ 22.05 ± 2.22	2.07 ± 0.62† 27.06 ± 1.90†‡	66.088 139.331	**.001** **.001**
(km/h) Jumps (n) Sprints (n)	0.53 ± 0.31†‡ 0.01 ± 0.04	0.34 ± 0.36† 0.01 ± 0.46	0.07 ± 0.09 0.13 ± 0.10†‡	37.54 96.149	**.001** **.001**

Legend: TD, total distance; Z4, threshold of zone 4; Z5, threshold of zone 5; AccEvents, acceleration; DecEvents, deceleration; Metpower, metabolic power; MaxSpeed, maximal speed.

10v10 game (1.84 ± 1.53 m, F = 123.64, $p < 0.001$), which is a significantly higher result compared to this kinematic parameter achieved in the 3v3 and 5v5 games, with the fact that no statistically significant difference was observed between the small and medium format of the game. The average number of accelerations made by the players during 1 min is statistically significantly higher in 3v3 (0.38 ± 0.18) and 5v5 (0.40 ± 0.32, F = 9.86, $p < 0.001$) than in 10v10 games (0.23 ± 0.12). The results further show that there was a significantly higher average number of decelerations in the medium 5v5 game format (0.62 ± 0.36 n, F = 6.42, $p < 0.001$) compared to the small and large game formats. The statistical parameters showed that there is no significant difference between the small (3v3) and medium (5v5) game formats. Energy requirements assessed based on the Metpower variable showed that the medium 5v5 game format was significantly more metabolically demanding (2.76 ± 0.67 W kg^{-1}, F = 66.08, $p < 0.001$) compared to the other two game formats, while between the small 3v3 (1.88 ± 0.37 W kg^{-1}) and large 10v10 (2.07 ± 0.62 W kg^{-1}) game format had no statistically significant differences. The average maximum running speed was statistically significantly higher in the large game format 10v10 (27.06 ± 1.90 km/h, F = 139.33, $p < 0.001$) compared to the remaining two game formats, however, it is interesting to note that the players in the small game format 3v3 (23.60 ± 1.84 km/h) achieved a statistically significantly higher average maximum speed compared to the medium format of the 5v5 game (22.05 ± 2.22 km/h).

The average number of jumps was significantly higher in the small game format 3v3 (0.53 ± 0.31 n, F = 37.54, $p < 0.001$) during 1 min of the game, compared to the other two games, while between the medium 5v5 (0.34 ± 0.36 n) and the large 10v10 (0.07 ± 0.09 n) game format confirmed a statistically significant difference. However, players achieved a significantly higher average number of sprints in the large 10v10 game format (0.13 ± 0.10 n, F = 96.14, $p < 0.001$) compared to the small 3v3 and medium 5v5 game formats, while no statistically significant difference was found between them.

Discussion

The goal of this paper is to determine what happens in 1 min (on average) in kinematic parameters and metabolic power in SSG (3v3; 5v5; 10v10) and in which games kinematic parameters and metabolic power are best developed. According to the author's knowledge so far, this is the first study that analysed what happens during 1 min (on average) in kinematic parameters and metabolic power in SSG. Small sided games are used in football training both for the development of technical-tactical skills and for developing performance, and have become one of the most popular training methods at all ages and levels. Exercises of this type put players in situations that closely resemble those they will encounter in real game conditions, and reproduce many of the physical, physiological and technical demands of competitive football (Castellano and Casamichana, 2013). Different variants of SSG (3v3, 5v5, 10v10) have a different impact on the development of certain kinematic parameters and metabolic power. The field size is considered a key factor in football training because the players' density conditions internal and external load (Sannicandro, 2021). The results obtained in this study indicates that in the 5v5 game the highest total distance passed was recorded (135.16 ± 18.78 m) compared to 3v3 and 10v10. In contrast to the results in this study, Guard et al. (2021), in a 5v5 game recorded a total distance of (242 m). Dellal et al. (2011) in the 3v3 game recorded values of (315 m) in elite soccer players, while in amateurs they recorded a value of (272 m). The results of the total distance obtained in this paper are significantly lower compared to the results obtained by (Dellal et al., 2011; Sannicandro, 2021) The reason for this is that in our study in SSG, the goalkeeper was used in all games, and the results represented average values during 1 min. Research indicates that the results obtained in SSG with goalkeepers lead to a lower heart rate and a lower total distance traveled by the players. Also, in SSG with a goalkeeper, players try to organize their team's defense to protect their goal, which affects the total distance during the game (Mallo and Navarro, 2008), which is confirmed by our results obtained in all SSGs. In practical terms, the results of this study indicate that coaches can adjust the intensity of training by varying the size of the field. In general, the dimensions of the field can change the kinematics of movement in relation to each player. Basically, the space for possession of the ball and the execution of actions are directly related to the space between the players, as well as the free space for decision-making. In this sense, the player can be limited by the dimensions of the field, causing changes in physiological and kinematic parameters. Smaller spaces can encourage more stops, changes in movement or acceleration. On the other hand, larger dimensions of the field can allow players more time to move, to perform their actions planned and with more space (Tessitore et al., 2006). The total high-intensity running distance and sprints is indicated as a key factor for success in football match performance in addition to the technical skills to maintain greater ball possession, the total distance covered with ball possession, and the tactical behaviors (Riboli et al., 2022). The results of this study indicate that in variable Z4 (≥19.8 km/h) and Z5 (≥25.2 km/h) in the 10v10 game recorded higher values compared to the medium and small format games. The reason for such results is that the players had modified rules, the goalkeeper could keep the ball in his possession for a maximum of 3 s, while the players had the right to three contacts with the ball. The results in our study are justified by the research carried out by Jake et al. (2012), stating that the modified rules of the game significantly affect the intensity of game in SSG. On the other hand; Dellal et al. (2011), in their research state that free play in SSG leads to a greater number of duels but a reduced number of sprints and high-intensity running compared to one and two-touch play. The reason for the reduced intensity of running in the game 3v3 and 5v5 is the presence of the goalkeeper and the size of the field on which SSG is implemented (Sassi et al., 2004; Mallo and Navarro, 2008; Koklu et al., 2011). In large sided games, di Prampero et al. (2005), noted an increase in physiological and kinematic parameters. This contradiction may be due to the inclusion of goalkeepers changing the physiological and tactical behavior of outfield players, as it is possible that some players were more motivated than others. Therefore, the goal of scoring goals and at the same time protecting one's own goal imposed greater physiological and kinematic activities on the players (Spalding et al., 2004). The average number of accelerations is significantly higher in the 3v3 and 5v5 games compared to the 10v10 game, while the number of decelerations is the highest in the 5v5 game compared to the 3v3 and 10v10 games. The results of this study are similar to another study by SSG in football (Guard et al., 2022). As stated by Guard et al. (2022), the higher loading of kinematic parameters (accelerations and decelerations) in the team that is not in possession of the ball, may be the result of higher average speed, acceleration and deceleration compared to the team that is in possession of the ball, creating a greater degree of consumption of anaerobic and aerobic energy, trying to regain possession of the ball. On the other hand, the distance traveled and the frequency of efforts performed for acceleration and deceleration are not feasible on small game formats. The reason for the large number of accelerations and decelerations is mainly due to the limited space where players, especially in the central areas, try to move away from the opponent and find space to receive the ball. Our statements are confirmed by the research of Seifert et al. (2013), in which it is stated that players can trigger powerful accelerations in their games, but are quickly hindered by the boundaries of the field. On the other side, player movements can be the result of continuous functional adaptation arising from game design to maximize success. According to the results of previous studies (Dellal et al., 2011; Hill-Haas et al., 2011; Castellano et al., 2013), the average energy consumption (Pmet) was higher as the surface of the field increased, the number of players decreased, or the number of players who had limited. The results of our study are not in agreement with previous studies because the higher energy consumption was recorded in the medium format 5v5 game. This suggests that small game areas stress different physiological components of performance compared to large areas, which cannot be detected by measuring distance traveled and speed achieved (Gaudino et al., 2014b). When it comes to maximum speed, the results obtained in this research indicate that the highest speed was recorded in the 10v10 game. On the other hand, a higher maximum speed was achieved in the 3v3 game compared to the 5v5 game. In previous research, it has been found that SSG with goalkeepers provides an environment where the total distance increases with more players and available playing space, which is explained by the higher average speed of players trying to find space away from their opponents. The higher average maximum speed also makes it difficult to accelerate and decelerate from a higher speed, given that the movement speed is already relatively high and the limited space in the SSG does not allow for pronounced high-speed activity. Therefore, it can be suggested that SSG appear to be highly contextual in how their design affects individual physical and subjective outcomes (Guard et al., 2021). Research comparing SSG with and without a goalkeeper indicates that games without a goalkeeper are physiologically more demanding in terms of kinematic parameters (Castellano and Casamichana, 2013). Identifying the most important kinematic predictors of jump performance allows coaches to monitor and strive to develop jump-specific performance (Murtagh et al., 2017). The results obtained in this study indicate that the highest number of rebounds (on average) was obtained in small and medium format games (3v3 and 5v5) compared to the large sided game (10v10). The reason for the large number of jumps in the 3v3 and 5v5 games lies in the fact that the goalkeeper had to return the ball to the game with his hand, which led to a large number of jumps and aerial duels. Future research should be carried out with the restriction that the goalkeeper cannot give high balls, in order to get a precise insight into how many jumps are realized in SSG. On the other hand, elite football players who presented moderate improvements in vertical jump ability, performing jumps during the preparatory period in SSG on the small space, could directly transfer these results to the sprint results in SSG on the large format (Loturco et al., 2015) which justifies the results obtained in our study of the SSG sprint numbers on the large format game.

Given that this study did not analyze kinematic parameters by player positions, we can consider this as a lack of research. Future research should be conducted on a larger sample and perhaps players of different levels of competition. However, this study will also have a practical application in the programming of individual trainings based on the knowledge of the requirements of different SSG formats when it comes to kinematic and metabolic parameters and as a comparative basis for monitoring training of a similar orientation.

Conclusion

These specific forms of the SSG format can be used for pre-season or in-season conditioning purposes for those players who are not exposed to regular match play and require a higher load and training volume during the training week. This is particularly relevant to the development of youngsters who are often asked to join first team training sessions and may not have had enough match exposure as seniors who are part of the starting team. The disadvantage of SSG is that not all players exercise at a similar intensity, with relatively large variations in physiological stress. In addition, according to the results of this study as well as previous literature, coaches should avoid involving goalkeepers during SSG and use only small goals to preserve player motivation and training intensity. Finally, based on the results, we can see that there is a significant difference in the manifestation of kinematic parameters, in relation to the game format. The results tell us that by adequate periodization of different SSG, we can induce different adaptive responses, and with the goal of better competitive performance, taking into account many factors that affect the performance of the games themselves. Given that the obtained results are shown per minute, we can have a more detailed insight into all phases of the game.

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 human participants were reviewed and approved by University of Banja Luka. The patients/participants provided their written informed consent to participate in this study.

Author contributions

Conceptualization, MJ and NZ; methodology, MJ, NZ, SE, and NE; formal analysis, MJ, NZ, and AK; investigation, NZ and SM; writing—original draft preparation, MJ, NZ, KG, and, SM.

Conflict of interest

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

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Effects of a neuromuscular training program on physical performance and asymmetries in female soccer

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Introduction: Women's football require optimal neuromuscular system development for injury prevention and performance optimization. Standardized neuromuscular training programs have shown promising results in reducing injuries and functional asymmetries, but evidence on their impact on performance is limited.

Methods: This research examined the effects of a 10-week neuromuscular training program on physical performance and asymmetries in female football players. Thirty-eight female players from two Spanish Second Division women's football teams participated in the study. The physical performance tests used were: ankle dorsiflexion, bilateral and unilateral horizontal jump, bilateral and unilateral vertical countermovement jump, 40 m sprint including partial times at 10, 20 and 30 m and the 505 test for change of direction evaluation. For 10 weeks, players in the experimental group performed three weekly 24-min neuromuscular training sessions. Participants in the control group completed their normal 24-min strength and conditioning program.

Results: The main results were that maximal linear velocity and change of direction skills showed the most notable improvements [effect size (ES), 0.46 to 0.59] after implementation of the training program, ankle dorsiflexion and jumping skills, also improved although, to a lesser extent (ES, <0.35) while asymmetries between limbs were reduced. Maximal running speed improved in the intervention group ($p < 0.001$) with a mean ES −0.59.

Discussion: We conclude that a 10-week neuromuscular training program can be a sufficient stimulus to improve football-specific performance variables in high-level female football players. Therefore, female players and coaches should be aware that weekly inclusion of strength, power and dynamic balance exercises following a neuromuscular paradigm is helpful for football-specific performance improvement.

KEYWORDS

soccer (football), intervention, physical performance, interlimb asymmetry, strength, power, dynamic balance

1 Introduction

Football is currently one of the most popular sports worldwide, attracting enormous media and commercial interest. Notably, women's football is experiencing dramatic growth in recent years, reflected in a continuous increase in female players each year (Association, 2007). It is spreading throughout many countries all over the globe through international and local promotion programs (Association, 2020). At the same time, this media and economic momentum have led to a refinement in-game analysis and improved training methods for performance optimization and injury prevention through scientific knowledge.

Regarding its physiological demands, football is an intermittent sport in which an average of 150–250 short, high-intensity actions are performed during the 90 min of the game (Mohr et al., 2003). The average distance covered during a match in women´s football ranges between −8,200–11,000 m among professional-level players, slightly higher in international competitions and minimally lower in collegiate players (Winther et al., 2022). For an exemplary implementation of these demands, cardiorespiratory capacity is a fundamental aspect of the players' physical condition (Stolen et al., 2005). However, football also requires coping with a large number of short and repeated high-intensity actions, such as shooting, sprinting, jumping, accelerating and decelerating, often including change of direction (COD), crucial determinantes of success or failure in the game, and also good predictors of players' performance level (Lockie et al., 2018).

Football-specific high-intensity actions add substantional physiological stress to the players, including the anaerobic and neuromuscular systems (Datson et al., 2014). Moreover, a study by Faude et al. (2012) confirmed that jumping, cutting, and sprinting generate more than 50% of inciting events that end as high-speed impacts with the opponent or intrinsic musculoskeletal injuries, underlining the relevance of preparing for these actions not only from a performance aspect (Pardos-Mainer et al., 2019) but also for injury prevention (Wright and Laas, 2016). In this regard, previous studies have investigated the existence of functional imbalances and lower limb asymmetries in women´s football through a field test (Pardos-Mainer et al., 2019; Pardos-Mainer et al., 2020), and others found that functional asymmetries not only lead to an increased likelihood of injury but also a decreased performance (Menzel et al., 2013; Lockie et al., 2014) Different valid physical tests such us unilateral jump tests including the vertical jump (i.e., the countermovement jump (CMJ)) and the horizontal jump have been considered in scientific studies to reflect functional asymmetries in football (Bishop et al., 2018; Bettariga et al., 2022).

Considering the relevance of repeated short, high-intensity actions in football performance and injury occurrence, a wide variety of standardized neuromuscular training programs look for optimal neuromuscular system development. These multicomponent protocols typically combine mobility, stability, plyometric strength, and COD exercises to enhance neuromuscular coordination and motor control in a sport-specific environment. Among them, the Sportsmetrics™, Harmoknee and FIFA 11+ protocols have already shown promising results in reducing injuries in male and female football players (Noyes et al., 2013). Furthermore, a recent systematic review and meta-analysis highlight the effects of neuromuscular training interventions on functional asymmetries in football, suggesting that reducing them could lead to a decreased risk of injury and improved performance (Bettariga et al., 2022).

Despite, the promising results of neuromuscular training programs on asymmetries and injuries, scientific evidence on the effects of these interventions on performance remains scarce. The limited number of studies that investigated the impact of these programs on football performance reported improvements in linear speed, jumping and COD ability (Noyes et al., 2013; Pardos-Mainer et al., 2019; Liu et al., 2021). In contrast, other studies that included part of, but not all, the components of a neuromuscular training program showed concurrent results (Pardos-Mainer et al., 2020; Pardos-Mainer et al., 2021).

Notwithstanding, the growing evidence on the effects of neuromuscular training in football, their role in improving critical performance skills remains unclear, and more studies are needed to understand better the potential of these training programs, particularly in women´s football. Therefore, the purpose of the present study was to evaluate the effects of a neuromuscular training program on physical performance and asymmetries in female football players. Based on the scientific literature (Pardos-Mainer et al., 2019; Pardos-Mainer et al., 2020; Roso-Moliner et al., 2022), we hypothesized that a 10 week neuromuscular intervention increases physical performance and reduces asymmetries in female football players.

2 Materials and methods

2.1 Participants

Thirty-eight female football players from two Spanish Women's Second Division teams participated in the current study. Both teams followed a weekly football training regimen comparable in volume and methodology (five sessions lasting 90 min and one match each week). All participants met the following inclusion criteria: 1) minimum 6 years of football training and competition experience; 2) regular football training and competition for 6 months prior to data collection; 3) being injury-free for at least 3 months; and 4) not participating in other NMT or diet programmes outside of this study. In addition, the following exclusion criteria were met 1) missing three or more NMT sessions or 2) missing one test day. Data collection started in the seventh month of the competitive season. The players were randomly assigned to an experimental group (E.G., n = 22) or a control group (CG, n = 22) (Figure 1). All participants signed informed consent, and the ethical standards of the Declaration of Helsinki were followed. The study was approved by the Local Clinical Research Ethics Committee (PI21/011, CEICA, Spain).

A priori sample size calculation was performed using G-Power software Version 3.1.9.7 (University of Dusseldorf, Dusseldorf, Germany) with the following specifications: F tests through ANCOVA with fixed effects, main effects, and interactions, effect size f = 0.50 based on previous studies (Zouhal et al., 2019; Isla et al., 2021; Nunes et al., 2021; Brini et al., 2023), α err prob = 0.05, power (1-β err prob) = 0.85, number of groups = 2, and numerator df = 1. The calculated sample size of 38 participants was found to provide an 85.01% chance of successfully rejecting the null hypothesis of no difference in the variables studied.

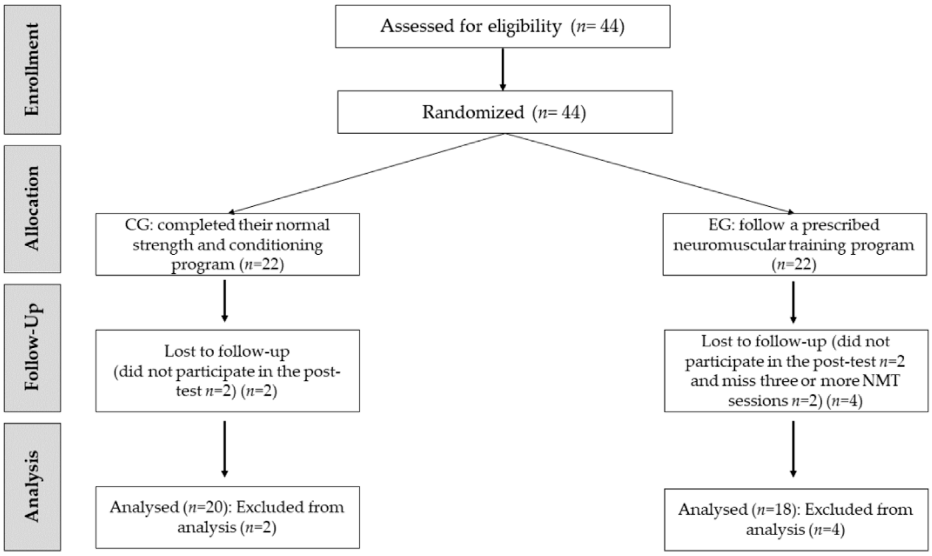

FIGURE 1
Recruitment process described in a CONSORT diagram.

2.2 Exercise protocol

All participants trained in the same schedule of football training. The, EG performed four familiarization sessions to practice the neuromuscular training routine 2 weeks before the start of the intervention. Before the data collection, all players did a warm-up of the lifting, activation, mobilization, and potentiation (RAMP) (Jeffreys, 2006). For 10 weeks, female players in the, EG performed three 24-minute neuromuscular training sessions per week. Control group participants completed their normal conditioning routine (i.e., mobility and strength exercises) at the same time. Neuromuscular training intervention included mobility (lunge to hamstrings dynamic stretch, standing hip out, 90–90 hip stretch), stability (star excursion balance, side jumps + balance, forward hop + balance), anterior chain strength (squat, squat jump, and walking lunge), lumbo-pelvic control (front, side, and add plank), posterior chain strength (1 leg glute bridge, 1 leg touch and hop, scissors lunge) and change of direction (lateral shuffle, t-test, 505 test). Each training session consisted of 6 exercises (one for each category mentioned above) performed as a circuit (i.e., four sets with a work-to-rest ratio of 40:20 s). The working leg was switched during each set for unilateral exercises. As previously suggested (Roso-Moliner et al., 2022), the selected exercises progressed in load and specificity during the intervention. Thus, level 1 activities were completed during the first 2 weeks and were upgraded to level 2 and 3 exercises in weeks 3 and 7, respectively. Additionally, a modified Borg scale (score from 0 to 10) (Zamunér et al., 2011) was used to individually monitor the perceived intensity of the training sessions in both groups.

2.2.1 Performance measurements

Pre- and post-tests were performed during the first days of the week before and after the intervention (17:00–19:00 h, same environmental conditions: ‒22°C and ‒20% humidity). Participants were instructed to abstain from vigorous exercise for at least 48 h before data collection, and all tests were carried out on a football field with football boots. In addition, to avoid possible confounding effects of diet on performance assessment, a registered dietician-nutritionist performed a 24-hour food recall on the test days and calculated the mean macronutrient and energy intake (DAPA Measurement Toolkit, Cambridge, UK). The Spanish Database of Food Composition (BEDCA) was used to analyse the information from these 24-hour food recalls (Roso-Moliner et al., 2022).

2.2.2 Ankle dorsiflexion range of motion

The LegMotion system (LegMotion, your Motion, Albacete, Spain) was used to assess the ankle dorsiflexion range of motion (ROM), and the test is described elsewhere (Pardos-Mainer et al., 2019). Each player performed three trials with each ankle to make the most appropriate measurement, recovering 10 s between each attempt. The intra-class correlation (ICC) was 0.86 in this test.

2.2.3 Horizontal jump test

The bilateral and unilateral horizontal power (unilateral and bilateral) was measured with the horizontal jump. A standard tape measure (30m M1; Stanley, New Britain, United States) was used to measure this test, described elsewhere (Pardos-Mainer et al., 2017). After two attempts, the best jump was recorded for future analysis, with a 60-second recuperation between each jump. The ICC was 0.84 and 0.88 in the bilateral and unilateral horizontal power.

2.2.4 Countermovement jump test

The CMJ was used to measure both bilateral and unilateral vertical jumping ability. Optojump (Optojump, Microgate, Bolzano, Italy) was used to determine jump height (Pardos-Mainer et al., 2017). The test was repeated three times, with at least a 45-second passive recovery period between each, and the best jump was

TABLE 1 Results of the range of motion variables in the control and experimental group.

Variables (cm)	CG (n = 20)				EG (n = 18)			
	Pre-intervention (mean ± SD)	Post-intervention (mean ± SD)	Pre-post (%)	ES (95% CI)	Pre-intervention (mean ± SD)	Post-intervention (mean ± SD)	Pre-post (%)	ES (95% CI)
ROM R	44.02 ± 4.31	44.32 ± 4.17	0.68	0.07 (-0.55; 0.69) T	41.09 ± 4.59	41.66 ± 4.35	1.38	0.12 (-0.53; 0.77) T
ROM L	43.75 ± 4.97	44.22 ± 5.19	1.07	0.09 (-0.53; 0.71) T	40.03 ± 4.68	40.69 ± 4.66	1.64	0.13 (-0.52; 0.79) T
% As ROM	4.16 ± 4.68	5.37 ± 4.53	29.24	0.25 (-0.37; 0.87) S	3.96 ± 3.77	3.81 ± 3.62	−3.97	−0.04 (-0.69; 0.61) T

CG, control group; EG, experimental group; SD, standard deviation; ROM, range of motion; R, right; L, left % As: percentage of asymmetry; ES, effect size; CI, confident interval; T, trivial; S: small, *$p< 0.05$.

registered for further analysis. The ICC was 0.89 and 0.90 in bilateral and unilateral horizontal power.

2.2.5 40-metre speed test

The sprint speed was assessed through 40-m sprint test with 10-, 20-, and 30-m split times. Total and partial times were measured using dual beam photocell systems (Witty, Microgate, Bolzano, Italy) placed 1 m above ground level at the abovementioned marks. All participants started standing once ready and 0.5 m behind the first photocell. The test was performed twice, separated by at least 3 min of passive recovery, and the best time was recorded for analysis. The ICC value was 0.93.

2.2.6 505 change of direction test

The agility was assessed using the 505 COD test with dual beam photocell systems placed 1 m above the ground level (Witty, Microgate, Bolzano, Italy) and performed as Spiteri et al. described (Spiteri et al., 2015). Players build up speed for 10 m, and as they pass through the electronic timing system, they sprint 5 m, make a 180o turn and sprint 5 m again. Each leg (right and left) completed the test twice, with at least three minutes of passive recovery in between, and the best time was recorded for analysis. The most effective time for analysis was noted. The ICC value was 0.84.

2.3 Statistical analysis

The normality of all variables was checked through the Shapiro-Wilk test. Relative reliability analysis was examined by the intra-class correlation coefficient (ICC). We have analysed covariance (ANCOVA) analysis to compare between groups, considering pre-test as the covariate and reported partial eta (ηp^2) ES. If the results of both groups were comparable, progress was compared using a *t*-test and percentage change. The standardized mean difference (Hedges' *g*), representing ESs, is shown along with 95% confidence intervals (CI). The categories of trivial (0.2), small (>0.2), moderate (>0.5), and large (>0.8) were used to classify the ES. The ESs were interpreted using Hopkins et al. guideline's for the standardized mean difference to determine the number of pairwise comparisons between the pre- and post-test (Hopkins et al., 2009). The significance of statistical analysis was considered when $p < 0.05$. All tests and statistical calculations were performed with the SPSS program (version 28.0, IBM SPSS Inc. Chicago, IL, United States).

3 Results

No significant differences ($p = 0.45$) were found during the intervention in the modified Borg scale of perceived exertion (CG: 7.26 ± 0.23; EG: 7.3 ± 0.25).

The ANCOVA results showed no significant group by time interactions of the improvement pre- and post-test in ROM and percentage asymmetry tests. Table 1 and Figure 1 illustrate the percentage changes in ROM variables between the pre- and post-test.

The ANCOVA results showed significant group by time interactions for CMJ ($p \leq 0.001$, f = 38.777, $\eta p^2 = 0.526$), CMJ right ($p \leq 0.001$, f = 30.455, $\eta p^2 = 0.465$), CMJ left ($p \leq 0.001$, f = 38.777, $\eta p^2 = 0.388$) and HJ ($p \leq 0.001$, f = 17.137, $\eta p^2 = 0.329$). When comparing the percent change from pre-to post-intervention in HJ, the independent groups *t*-test revealed a significant difference between, EG and CG ($p = 0.001$). HJ in the, EG increased by 0.55% compared to −0.07% in CG. Table 2 and Figure 2 illustrate the percentage changes in jump variables between the pre- and post-test.

The ANCOVA results showed significant group by time interactions for 10 m ($p \leq 0.001$, f = 18.993, $\eta p^2 = 0.352$), 20 m ($p \leq 0.001$, f = 10.345, $\eta p^2 = 0.228$), 30 m ($p = 0.040$, f = 4.534, $\eta p^2 = 0.115$), 40 m ($p \leq 0.001$, f = 17.430, $\eta p^2 = 0.332$), COD right ($p = 0.009$, f = 7.653, $\eta p^2 = 0.179$), COD left ($p = 0.009$, f = 7.660, $\eta p^2 = 0.180$). When comparing the percent change from pre-to post-intervention in 40m, the independent groups *t*-test revealed a significant difference between, EG and CG ($p \leq 0.001$). 40 m in the, EG increased by −3.01% compared to 0.68% in CG. Table 3 and Figure 3 and Figure 4 illustrate the percentage changes in sprint and COD variables between the pre- and post-test.

TABLE 2 Results of vertical and horizontal jump variables in control and experimental group.

Variables (cm)	CG (n = 20)				EG (n = 18)			
	Pre-intervention (mean ± SD)	Post-intervention (mean ± SD)	Pre-post (%)	ES (95% CI)	Pre-intervention (mean ± SD)	Post-intervention (mean ± SD)	Pre-post (%)	ES (95% CI)
HJ	168.10 ± 10.34	167.98 ± 10.27	−0.07	−0.01 (−0.63; 0.61) T	179.99 ± 9.00	180.97 ± 8.78	0.55	0.10 (−0.55; 0.76) T
HJ R	141.26 ± 11.88	141.33 ± 12.29	0.52	0.01 (−0.61; 0.63) T	152.19 ± 9.92	152.43 ± 9.45	0.16	0.02 (−0.63; 0.68) T
HJ L	141.88 ± 10.66	142.62 ± 11.31	0.05	0.06 (−0.56; 0.68) T	153.07 ± 8.86	153.82 ± 9.23	0.49	0.08 (−0.57; 0.73) T
% As HJ	2.46 ± 1.67	2.58 ± 1.57	4.88	0.07 (−0.55; 0.69) T	2.31 ± 1.94	2.29 ± 1.71	−0.87	−0.01 (−0.66; 0.64) T
CMJ	28.23 ± 2.09	28.25 ± 2.16	0.07	0.01 (−0.61; 0.63) T	27.19 ± 10.34	27.73 ± 10.34	1.95	0.23 (−0.43; 0.88) S
CMJ R	13.86 ± 1.63	13.82 ± 1.66	−0.31	−0.02 (−0.64; 0.60) T	13.17 ± 10.34	13.67 ± 10.34	3.78	0.25 (−0.41; 0.91) S
CMJ L	13.85 ± 1.21	13.81 ± 1.20	−0.27	−0.03 (−0.65; 0.59) T	13.15 ± 10.34	13.53 ± 10.34	2.84	0.20 (−0.45; 0.86) S
% As CMJ	5.61 ± 4.97	5.50 ± 4.98	−1.90	−0.02 (−0.64; 0.60) T	5.22 ± 10.34	5.09 ± 10.34	−2.37	−0.02 (−0.68; 0.63) T

CG, control group; EG, experimental group; SD, standard deviation; ES, effect size; CI, confident interval; T: trivial; S, small; HJ, horizontal jump; R, right; L, left; CMJ, countermovement jump; % As: percentage of asymmetry; $^{*}p < 0.05$.

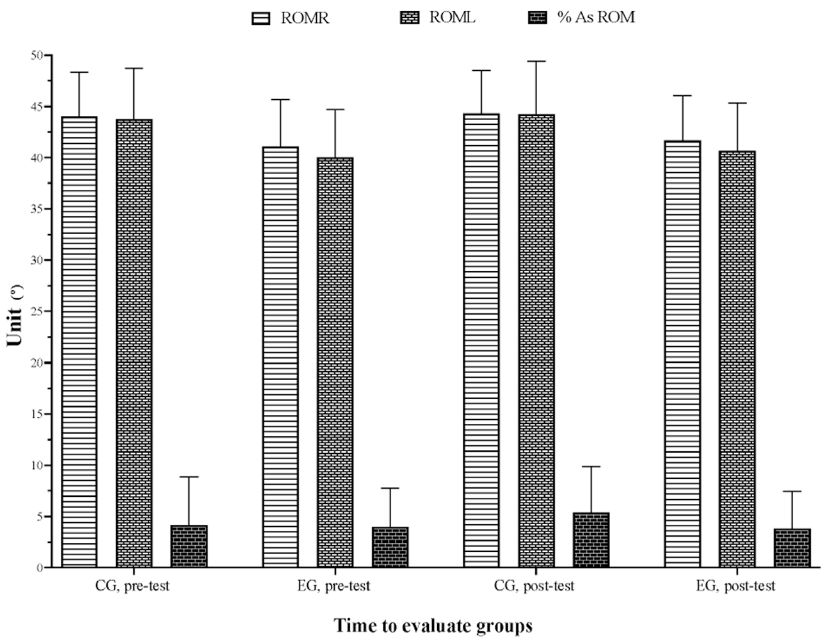

FIGURE 2
Variation in ROM variables for control and experimental group.

TABLE 3 Results of sprint and change of direction variables in control and experimental group.

Variables s)	CG (n = 20)				EG (n = 18)			
	Pre-intervention (mean ± SD)	Post-intervention (mean ± SD)	Pre-post (%)	ES (95% CI)	Pre-intervention (mean ± SD)	Post-intervention (mean ± SD)	Pre-post (%)	ES (95% CI)
10 m	1.98 ± 0.24	2.01 ± 0.13	1.51	0.15 (−0.47; 0.77) T	1.87 ± 0.10	1.83 ± 0.09	−2.11	−0.40 (−1.06; 0.26) S
20 m	3.49 ± 0.17	3.52 ± 0.19	1.03	0.16 (−0.46; 0.78) T	3.22 ± 0.16	3.19 ± 0.12	−0.95	−0.20 (−0.86; 0.45) S
30 m	4.91 ± 0.21	4.93 ± 0.26	0.51	0.08 (−0.54; 0.70) T	4.50 ± 0.22	4.48 ± 0.18	−0.54	−0.09 (−0.75; 0.56) T
40 m	6.36 ± 0.26	6.40 ± 0.31	0.68	0.13 (−055.; 0.69) T	5.87 ± 0.30	5.69 ± 0.28	−3.01	−0.59 (−1.26; 0.08) M
COD R	2.61 ± 0.19	2.62 ± 0.19	0.19	0.05 (−057.; 0.67) T	2.66 ± 0.18	2.58 ± 0.15	−3.01	−0.46 (−1.12; 0.20) S
COD L	2.58 ± 0.16	2.61 ± 0.19	1.08	0.16 (−0.46; 0.78) T	2.65 ± 0.20	2.55 ± 0.17	−3.81	−0.51 (−1.18; 0.15) M
% As COD	3.77 ± 3.06	4.60 ± 5.07	22.14	0.19 (−0.43; 0.81) T	2.82 ± 2.43	2.75 ± 2.05	−2.58	−0.03 (−0.68; 0.62) T

CG, control group; EG: experimental group; SD, standard deviation; COD, change of direction; R, right; L, left; % As: percentage of asymmetry; ES, effect size; CI, confident interval; T, trivial; S, small; M, medium; *$p < 0.05$.

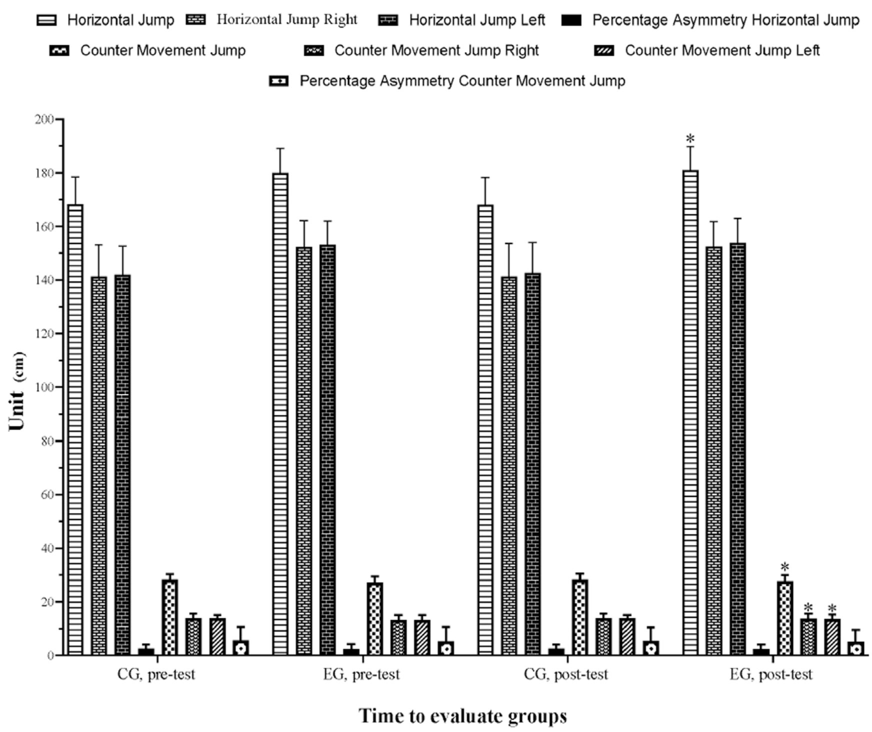

FIGURE 3
Variation in jump variables for control and experimental group.

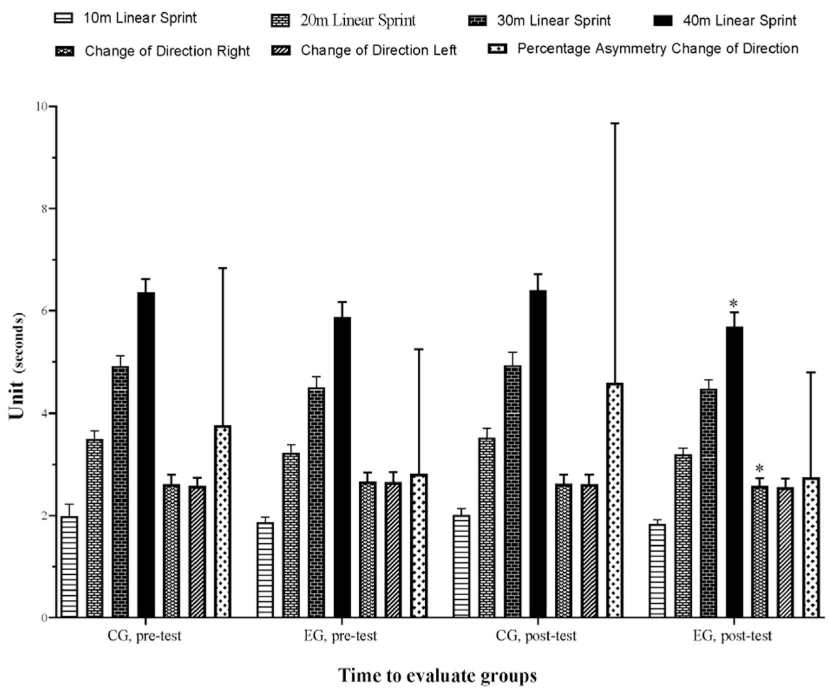

FIGURE 4
Variation in sprint and change of direction variables for control and experimental group.

4 Discussion

This study aimed to determine whether a 10-week neuromuscular intervention improves physical performance and reduces functional asymmetries of the lower extremities in female football players. The main results were that there were no significant group by time interactions in ROM and percentage asymmetry tests. However, significant group by time interactions were observed for CMJ, HJ, 10 m, 20 m, 30 m, 40 m, and COD tests. The experimental group showed a significant increase in HJ (0.55%) compared to the control group (−0.07%). In addition, the experimental group also showed a significant increase in 40 m (−3.01%) compared to the control group (0.68%). These findings suggest that the intervention had a positive impact on lower body power and speed performance in the experimental group.

Decreased ankle dorsiflexion ROM has been pointed out as an essential risk factor for developing lower limb injuries (Kaufman et al., 1999), as it increases strain on the soleus and gastrocnemius muscles during running (Sasaki and Neptune, 2006) and increases dynamic knee valgus in landings (Fong et al., 2011). As mentioned above, lower extremity misalignments could decrease performance in key football actions, such as recently presented. The lack of significant group by time interactions in ROM test in the present study may be due to various factors, such as the duration and intensity of the neuromuscular training program, the athletes' initial level of physical fitness, and the specific exercises used in the program. Evidence regarding the effects of neuromuscular interventions on dorsiflexion ROM is scarce. Previous studies (Noyes et al., 2013; Pardos-Mainer et al., 2019) indicated small ES (~0.23 and 0.30, respectively), and a systematic review of post-ankle sprained subjects (Terada et al., 2013) pinpointed that static stretching plus proprioceptive and strengthening exercises may be the most effective stimulus. These studies suggest that longer duration and higher intensity of neuromuscular training programs than in the present study may be necessary to elicit significant improvements in ROM in female soccer players. However, the effectiveness of such programs may depend on various factors, and more research is needed to determine the optimal duration, intensity, and exercises in neuromuscular training programs for improving ROM in this population.

Straight sprinting is a key performance factor in professional football, as it has been identified as the most frequent action in goal-scoring situations (Faude et al., 2012). The results of the present study suggest that the intervention had a positive effect on sprint performance. The results of the significant post-hoc analysis for 10 m, 20 m, and 30 m sprints ($p \leq 0.001$), indicate that the intervention had a greater impact on these variables in the experimental group compared to the control group. In this regard, Noyes et al. (Noyes et al., 2013) implemented a 6-week comparable training intervention on female football players aged 12–18 years, showing significant improvements ($p = 0.02$; ES = −0.14) in linear speed (37 m), whereas Pardos-Mainer et al. (2019) found similar results ($p = 0.01$; ES = −1.16) in adolescent female football players. Despite the age difference, both intervention protocols were very similar to ours and support the idea that neuromuscular training programs, which include strength, power and plyometric exercises, can be consistent in training methods with the intention to improve acceleration and short-distance sprint performance. In this sense, improvements in the power of the hip, knee and ankle extensors have previously been related to gains in sprinting ability (Morin et al., 2012), and it is also likely that the selection of exercises focusing on the horizontal stimulus has increased the chances of obtaining adaptations related to acceleration performance (González-García et al., 2019). On the other hand, Vescovi et al. (Vescovi and VanHeest, 2010) found a time effect in the speed improvements as the gains obtained in their study at week six disappeared at follow-up (week 12), underlining the importance of maintaining a minimum stimulus dose. These findings have implications for coaches and athletes seeking to improve sprint performance, as they suggest that a targeted intervention can be effective in enhancing these aspects of athletic performance. Further research is needed to identify the most effective components of such interventions and to determine the optimal duration and intensity of training needed to achieve maximum benefits in sprint performance.

Improving the speed of COD has become one of the main objectives of preparation programs (Vescovi and VanHeest, 2010). Of note, a recent investigation (Loturco et al., 2018) revealed that a higher linear speed is not necessarily related to better results in COD tests. The results of the significant post-hoc analysis for COD to the right and left indicate that the intervention had a greater impact on these variables in the experimental group compared to the control group. In the same way, a recent systematic review and meta-analyses (Liu et al., 2021) on the effects of a neuromuscular standardized warm-up protocol reported an overall improvement in COD tests in football players (ES = 0.87). In-season neuromuscular strength training intervention presented a −3.5% COD performance improvement after only 8 weeks (Panagoulis et al., 2020). Similar results were reported by Pardos-Mainer et al. after the combination of dynamic and isometric strength training showed a moderate effect (ES = −0.71) on COD performance (Pardos-Mainer et al., 2020). Plyometric training resulted in superior outcomes in COD tests, exhibiting a large effect (ES: -3.12) (Ramirez-Campillo et al., 2018). This may be attributed to the incorporation of vertical, horizontal, and unilateral jumps in these programs, which effectively enhanced COD performance. It is important to note that neuromuscular training programs can include a variety of exercises and techniques, such as plyometrics, balance and stability training, and agility drills, among others. Therefore, it is impossible to conclude if specific, or the combination of exercises in this intervention elicted the performance improvements. This also limits our ability to make direct comparisons with other studies. Nonetheless, the present results provide additional evidence supporting the effectiveness of neuromuscular training programs in improving COD performance.

The present study offers valuable insights into the impact of a neuromuscular training program on CMJ performance (ES = 0.23) in female football players, with only minor improvements observed in HJ (ES ≤ 0.10). These results are consistent with those reported in prior studies by Ozbar et al. (2014); Pardos-Mainer et al. (2019), which suggest that the nature of the power drills included in the neuromuscular program may have contributed to the observed outcomes, as vertical stimulus predominated over horizontal jumping tasks. Interestingly, the results of our study demonstrate that the neuromuscular training program had a specific effect on lower interlimb jump performance. This is supported by the significant post-hoc analysis observed for CMJ left and right. Although other studies (Gorostiaga et al., 2004; Wong et al., 2010) have demonstrated superior results in CMJ height (ES = −0.95) when applying longer explosive and plyometric strength programs to younger football players, the effect of neuromuscular interventions on the vertical jumping ability of female football players has been unclear in some (Noyes et al., 2013; Pardos-Mainer et al., 2019). Furthermore, a recent meta-analysis (Pardos-Mainer et al., 2021) compared the effects of plyometric versus strength training on essential factors of football performance. The results from this study highlight the importance of including high-speed exercises in the design of football conditioning programs, as plyometric training provides more significant benefits than strength training on vertical jump in female football players. Thus, incorporating a variety of exercises that promote explosive power and speed, rather than solely focusing on extra load exercises (Pedersen et al., 2019), may be a more effective strategy for improving vertical jump in female football players.

Historically, more significant interlimb asymmetry has been associated with lower athletic performance and increased risk of injury. However, recent studies show contradictory results (Bishop et al., 2018). Furthermore, Bishop et al. (2021) indicate that asymmetries are task-specific and that results may vary depending on the test performed. Focusing on analysing asymmetries and their relationship with performance, a recent systematic review with meta-analysis (Bettariga et al., 2022) confirms the importance of studies in which strength training interventions have been carried out with unilateral and bilateral exercises, plyometric work, balance and lumbopelvic stability. Despite our neuromuscular training program did not result in significantly different improvements in asymmetry tests results between the groups, the intra-group analysis showed that the experimental group has reduced ROM asymmetry by −3.97% (ES = −0.04), CMJ asymmetry by −2.37% (ES = 0.02), HJ asymmetry by −0.87% (ES = 0.01), and COD asymmetry by −2.58% (ES = 0.03). These results are reinforced in a previous review (Bettariga et al., 2022), in which slight to moderate effects on asymmetry reduction were observed across all interventions, but no significant differences were found for the HJ (ES: 0.22), the CMJ (ES = 0.53) and the COD (ES = 0.23). However, it is important to note that the lack of significance may be due to a variety of factors, such as the sample size, the specific measures used, and/or the duration and intensity of the training program. Finally, these results continue to confirm that the reduction of asymmetries and their relationship to improved performance should be further investigated.

4.1 Limitations

Of note, there exist a few limitations in the current study. Firstly, the small sample size prevented us from assessing differences between players' positions. However, the primary objective of the present investigation was to analyse the overall effects of a neuromuscular training program on football performance variables and to determine whether the effects are position-specific, thus suggesting a potential area for future research. Furthermore, only high-level female football players were selected for the final analyses, so our results cannot be generalized to another level of performance or different team sports. Despite these considerations, the present research provides relevant data on the positive effects of the weekly application of strengthening programs with a neuromuscular emphasis on crucial performance variables of female football players.

5 Conclusion

The results of the present work emphasize that a 10-week neuromuscular training intervention may be a sufficient stimulus to improve physical fitness variables in high-level female football players. Significant improvements in COD tests and straight sprinting time were found after the intervention, while slight to trivial gains in jumping, ankle mobility, and interlimb symmetries were also registered. Therefore, players and coaches should be aware that the weekly inclusion of strength, power and dynamic balance exercises following a neuromuscular paradigm is useful for improving football fitness. Such gains can be achieved with an on-field resistance training program without supplemental materials to body mass.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by the Local Clinical Research Ethics Committee (PI21/011, CEICA, Spain). The patients/participants provided their written informed consent to participate in this study.

Author contributions

Conceptualization, AR-M and EM-P; methodology, AR-M, HN, EM-P, and AC-L.; formal analysis, AR-M, HN, and EM-P; data curation, DL and SP; writing—original draft preparation, AR-M, AC-L, and DL; writing—review and editing, DL, SP, and HN; visualization, EM-P; supervision, SP and HN All authors have read and agreed to the published version of the manuscript.

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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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Investigating the impact of inter-limb asymmetry in hamstring strength on jump, sprint, and strength performance in young athletes: comparing the role of gross force

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The main purpose of this cross-sectional study was to examine the impact of the inter-limb asymmetry of hamstring strength on jump, sprint and strength performance and to compare the effects of inter-limb asymmetry of hamstring strength with gross force (GF) of the hamstring on these physical qualities in youth volleyball athletes. Eighty-one youth volleyball players (age: 16.6 ± 1.9 years; training experience: 3.0 ± 0.9 years; height: 191.4 ± 7.1 cm; body mass: 78.5 ± 12.9 kg; lean body mass: 63.5 ± 10.5 kg; body fat rate: 18.6% ± 6.1%) performed a mid-season battery of tests consisting of morphological test, depth jump (DJ), counter movement jump (CMJ), squat jump (SJ), 10 m sprint, isometric mid-thigh pull (IMTP) and hamstring strength test. All tests reported good to excellent reliability (ICC range = 0.815–0.996) and acceptable variability (CV range = 3.26–7.84%). Results show a significant negative relationship between inter-limb asymmetry of hamstring strength and all physical qualities (r = −0.271 to −0.445; $p < 0.05$), and a significant positive relationship between GF of hamstring and all physical qualities (r = 0.303 to 0.664; $p < 0.05$). Additionally, GF of hamstring was more relevant to IMTP-PF (peak force) (r = 0.664) and inter-limb asymmetry of hamstring strength was more relevant to 10 m sprint (r = −0.445). The findings from this study indicate that, for youth athletes, the GF of the hamstring is crucial for overall lower limb strength performance, and the importance of inter-limb symmetry of hamstring strength increases with the complexity of the task.

KEYWORDS

asymmetry, hamstring, kinetics, performance, youth athletes

Introduction

Strength asymmetry refers to a lack of equality between limbs or muscle groups and the impact of this asymmetry on injury risk and sports performance has been extensively investigated in the literature, particularly in strength and conditioning research (Keeley, Plummer, & Oliver, 2011; Parkinson et al., 2021). Evidence has confirmed that strength differences between limbs increase the risk of injury (Croisier et al., 2008; Brumitt et al., 2013). However, there is debate as to whether inter-limb strength asymmetry impairs sports performance. The literature suggests that inter-limb strength asymmetry appears to have a negative effect on performance in jumping, sprinting and change of direction (COD) (Bell et al., 2014; Bishop et al., 2018; Michailidis et al., 2020; Bishop et al., 2021). However, there is also evidence to suggest that inter-limb strength asymmetry may not always negatively impact performance (Lockie et al., 2014; Dos'Santos et al., 2018). For example, higher division soccer players have been found to show larger asymmetries compared to lower division players (Ferreira et al., 2018). Furthermore, inter-limb differences have been identified in a variety of sports including sprinting (Rumpf et al., 2014; Exell, Irwin, Gittoes, & Kerwin, 2017; Meyers, Oliver, Hughes, Lloyd, & Cronin, 2017), kickboxing (Stanton, Reaburn, & Delvecchio, 2015), swimming (Evershed, Burkett, & Mellifont, 2014), basketball (Schiltz et al., 2009), and rowing (Buckeridge, Hislop, Bull, & McGregor, 2012), suggesting that inter-limb asymmetry may be reasonable under certain circumstances. Therefore, further research is needed to explore the relationship between inter-limb strength asymmetry and sports performance.

Previous studies have highlighted the importance of hamstring function for athletic performance, especially in terms of explosive strength characteristics. Hamstrings are vital for sprint acceleration by increasing the production of horizontal ground reaction force (GRF) (Morin et al., 2015). Nordic hamstring exercise (NHE) training has been found to induce sustained improvements in hamstring function in athletes, which can be transferred to 5 m and 10 m sprint speeds as well as maximum countermovement jump (CMJ) height (Goran skok et al., 2017; Krommes et al., 2017; Ishøi et al., 2018; Timmins et al., 2021). Additionally, evidence suggests that hamstring strength is positively correlated with sprinting performance (Timmins et al., 2021). In addition to monitoring hamstring strength, recent research has also focused on examining inter-limb asymmetry of hamstring strength (Cuthbert et al., 2021; Bishop et al., 2022). Studies have indicated that inter-limb asymmetry of hamstring strength (>15%) may significantly increase an athlete's risk of hamstring injury (Croisier et al., 2008; Kyritsis et al., 2016). However, it is unclear whether inter-limb asymmetry of hamstring strength has negative effects on sports performance, including jump, sprint, and strength performance, beyond increasing the risk of injury.

Given that inter-limb strength asymmetry may affect health and performance, and hamstring strength plays an important role in athletic performance, inter-limb asymmetry of hamstring strength has been proved to be harmful to the safety of hamstring muscle during exercise, further studies are needed to determine its impacts on athletic performance, which could help to further clarify the role of inter-limb asymmetry of hamstring strength and its impacts on performance. Therefore, the aims of the present study were 2-fold: 1) to examine the effects of the inter-limb asymmetry of hamstring strength on jump, sprint and strength performance and, 2) to compare the difference between the effects of inter-limb asymmetry of hamstring strength and gross force (GF) of hamstring on these physical qualities. It was hypothesized that the larger inter-limb asymmetry of hamstring strength would be correlated with reduced physical performance and inter-limb asymmetry of hamstring strength played a different role in these athletic performance than GF of hamstring. Given that inter-limb strength asymmetry has been shown to potentially impact health and athletic performance, and hamstring strength is known to play a crucial role in physical performance, it is important to investigate the effects of inter-limb asymmetry of hamstring strength on athletic performance. Specifically, understanding the relationship between inter-limb asymmetry of hamstring strength and jump, sprint, and strength performance may help to clarify the role of this asymmetry and its impact on athletic performance. Therefore, the present study aims to achieve two goals: 1) to examine the impact of inter-limb asymmetry of hamstring strength on jump, sprint, and strength performance and 2) to compare the effects of inter-limb asymmetry of hamstring strength with gross force (GF) of the hamstring on these physical qualities. Our hypothesis was that greater inter-limb asymmetry of hamstring strength would be associated with decreased physical performance, and that inter-limb asymmetry of hamstring strength played a different role in athletic performance compared to GF of the hamstring.

Methods

Participants

Eighty-one youth volleyball players (age: 16.6 ± 1.9 years; training experience: 3.0 ± 0.9 years; height: 191.4 ± 7.2 cm; body mass: 78.5 ± 12.9 kg; lean body mass: 63.5 ± 10.5 kg; body fat rate: 18.6% ± 6.1%) volunteered for this study. Of the participants, 60 were male (age: 16.6 ± 1.9 years; training experience: 3.0 ± 0.9 years; height: 194.1 ± 5.8 cm; body mass: 80.6 ± 12.8 kg; lean body mass: 66.8 ± 9.4 kg; body fat rate: 15.9% ± 4.2%) and 21 were female (age: 16.4 ± 2.1 years; training experience: 3.0 ± 0.9 years height: 183.5 ± 4.5 cm; body mass: 72.4 ± 11.3 kg; lean body mass: 54.0 ± 7.5 kg; body fat rate: 26.3% ± 3.5%).

The local volleyball club policy required players to perform 3–4 volleyball drills per week and at least 2 structured strength and conditioning sessions per week during the testing cycle. All subjects met the following inclusion criteria: a) a background of ≥2 years of systematic volleyball training and competitive volleyball match experience, b) continuous volleyball training for the previous 2 months without having sustained any musculoskeletal injuries, c) the absence of potential medical problems that could compromise participation or performance in the study, and d) the absence of any lower-extremity injury in the past 3 months.

All subjects provided written informed consent and their personal information was handled anonymously, and parental or guardian consent for all subjects under the age of 18 involved in this investigation were obtained. The study received ethical approval from the Sports Science Ethics Committee of Beijing Sports

University. To calculate the sample size, a free statistical software (G * Power, v.3.1.9.7, Dusseldorf, Germany) was used. Given the applied a bivariate linear regression, a medium overall effect size (ES) = 0.4, an alpha-error = 0.05 and the desired power (1-ß error) = 0.8, the total sample size resulted in 44 participants (Beck, 2013). To reduce the risk of experimental mortality we recruited a larger sample.

Experimental design

This study employed a cross-sectional design and recruited youth volleyball players from several local volleyball clubs. This experiment was conducted from April to May 2022, with a total duration of 4 weeks, consisted of multiple assessments including morphological test, depth jump (DJ), counter movement jump (CMJ), squat jump (SJ), 10 m sprint, isometric mid-thigh pull (IMTP) and hamstring strength test.

Prior to the test, all participants were familiarized with the entire testing programs, and their information was recorded according to the study requirements. To ensure the validity and reliability of the test data, all subjects underwent a standardized warm-up protocol. Moreover, participants were instructed to avoid any strenuous physical activity 48 h before testing and maintain their usual diet.

Procedures

Due to the large number of participants and testing items in this experiment, the testing period lasted for 4 weeks. All participants performed testing items according to a standardized warm-up procedure and testing sequence. A rest interval of at least 2 min was allowed between each physical fitness trial. During the waiting time, participants engaged in low-intensity activities, such as walking and jogging, to keep themselves prepared for the subsequent test. A warm-up consisting of 10 min of submaximal running and specific exercises (i.e., submaximal vertical and horizontal jumps) was carried out before each testing session. The testing sequence was as follows: morphological test, DJ, CMJ, SJ, 10 m sprint, IMTP and hamstring strength test.

Morphological test

Stature was measured using a stadiometer (Bodymeter 206; SECA, Hamburg, Germany), while lean, fat, and total mass distribution were assessed utilizing DEXA (DXA; Hologic Discovery A, Waltham, MA, United States). Participants were instructed to wear minimal garments made of light fabric, free of metal components (zippers, wires, or fasteners), and to remove metallic items from their pockets before lying in a supine position on the scanning bed with both arms pronated to their side. To guarantee consistent and reproducible positioning, participants were aided in aligning their head in a straight line with their torso and pelvis, internally rotating and securing their legs and feet at a 45° angle, and placing their arms adjacent to their body within the scanning area (Stewart and Hannan, 2000). Subsequently, full-body scan images were analyzed using proprietary software (version 12.4; QDR for Windows, Hologic, Waltham, MA, United States).

Depth jump (DJ), countermovement jump (CMJ) and squat jump (SJ)

Jump tests were conducted using the ForceDecks FD4000 dual force platforms (Vald Performance, Brisbane, Queensland, Australia) sampling at 1,000 Hz, which has been previously proposed as a reliable device (CV < 10%, ICC >0.70; Heishman et al., 2020). The commercially available ForceDecks software (Vald Performance, Brisbane, Queensland, Australia) was used to analyse and generate the jumping variables using conventional methods. To perform the SJ, athletes stood in a comfortable bilateral position in the center of the ergometer with hands at their waist and then assumed a half-squat position for 2–3 s. When instructed, athletes accelerated vertically upward from the half-squat position, jumped as fast as possible, and returned to an upright standing position. Similar procedures were followed for the CMJ and DJ. For the CMJ, athletes stood in a comfortable bilateral position in the center of the ergometer with their hands secured at the waist. When instructed, athletes bent at the hips and knees to a depth of their choice and then accelerated vertically to jump as fast as possible. For the DJ, athletes stood on a 45 cm jumping box with one foot hanging in the air and their hands fixed at their waist. When instructed, athletes naturally jumped down, landed on both feet, and then jumped up as fast as possible, finishing the jump with both feet landing at the same time. Each jump test was repeated three times with 1–2 min of rest between each trial. Athletes returned to the starting position and held it for 2–3 s to prepare for the next jump. The height of the jumps was recorded in centimeters (cm) for all trials, and the highest jump was subsequently used for further analysis. Athletes were instructed to jump as high as possible and to extend their legs as fast as possible to maximize explosive power. If an athlete's hand left their waist, the jump was considered invalid and restarted after 1–2 min of rest.

10 m sprint

Linear speed was measured using a 10 m sprint test with a SMARTSPEED timing gate system (Fusion Sport, Queensland, Australia), which included an electric light gate placed at the starting and ending points. The timing system selected has been proven to be reliable in previous studies (CV = 0.6–4.2%, ICC = 0.82–0.97; Austin et al., 2013). The sprint test was conducted on the outdoor athletic track. The electro-optical gate sensors were connected to the SMARTSPEED timing gate system software to collect data. Athletes started in a standing position 0.5 m behind the first photoelectric gate and upon instruction, sprinted as quickly as possible for 10 m. The timing was accurate to one 100th of a second. Athletes performed three trials with 60-s rest intervals between each trial, and the fastest trial was selected for further analysis.

Isometric mid-thigh pull (IMTP)

The IMTP test was conducted using dual force plates (Force Decks, VALD Performance, FD4000, Queensland, Australia) sampling at 1,000 Hz, which has demonstrated sufficient reliability (CV = 5%, ICC = 0.94; Ritti-Dias et al., 2011). To ensure consistent positioning, the mid-thigh position was marked for each participant as the midpoint between the knee and hip joints. The barbell height was then adjusted to align with the mid-thigh. Participants stood on the force platform and grasped the barbell with an overhand grip, ensuring that the knee joint was within 120°–145°

and the hip joint was within 140°–150° using a protractor. They were strapped to the barbell in a manner similar to previous investigations (Dos' Santos et al., 2017; Haff et al., 2005), with the torso upright and the knee and hip angles maintained during testing. At the start signal, athletes exerted maximal force as quickly as possible and sustained the force for 6 s without leaning forward or backward. All athletes were instructed to relax before the command "GO!" to avoid precontraction. Peak force was calculated as the highest force achieved during the 6-s isometric test, adjusted for body weight in Newtons. Each athlete performed three trials of the IMTP test, with 2–3 min of rest between trials. The highest peak force achieved across the three trials was used for further analysis.

Hamstring strength test

The NordBord device (Vald Performance, Newstead, Australia) was used to assess hamstring strength with a sampling frequency of 50 Hz. The reliability of this assessment has been described (ICC = 0.83–0.90, typical error = 21.7–27.5; van Dyk et al., 2018). Prior to the test, athletes completed a 5-min warm-up on a stationary bike with an RPE between 5 and 10, followed by 1 × 10 repetitions of dynamic stretches, including multiplanar lunges, multiplanar leg swings, body mass squats, and the "world's greatest stretch". During the test, each athlete was positioned in a kneeling position on the NordBord device's pads, with their ankles secured by a single hook perpendicular to the ground, which was attached to a custom single-axis load cell with wireless data acquisition capability. The athlete raised their head and chest, maintained an upright body posture with straight trunk and hips, and extended their knees to lean forward. The hamstrings fired to resist a rapid descent, and the athlete's palms faced forward while bending their elbows until their palms touched the ground. Athletes completed a warm-up set of three attempts without data collection, followed by a 3-min rest period. Then, a formal single set of three hamstring strength tests was performed for data collection. Test scores were output as the maximum force in Newtons (N) for each limb, and the GF of hamstring was calculated as the sum of the maximum force of each limb. The mean of the three trials was used for further analysis.

Statistical analyses

All data was recorded as mean and SD. Data were analyzed by the IBM SPSS Statistics (version 24.0; SPSS, Inc., Armonk, NY, United States). Normality of the data was confirmed ($p < 0.05$) using the Shapiro-Wilk test. Absolute and relative reliability was calculated via the coefficient of variation (CV) and intraclass correlation coefficient (ICC) with absolute agreement (95% confidence intervals), respectively. CV values <10% were considered acceptable (Cormack et al., 2008) and ICCs were interpreted in line with previous suggestions from Koo and Li (2016) where values >0.9 = excellent, 0.75 to 0.9 = good, 0.5 to 0.74 = moderate, and <0.5 = poor. Independent-samples t-tests were used to determine possible differences in all fitness test between males and females. Practical differences were assessed using Hedges' g effect size (ES) data, and were interpreted in line with suggestions by Hopkins et al. (2009) where 0.00 to 0.19 = trivial, 0.20 to 0.59 = small, 0.60 to 1.19 = moderate, 1.20 to 1.99 = large, and ≥2.00 = very large. Pearson's r correlations were conducted to determine the relationships between each sports performance test with inter-limb asymmetry of hamstring strength and GF of hamstring, with statistical significance set at $p < 0.05$. Magnitudes of correlation were interpreted as 0.00 to 0.09 = trivial, 0.10 to 0.29 = small, 0.30 to 0.49 = moderate, 0.50 to 0.69 = large, 0.70 to 0.89 = very large, 0.90 to 0.99 = nearly perfect, and 1.00 = perfect (Hopkins et al., 2009). Interlimb asymmetries were quantified using a standard percentage difference equation: 100/(max value) * (min value)*-1 + 100 (Bishop et al., 2021; Cuthbert et al., 2021).

Results

81 participants completed all fitness tests, including 60 male athletes (age: 16.6 ± 1.9 years; training experience: 3.0 ± 0.9 years; height: 194.1 ± 5.8 cm; body mass: 80.6 ± 12.8 kg; lean body mass: 66.8 ± 9.4 kg; body fat rate: 15.9% ± 4.2%) and 21 female athletes (age: 16.4 ± 2.1 years; training experience: 3.0 ± 0.9 years height: 183.5 ± 4.5 cm; body mass: 72.4 ± 11.3 kg; lean body mass: 54.0 ± 7.5 kg; body fat rate: 26.3% ± 3.5%) (Table 1).

Mean test scores and ES between male and female groups are presented in Table 2. The results between male and female groups for all test were significant ($p < 0.05$). The ES of Hamstring-Asymmetry and IMTP-PF between male and female groups showed moderate standard with 0.55 and 0.78, respectively. The ES of all other indicators showed large standard.

Table 3 shows mean test scores and SD for each test and accompanying reliability data using the CV and ICC. For absolute reliability, all the performed tests had acceptable between-trial consistency with all CV values below 8%. For relative reliability, all ICC values were found to be excellent (ICC range = 0.918–0.978), with the exception of the 10 m sprint, which showed a slightly lower ICC of 0.815.

Table 4 shows the Pearson's r correlations between inter-limb asymmetry scores and GF of hamstring with each test data. Significant negative correlations were shown for total group between asymmetry and all physical qualities ($p < 0.05$), and significant positive correlations were shown for total group between GF and all physical qualities ($p < 0.05$). In the male group, asymmetry showed a significant negative correlation with SJ (r = −0.361; $p = 0.005$) and 10 m sprint (r = −0.471; $p < 0.001$) performance, respectively, and GF showed a significant positive correlation with the IMTP-PF (r = 0.648; $p < 0.001$) performance. In the female group, asymmetry showed a significant negative correlation with DJ (r = −0.491; $p = 0.024$) and IMTP-PF (r = −0.460, $p = 0.036$) performance, respectively, and GF showed a significant positive correlation with IMTP-PF (r = 0.458; $p = 0.037$) performance.

Discussion

The aim of this study was to investigate the effects of inter-limb asymmetry of hamstring strength and GF of hamstring on jump, sprint, and strength performance, and to compare the differences between them. The results indicated that inter-limb asymmetry of hamstring strength had a greater impact on sprint performance, while GF of hamstring was found to have a greater influence on

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TABLE 1 Baseline data of the subjects.

Basic information	Total (n = 81)	Male (n = 60)	Female (n = 21)
Age (years)	16.6 ± 1.9	16.6 ± 1.9	16.4 ± 2.1
Training experience (years)	3.0 ± 0.9	3.0 ± 0.9	3.0 ± 0.9
Height (cm)	191.4 ± 7.2	194.1 ± 5.8	183.5 ± 4.5
Body mass (kg)	78.5 ± 12.9	80.6 ± 12.8	72.4 ± 11.3
Lean body mass (kg)	63.5 ± 10.5	66.8 ± 9.4	54.0 ± 7.5
Body fat rate (%)	18.6 ± 6.1	15.9 ± 4.2	26.3 ± 3.5

TABLE 2 Mean testing data ± standard deviations for each group and effect sizes between male and female groups.

Fitness test	Total (n = 81)	Male (n = 60)	Female (n = 21)	Male vs. Female (ES)
Hamstring-Left (N)	366.25 ± 91.95	388.12 ± 88.08	303.81 ± 73.54	1.00 (large)***
Hamstring-Right (N)	358.28 ± 96.12	380.65 ± 93.85	294.38 ± 72.01	0.97 (large)***
Hamstring-GF (N)	724.54 ± 185.19	768.77 ± 179.06	598.19 ± 141.30	1.00 (large)***
Hamstring-Asymmetry (%)	7.50 ± 5.90	6.67 ± 5.68	9.87 ± 6.02	0.55 (moderate)*
DJ (cm)	33.94 ± 6.91	36.05 ± 6.28	27.90 ± 4.79	1.37 (large)***
CMJ (cm)	34.44 ± 7.12	36.76 ± 6.42	27.84 ± 4.38	1.49 (large)***
SJ (cm)	31.26 ± 6.82	33.29 ± 6.32	25.45 ± 4.53	1.32 (large)***
10 m-Sprint (s)	1.98 ± 0.15	1.91 ± 0.10	2.17 ± 0.11	2.53 (large)***
IMTP-PF (N)	2814.94 ± 856.30	2980.17 ± 856.65	2342.86 ± 672.48	0.78 (moderate)**

GF, gross force; DJ, depth jump; CMJ, counter movement jump; SJ, squt jump; IMTP, isometric mid-thigh pull; PF, peak force; ES, effect size.
*$p<0.05$; **: $p < 0.01$; ***: $p < 0.001$.

TABLE 3 Mean test scores and standard deviations, inter-limb asymmetry, and accompanying reliability data for each test.

Fitness test	Mean ± SD	Asymmetry (%)	CV(%)	ICC(95% CI)
Hamstring-Left (N)	366.25 ± 91.95	7.50 ± 5.90	6.94	0.925 (0.890–0.949)
Hamstring-Right (N)	358.28 ± 96.12		7.83	0.918 (0.884–0.944)
Hamstring-GF (N)	724.54 ± 185.19	—	5.24	0.958 (0.935–0.973)
DJ (cm)	33.94 ± 6.91	—	3.71	0.969 (0.809–0.989)
CMJ (cm)	34.44 ± 7.12	—	3.24	0.978 (0.882–0.992)
SJ (cm)	31.26 ± 6.82	—	3.63	0.976 (0.839–0.991)
10 m-Sprint (s)	1.98 ± 0.15	—	3.26	0.815 (0.341–0.927)
IMTP-PF N)	2814.94 ± 856.30	—	5.39	0.976 (0.813–0.992)

GF, gross force; DJ, depth jump; CMJ, counter movement jump; SJ, squt jump; IMTP, isometric mid-thigh pull; PF, peak force; SD, standard deviation; CV, coefficient of variation; ICC, intraclass correlation coefficien; CI, confidence interval.

strength performance. Interestingly, inter-limb asymmetry was just as important as GF for jump performance.

Mean data for all test protocols, including test reliability and mean inter-limb asymmetry values, were calculated and reported in Table 3. All tests showed good to excellent reliability (ICC range = 0.815–0.996) and acceptable variability (CV range = 3.26–7.84%), indicating that results can be interpreted with confidence. Furthermore, this study examined gender differences in each test, and the results showed statistically significant differences between male and female athletes. Regarding the correlations between each indicator with inter-limb asymmetry of hamstring strength and GF of hamstring, the results were found to be inconsistent between males and females. Due to the large difference in sample size between the genders, the analysis of different characteristics

TABLE 4 Correlation between inter-limb asymmetry of hamstring strength and gross force of hamstring with performance scores on each test.

Fitness test	Hamstring-asymmetry			Hamstring-GF		
	Total (n = 81)	Male (n = 60)	Female (n = 21)	Total (n = 81)	Male (n = 60)	Female (n = 21)
DJ (cm)	−0.308**	−0.150	−0.491*	0.339**	0.161	0.178
CMJ (cm)	−0.329**	−0.211	−0.375	0.340**	0.180	0.043
SJ (cm)	−0.394***	−0.361**	−0.202	0.303**	0.140	0.081
10 m-Sprint (s)	−0.445***	−0.471***	−0.247	0.328**	0.032	0.321
IMTP-PF N)	−0.271*	−0.141	−0.460*	0.664***	0.648***	0.458*

GF, gross force; SJ, squat jump; CMJ, counter movement jump; DJ, depth jump; IMTP, isometric mid-thigh pull; PF, peak force.
*$p<0.05$; **: $p < 0.01$; ***: $p < 0.001$.

between them was restricted, which is also a limitation of this study. Moreover, the primary aim of this study was to determine the effects of inter-limb asymmetry of hamstring strength and GF of hamstring on jump, sprint, and strength performance, rather than comparing the differences between genders. Therefore, further investigation is needed to examine gender differences. It is also important to note that long-term specialized training may induce the adaptation of inter-limb asymmetry (Maloney, 2019), which could limit the true reflection of the relationship between inter-limb asymmetry and physical performance. As a result, this study chose youth athletes with relatively less training experience as experimental subjects.

The present study found that inter-limb asymmetry of hamstring strength had a greater impact on sprint performance than GF. It is worth noting that the tests in this experiment were performed using bilateral movements, except for the 10 m sprint. Sprinting is a typical alternating limb movement and requires high levels of stability and neuromuscular control (Struzik et al., 2016). Gonzalo-Skok et al. (2017) reported that unilateral resistance training could effectively reduce inter-limb asymmetry and lead to greater enhancements in actions that require unilateral force application. Therefore, reducing inter-limb asymmetry may be beneficial for improving unilateral movements. Although Meyers et al. (2017) reported weak relationships (r = −0.24 to 0.39; $p < 0.05$) between various asymmetry metrics (step frequency, step length, flight time, and vertical stiffness) and sprint velocity in youth athletes (344 school aged boys; 11–16 years), large kinetic asymmetries did not appear to be detrimental to mean sprint velocity in sprint-trained athletes (Bishop et al., 2018). However, as the participants in this study were youth athletes (16.56 ± 1.93 years) without professional sprint training, inter-limb asymmetry of hamstring strength may impair sprint performance. During sprinting, the average activity in hamstring muscles was 33% greater in comparison to the quadriceps muscles, which meant that the greater involvement of hamstring muscles in this motor task (Pietraszewski et al., 2020). Accordingly, we suggested that reducing the inter-limb asymmetry of hamstring strength may effectively enhance sprint performance by improving the efficiency of alternating limb movements, especially for the youth cohort.

Compared to the small correlation observed between inter-limb asymmetry of hamstring strength and IMTP-PF (r = −0.271; $p < 0.05$), GF of the hamstring showed a large correlation with IMTP-PF (r = 0.664; $p < 0.001$). Anderson and Behm (2004) reported that unstable isometric maximum force output was 59.6% lower than under stable conditions. Since IMTP can evaluate the maximum strength of the lower limbs in an extremely stable condition, this may partly offset the negative impact of inter-limb asymmetry of hamstring strength. Thus, when performing tasks on a stable plane, GF of hamstring muscles appeared to be a more critical factor in determining strength performance than inter-limb asymmetry of hamstring strength. However, in jump tests, inter-limb symmetry of hamstring strength and GF of hamstring appeared to be equally important to jump performance. From a kinetic chain perspective, both sprint and jump tests belong to a closed kinetic chain (CKC) action, whereas the IMTP test is an open kinetic chain (OKC) action. Compared to OKC, CKC requires more intermuscular coordination and neuromuscular control (Karandikar and Vargas, 2011). In all physical qualities, only sprint is both a unilateral and OKC exercise, making it more relevant to inter-limb symmetry of hamstring strength than jump and strength performance. Therefore, we deduced that the importance of inter-limb symmetry of hamstring strength appeared to increase with the complexity of the task. Bishop et al. (2018) and Madruga-Parera et al. (2020) also indicated that strength asymmetries appeared to have a negative effect on performance tasks, including jumping, change-of-direction speed (CODS) and repeated sprint performance, thus minimising these differences would be beneficial.

In practical applications concerning sports injury prevention and performance improvement, hamstring GF seems to attract more attention than inter-limb asymmetry in hamstring strength. Numerous studies had validated that the increasement of hamstring strength had a positive impact on sprint and jump performance (Markovic et al., 2020; Váczi et al., 2022). However, studies examining inter-limb asymmetry of hamstring strength are still in the early stages, and the majority of them have focused on the prevention of sports injuries. It is commonly held that large inter-limb asymmetry may increase the risk of injury (Bishop et al., 2018), and sufficient hamstring strength could effectively prevent injuries during running or sprinting (Bishop et al., 2022). Therefore, from a health perspective, it is necessary to boost the hamstring strength and properly reduce inter-limb asymmetry of hamstring strength for running and sprinting. From a sports performance perspective, we also believe that increasing inter-limb symmetry of hamstring strength is critical. Based on the findings of this study and previous research, it is reasonable to speculate that more complex tasks may require greater inter-limb symmetry of hamstring muscles. A more symmetrical hamstring strength may contribute to improved overall stability in movements, help maintain proper technique, and enhance athletic performance. As a consequence, bilateral hamstring strength and inter-limb asymmetry of hamstring strength can affect movement efficiency in different ways. When bilateral hamstring strength approaches the limits of human body, appropriately reducing inter-limb asymmetry of hamstring strength may be the key to achieving a breakthrough, particularly for youth athletes.

Despite the usefulness of these findings, this study presents some limitations. Firstly, only a preliminary correlation analysis and a data-based theoretical inference were performed, therefore, more specific evidence is needed to verify whether reducing inter-limb asymmetry of hamstring strength can enhance the adaptability of complex tasks for youth athletes. Additionally, the research pointed out that asymmetries are an adaptive consequence that is magnified with long-standing sporting participation (Maloney, 2019), and may have no or active effects on the sports performance (Bishop et al., 2018). This finding may conflict with the results obtained for the youth cohort, so it is necessary to compare the difference between athletes of different levels. Moreover, there are many ways to calculate asymmetry, and other formulas could have let to different findings. Indeed, as absolute symmetry is almost non-existent, further exploration is required to determine what range of inter-limb asymmetry of hamstring strength is safe and beneficial for sports performance.

In summary, the results of this study indicate that the GF of the hamstring is crucial for overall lower limb strength performance, and the importance of inter-limb symmetry of hamstring strength increases with the complexity of the task. Therefore, we suggest that for youth athletes, it is important to concurrently develop hamstring strength and reduce inter-limb asymmetry of hamstring strength to enhance sprint and jump performance.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by Sports Science Ethics Committee of Beijing Sports University. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

DJ, XL and JD designed the study. ZL, LL, and YL were responsible for conducting literature searches and collecting data. DJ, ZL and XL performed the statistical analysis, and all authors contributed to data interpretation. DJ and XL provided methodological insight and guidance throughout the process. DJ, ZL and XL drafted the manuscript, while JD, LL and SZ critically revised the article and contributed to the final version of the manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

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

Publisher's note

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Post-activation performance enhancement of flywheel training on lower limb explosive power performance

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The study aimed to investigate the post-activation performance enhancement (PAPE) of flywheel training (FT) on lower limb explosive power performance. Using a randomized crossover design, 20 trained men (age = 21.5 ± 1.4 years; training experience 5.5 ± 1.2 years) completed seven main conditions after three familiarization sessions. The first three conditions tested the PAPE of the FT on the counter movement jump (CMJ) under three different inertial loads (0.041 kg·m^2 as L; 0.057 kg·m^2 as ML; and 0.122 kg·m^2 as P), whereas the following four conditions tested the PAPE of FT on the 30 m sprint, which consisted of three inertial loads (L, ML, and P) and a control condition. Participants were required to perform the CMJ or 30 m sprint at baseline (Tb) and immediately (T0), 4 min (T4), 8 min (T8), 12 min (T12), and 16 min (T16) after exercise, respectively. The results of the CMJ conditions showed that PAPE peaked at T4 ($p < 0.01$) and almost subsided at T12 ($p > 0.05$) in ML and P conditions. Meanwhile, PAPE appeared earlier in the P condition, and the effect was more significant (P:ES = 1.09; ML:ES = 0.79). 30 m sprint results showed significant improvement only in the ML condition. The PAPE peaked at T4 ($p < 0.05$, ES = −0.47) and almost subsided at T8 ($p > 0.05$). It was mainly due to the significant enhancement of the 10–30 m segmental timing performance at T4 ($p < 0.05$, ES = −0.49). This study indicates that the size of the inertial load could influence the magnitude of the PAPE produced by the explosive force of the lower limb. The PAPE of the vertical explosive force increased with increasing inertial load, but the PAPE of the horizontal explosive force did not appear at the maximum inertial load. The most effective elicitation of the PAPE was at 4–8 min after the FT.

KEYWORDS

flywheel training, accentuated eccentric loading, warm up, jump, sprint

1 Introduction

Strength and power characteristics are highly demanded in many sports and conditioning drills (Philpott et al., 2021). Athletes are required to generate high levels of force and power in performing different movements and skills in a speedy manner such as acceleration, sprinting, jumping, stopping, and turning. In this regard, high strength and power output have been identified as the most important contributor to the success of various sports (Hori et al., 2009). To effectively monitor the individual power output in both the lab and field setting, vertical jump tests, such as counter movement jump (CMJ), and sprint test (e.g., 30 m sprint) are widely adopted (Souza et al., 2020). The quick and easy administration of these tests allows coaches to monitor the neuromuscular status and training progression without interfering with their training (Claudino et al., 2017). Meanwhile, strength coaches and sports scientists are always interested in exploring new exercise methods in acute enhancing jumping and sprinting performance.

Post-Activation Performance Enhancement (PAPE) (Cuenca-Fernandez et al., 2017) has increasingly become a topic of interest in sports science and exercise physiology, owing to its potential to improve athletic performance. PAPE was suggested to indicate the enhancement of maximal voluntary (dynamic or isometric) strength, power, or speed following a conditioning contraction. These enhancements of maximal and powerful performances are typically represented by improved strength or jumping and sprinting exercises (Blazevich and Babault, 2019; Prieske et al., 2020). This neuromuscular phenomenon refers to enhancing voluntary muscle performance following a conditioning activity, generally over a time window exceeding 5 min (Cuenca-Fernández et al., 2017; Cuenca-Fernández et al., 2019; Cuenca-Fernández et al., 2020; Cuenca-Fernández et al., 2023). Above all, it contributes significantly to understanding this mechanism and its practical applications in athletic performance enhancement. In light of these findings, the potential benefits of incorporating PAPE into warm-up before training and competition strategies become apparent, and the importance of further research into understanding its underlying mechanisms and optimal application is underscored.

Recently, flywheel training (FT) has emerged as an efficacious strategy for a wide range of athletes to enhance sports performance (Buonsenso et al., 2023). For instance, the physical capacities of soccer players (i.e., strength, power, jump, and direction changes) (Allen et al., 2021), running economy of distance runners (Weng et al., 2022), lower-body strength and power qualities in male academy rugby players (Murton et al., 2021), and the CMJ performance of basketball players (Stojanović et al., 2021) were shown to be significantly improved using FT. Strength and conditioning practitioners may acutely or chronically improve athletes' performances with the FT as the eccentric phase is associated with a high mechanical overload (Gonzalo-Skok et al., 2017). It is also believed that the higher force output potential during the eccentric phase may maximize the stretch-shortening cycle (SSC) and force production in the subsequent concentric phase. The enhanced SSC performance can be further transferred to many explosive athletic tasks like vertical jumps, horizontal jumps, and sprinting (Beato et al., 2019).

Furthermore, it was proposed that a higher eccentric load may be positively associated with a greater PAPE by recruiting fast-twitch muscle fibers more effectively in sport-specific performance (Beato et al., 2019; Beato et al., 2021a). On the other hand, a recent study compared the PAPE difference between squat and deadlift FT exercises on isokinetic quadriceps and hamstrings. Despite the higher observable concentric power in FT-squat, no significant PAPE difference in hamstring and quadriceps isokinetic performance was found (Beato et al., 2020). Therefore, PAPE responses on these lower limb FT exercises with fundamental biomechanical difference seem comparable. The recent review conducted by Beato et al. (Beato et al., 2019) has given a provisional summary regarding the effective inertia intensities (0.03–0.11 kg·m^2), volume (3 sets of a large force and power outputs exercises), and rest period (3–9 min).

Despite the extensive evidence on the use of FT and PAPE in jumping and sprinting performance enhancement, many studies in this review either did not clearly report the flywheel intensity or analyze the manipulation of inertial loads for performance, limiting the generalization of the result findings. In addition, only very few studies compared the difference between FT and traditional resistance modality. Many aspects regarding the FT-based PAPE are still not well understood or inconclusive. For example, the influence of prior traditional weightlifting experience on the FT-induced PAPE, and whether FT is more beneficial than traditional gravitational-based resistance methods are both unclear (Seitz and Haff, 2016; Bauer et al., 2019). Moreover, only very few studies addressed the change in the sprint performance (5–20 m), and these studies did not reveal all the essential training parameters (e.g., inertial load) explicitly (Cuenca-Fernández et al., 2015). In the recent study conducted by Beato et al. (Beato et al., 2021b), their FT condition using high load (0.061 kg·m^2) seemed to be inducing a slightly more performance increase (although not reached statistical significance) in both CMJ height and peak power, and the change of direction 6 min after FT implemented. Theoretically, the use of higher FT volume or inertial load should increase the mechanical power output leading to higher metabolic demand and hence the potential increase of muscle temperature, whereas the muscle temperature was identified to be one of the most impactful positive factors for PAPE (Blazevich and Babault, 2019). However, most of the previous FT studies did not investigate and compare the magnitude of PAPE using the inertia over 0.1 kg·m^2. It is therefore hypothesized that FT using different inertial loads (especially the condition over 0.1 kg·m^2) could provide different PAPE responses on jumping and sprinting tasks.

To bridge some of the aforementioned research gaps, this study aimed to compare different inertial loads that could potentially provide different PAPE responses. We also aimed to outline the optimum FT-based PAPE when compared with the traditional resistance modality. Furthermore, several previous studies have only given at least 48 h of inter-session recovery (Beato et al., 2020; de Keijzer et al., 2020). Since muscle damage and soreness after performing unaccustomed or eccentric FT strength training can be highly prominent and reach the peak, especially for males in 48 h (Fernandez-Gonzalo et al., 2014), the complete elimination of post-session carryover fatigue using standard recovery interval (i.e. 48 h) is questionable. Therefore, a longer separation period (i.e., at least 72 h) was adopted to minimize the uncertain impact in this regard. By comparing the FT and gravitational-based strength exercise using a wide spectrum of inertial loads and post-activation rest intervals the acute effect on sport-specific, lower limb explosive power performance (CMJ and sprint) can be better informed.

2 Materials and methods

2.1 Participants

Twenty healthy trained men were recruited into the study (age 21.5 ± 1.4 years, height 177.5 ± 5.2 cm, weight 74.6 ± 5.8 kg, training experience 5.5 ± 1.2 years). Participants in this study must meet the following inclusion criteria to minimize potential biases: 1) free from lower extremity injuries in the past 3 months and; 2) with a minimum of 3 years of strength training experience at least 3 days per week; 3) could squat at least 1.5 times of their body weight. All procedures conformed to the Declaration of Helsinki. Informed consent were acquired prior to the experiment with all the benefits and potential risks associated with the study explained to participants.

2.2 Experimental procedures

The study was conducted in a randomized crossover design, with each subject required to complete a total of seven main trials (three CMJ conditions and four sprint conditions). All trials were performed at least 72 h apart to eliminate fatigue or carryover effects (Figure 1). All participants completed three familiarization sessions of FT to fully understand and get used to the proper FT techniques before the main trials. The baseline values of CMJ or 30 m sprint (depending on the experimental conditions) were acquired for comparison in each of the seven conditions. The three CMJ conditions were conducted to investigate the PAPE of the FT on the CMJ under different inertial loads (0.041 kg·m^2 as large [L]; 0.057 kg·m^2 as medium-large [ML]; and 0.122 kg·m^2 as Pro [P]). Subjects performed the CMJ trials before, and immediately (within 15 s; T0), 4 min (T4), 8 min (T8), 12 min (T12), and 16 min (T16) after the flywheel intervention, respectively. Similarly, subjects completed four 30 m sprint conditions using L, ML, and P inertial loads of FT and a controlled condition without intervention using the same time point as the CMJ conditions. A standardized 15-minute warm-up protocol was used in each session before the baseline test, including a 10-minute cycling at constant power (1 W per kg of body mass) and a 5-minute dynamic warm-up drills focusing on the hip, knee, and ankle as well as mimicking the squat, jumping and sprinting movements.

2.2.1 Flywheel intervention

The experimental intervention protocol consisted of 4 sets of 7 repetitions of half squat exercise (above parallel) using a flywheel device (DESMOTEC, Italy). After the completion of a 15-minute standardized warm-up protocol, participants were required to perform each repetition at maximal velocity interspersed by a 3-minute inter-set passive rest (Seitz and Haff, 2016; Beato et al., 2020). The squat kinematics and quality were monitored and immediately feedback by an investigator with extensive strength training experience. Standardized verbal encouragements were provided to safeguard the maximum movement speed of each repetition. Three specific inertial loads (L, ML, and P; described above) were adopted in different conditions. For each set of FT squats, two additional preparator repetitions with partial range and speed were given to facilitate the flywheel recoil and maximum loading speed in the subsequent seven training repetitions. During FT, relevant parameters (e.g., average velocity) were monitored based on the participants' performance so that appropriate adjustments could be made.

2.2.2 CMJ trials

CMJ trials were measured by a HD force platform (Hawkin Dynamics Inc., United States; 1,000 Hz) (Badby et al., 2022). Participants stepped on the force plates and stood completely upright (extended hips and knees) and motionless for at least one second before completing a maximum CMJ with arms akimbo after the command "3, 2, 1, begin" given. Participants were cued to jump "as high as possible" for three CMJ trials whereas the average value was used for further analyses. An excellent test-retest intraday reliability (ICC = 0.906) was observed while the smallest worthwhile change (SWC) was 0.53 cm.

2.2.3 30 m sprint trials

The 30 m sprint trials were measured by the Smart Speed timing Gates System (Fusion Sport Inc., Australia) whereas the timing gates were placed at the starting point, 10 m and 30 m. Subjects stood at the starting point in a ready position and sprinted to the finish line at full speed after the "3, 2, 1, go" command was given. The test was conducted once and the split times were recorded. A good (ICC = 0.881) test-retest inter-day reliability was found and the SWC was 0.01 s and 0.02 s for 10 m and 30 m respectively.

2.3 Statistical analyses

The data were analyzed by SPSS 23.0 while descriptive statistics were presented using the mean ± standard deviation ($\bar{x}$ ±s). The test-retest intraday and inter-day reliability (during the baseline measurement) was assessed using the intraclass correlation coefficient (ICC). The ICCs are classified as ≥ 0.9 = excellent; 0.9 ≥ ICC ≥0.8 = good; 0.8 ≥ ICC ≥0.7 = acceptable; 0.7 ≥ ICC ≥0.6 – questionable; 0.6 ≥ ICC ≥0.5 = poor; ICC ≤0.5 = unacceptable (Beato et al., 2019). Normality tests of dependent variables were verified and all passed with Skewness-Kurtosis tests. The change of PAPE within conditions was calculated by percentage differences (diff%) and the formula is as follows: (Ti–baseline)/baseline × 100, with i representing any time point of CMJ/30 m sprint trial after the intervention. The difference between conditions was compared using two-way repeated measures ANOVA (Time × Condition). The significance level was set at $p < 0.05$. Cohen's d effect sizes (ES) were calculated from the original data to quantify the magnitude of the difference of PAPEs. The ES is classified as small = 0.2, moderate = 0.5, and large = 0.8 (Cohen, 1988).

3 Results

3.1 PAPE of different inertial loads on CMJ

The two-way repeated ANOVA showed significant differences ($F(4,80) = 5.008$, $p = 0.001$) of condition and time interaction on PAPE. The simple effects of the CMJ showed a trend that PAPE

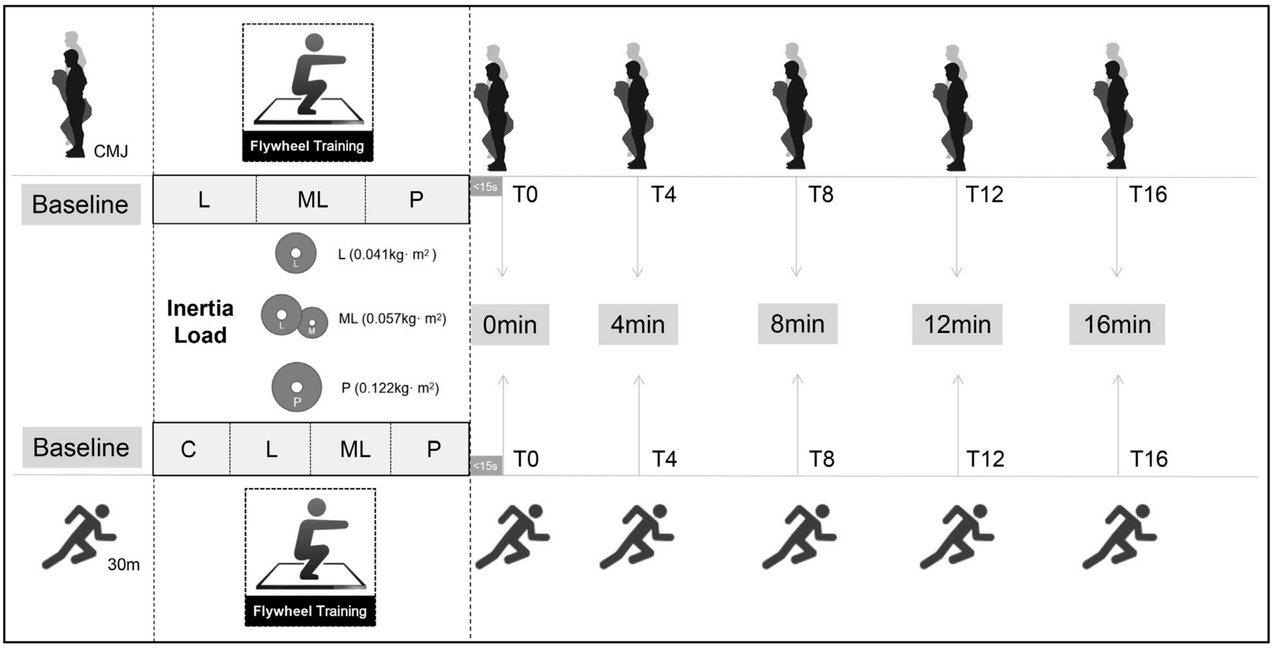

FIGURE 1
Experimental procedure diagram.

peaked at T4 ($p < 0.01$) and almost subsided at T12 ($p > 0.05$) in ML and P conditions. Regarding the magnitude of effect, T4 showed large (ES = 1.09) and moderate (ES = 0.79) effects on P and ML conditions respectively when compared to the pre-test baseline (Tp). Meanwhile, an earlier significant PAPE was observed in the P condition (T0, $p = 0.003$; ES = 0.60) only but not in L or ML conditions (T0, $p > 0.05$). Conversely, there was no significant CMJ difference before and after the intervention in the L condition (Figure 2). When comparing the diff% between conditions, the ML condition showed a significant difference at T4 ($p = 0.049$) whereas both T0 ($p = 0.003$) and T4 ($p = 0.005$) showed significant differences in the P condition.

3.2 PAPE of different inertial loads on 30 m sprint

The two-way repeated ANOVA showed significant differences ($F(12,180) = 2.146$, $p = 0.016$) of condition and time interaction on the 30 m sprint times. The simple effect showed a significant difference in sprint time when compared to the baseline Tp ($p = 0.04$) in the ML condition. Apparently, in the ML condition, the T4 showed a significant and moderate reduction in sprint time ($p < 0.05$, ES = −0.47) while no significant differences were observed in all other time conditions ($p > 0.05$). Conversely, significant moderate ($p < 0.05$, ES = 0.68) and large ($p < 0.05$, ES = 1.0) increases in sprint time were observed in the T0 time point during L and P conditions respectively (Figure 3). In addition, a small decrease in sprint time in T8 during L ($p < 0.05$, ES = −0.23) was observed. When compared with the control condition, both the L condition ($p = 0.007$) and P condition ($p = 0.001$) showed a significant increase at T0 (Figure 6A).

The results of the 30 m sprint split time showed no significant difference in 0–10 m either in between or within the condition comparisons (Figures 4, 6B). The effect of condition × time interaction on PAPE during 10-3 m split time showed a significant difference ($F(5,92) = 9.654$, $p < 0.001$) while the simple effects showed a significant decrease in the ML condition at T4 ($p < 0.05$, ES = −0.49) and T8 ($p < 0.05$, ES = −0.34) (Figures 5, 6C).

4 Discussion

The current study investigated the PAPE of FT on lower limb explosive power performance. Regarding the vertical explosive power (i.e., CMJ), our results showed a general trend that the magnitude of peak PAPE was positively related to the size of inertial loads applied (P > ML > L). Except for the insignificant result in the low load (L) condition, peak PAPE appeared at T4 and mostly subsided at T12 in both ML and P conditions. When the large inertial load ($p = 0.122$ kg·m^2) was applied, the PAPE was induced immediately (T0). Therefore, our optimum time window for yielding PAPE in the CMJ task was 0–12 min post-intervention. Conversely, The PAPE of horizontal explosive power (i.e. 30 m sprint) showed a distinct characteristic. The 30 m sprint time was slower than the baseline immediately (T0) after the FT using P and L inertial loads. Only the ML condition showed some beneficial effects at T4 (ES = −0.47) without any significant detrimental effects at other time points. When a light inertial load was used (L), only a small beneficial effect (ES = −0.23) was observed at T8. All the observable PAPEs took place between a 10–30 m split, while no significant PAPE was observed between a 0–10 m split.

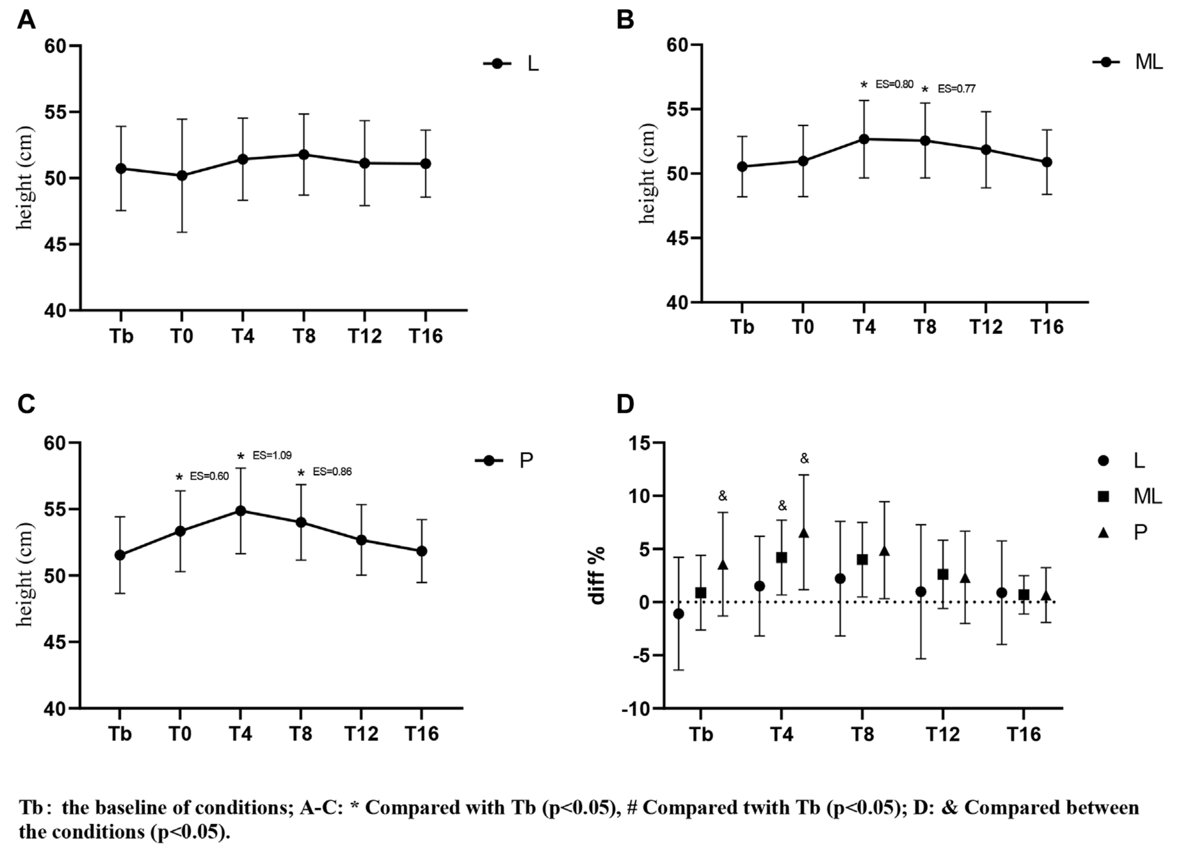

FIGURE 2
Variation of PAPE in CMJ with time under different inertial loads.

Several mechanisms for enhancing lower limb performance acutely using heavy resistance exercise, weightlifting, and FT have been described in the literature (Beato et al., 2019; Beato et al., 2020; Beato et al., 2021a). The most commonly cited physiological factors underpinning the performance enhancement effect included the increased calcium sensitivity of the actin-myosin interaction and better myosin light chain (MLC) phosphorylation. Traditionally termed "post-activation potentiation" (PAP), these cascades of events have been proposed to increase the rate of cross-bridge formation and the transient enhancement of muscles' contractile capacities, force output, power development, and the rate of force development (Tillin and Bishop, 2009; Boullosa et al., 2018). However, PAP is a muscle-memory mechanism and the effect typically lasts <30s (Blazevich and Babault, 2019; Boullosa et al., 2020), which may not fully explain the performance enhancement effect observed in our study. Alternatively, it is known that high-load contractions increase significantly muscle fiber temperature, and that speed contractions (i.e., RFD) are highly dependent on the muscle temperature because of the ergogenic effect obtained in the muscle mechanics with the increase of the temperature e.g., reduction of the muscle viscosity, an increase of the nerve conduction velocity, and an increase of the water content favoring cross-bridge attachment (Blazevich and Babault, 2019). Furthermore, nerve impulses to the muscle and the H-reflex were thought to be enhanced via the proper preload of muscles from a central perspective. All these proposed mechanisms may collectively explain the observable improvements in the explosive performance of lower limb tasks in the current study.

To achieve the best transformation of PAPE and lower limb explosive performance, the existing literature recommended performing the FT 4–12 min before the formal training tasks or competition (Tillin and Bishop, 2009; Dobbs et al., 2019). One particular study also highlighted the use of FT using medium (0.029 kg·m^2) and high inertial load (0.061 kg·m^2) to enhance the CMJ performance (8.5%–11.3%) (Beato et al., 2021a). Interestingly, our study only partially echoed their findings. In the study of Beato et al. (2021b), the CMJ performance dropped almost immediately (30 s post-intervention) in both their medium and high load conditions whereas no immediate detrimental effect on CMJ performance was observed in the current one. Furthermore, our CMJ even improved immediately (T0) when the very high inertial load (0.122 kg·m^2) was applied. The authors of previous studies believed that the dominant fatigue effect had masked the observable PAPE and therefore, a sufficient post-exercise recovery interval is required to dissipate the accumulated fatigue in the FT training. However, it is worth noting that most of the previous studies used a shorter (2 min) inter-set rest during FT exercises, whereas the use of a relatively longer inter-set rest (3 min) in our study may explain the discrepancy of immediate PAPEs. Therefore, it is speculated that the sufficiently long inter-set recovery period (i.e. 3 min or above) or

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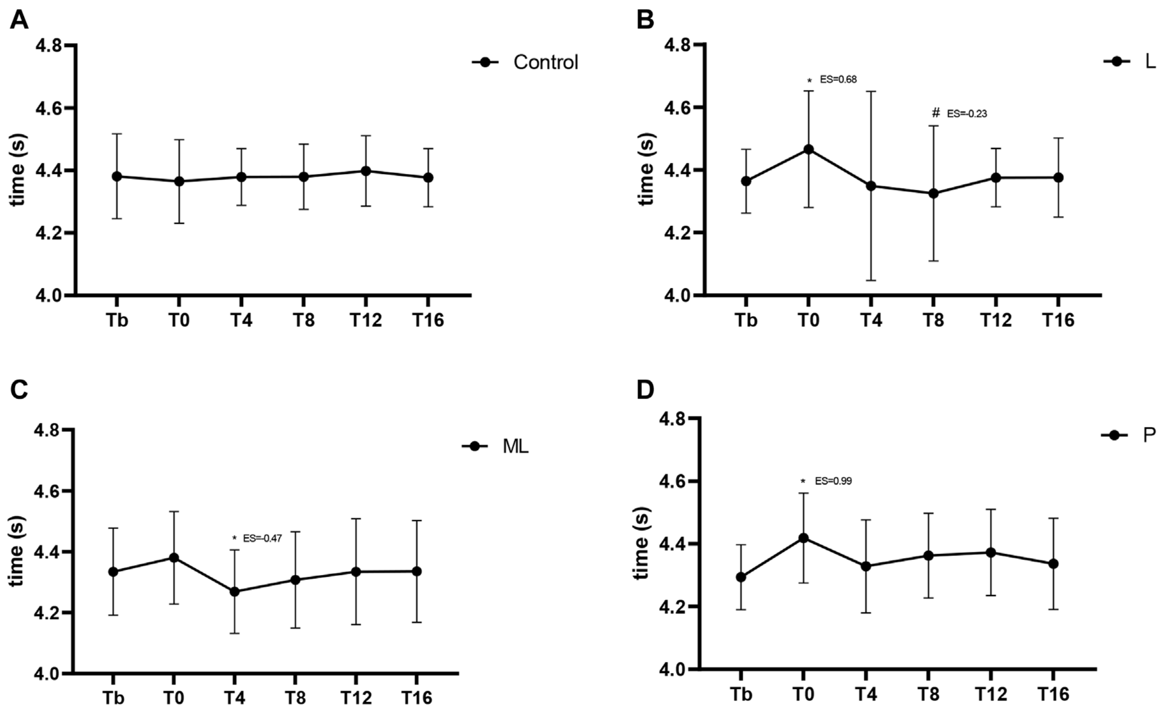
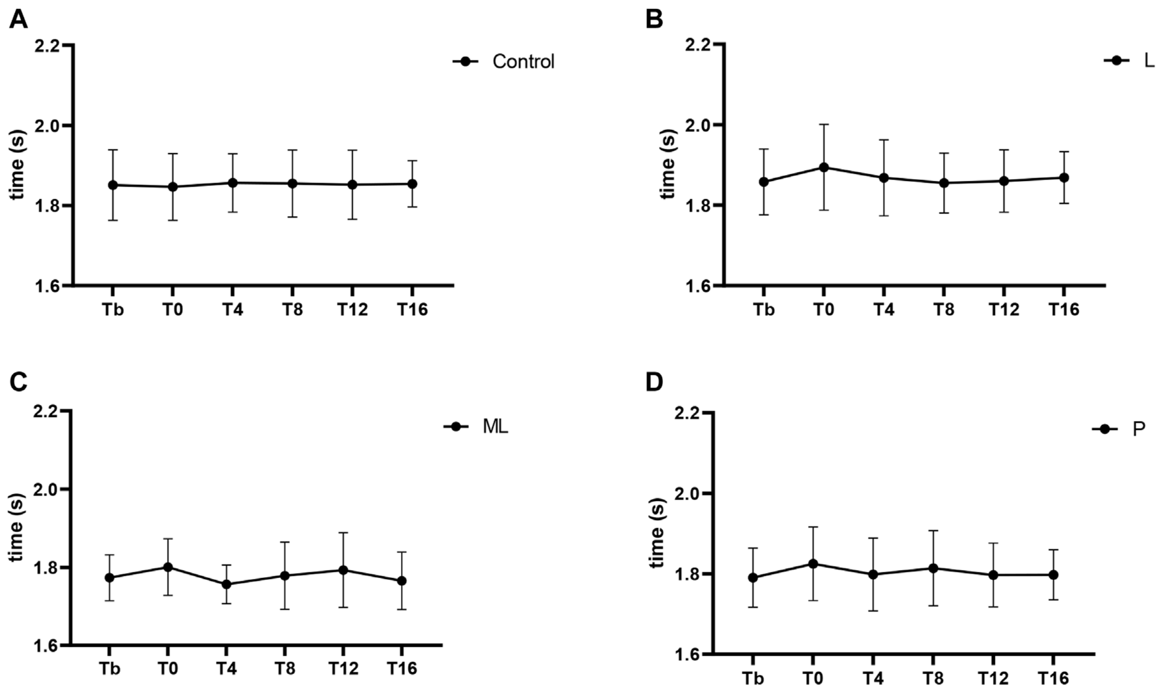


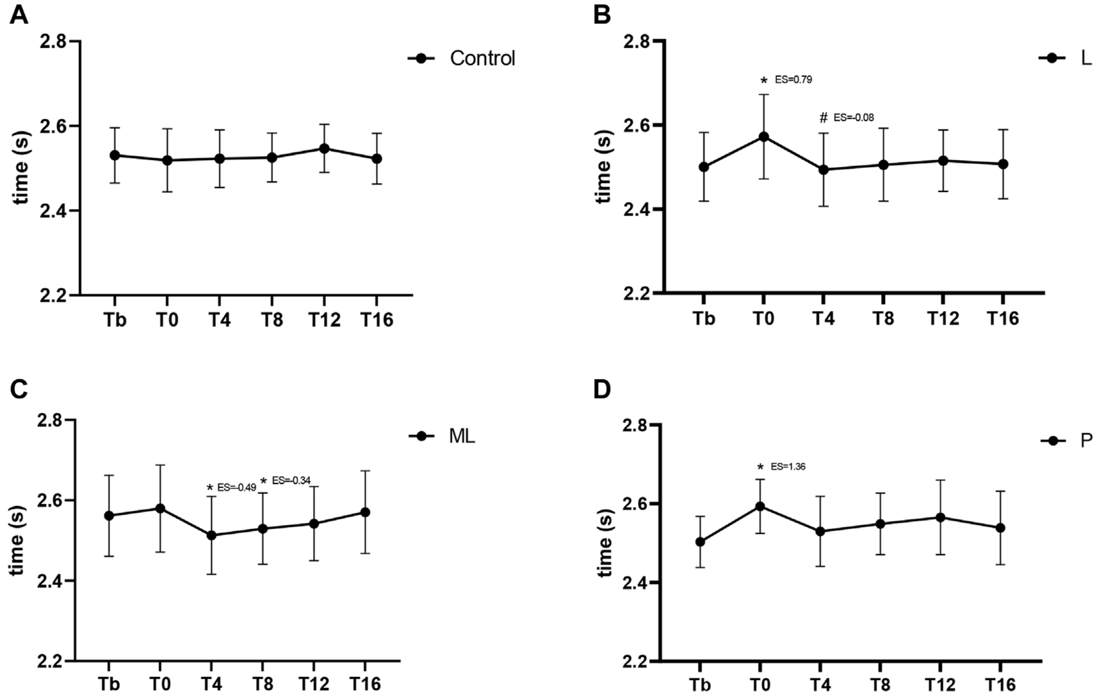
* Compared with Tb (p<0.05), # Compared with Tb (p<0.05).

FIGURE 3
Variation of PAPE in 30 m sprint with time under different inertial loads.



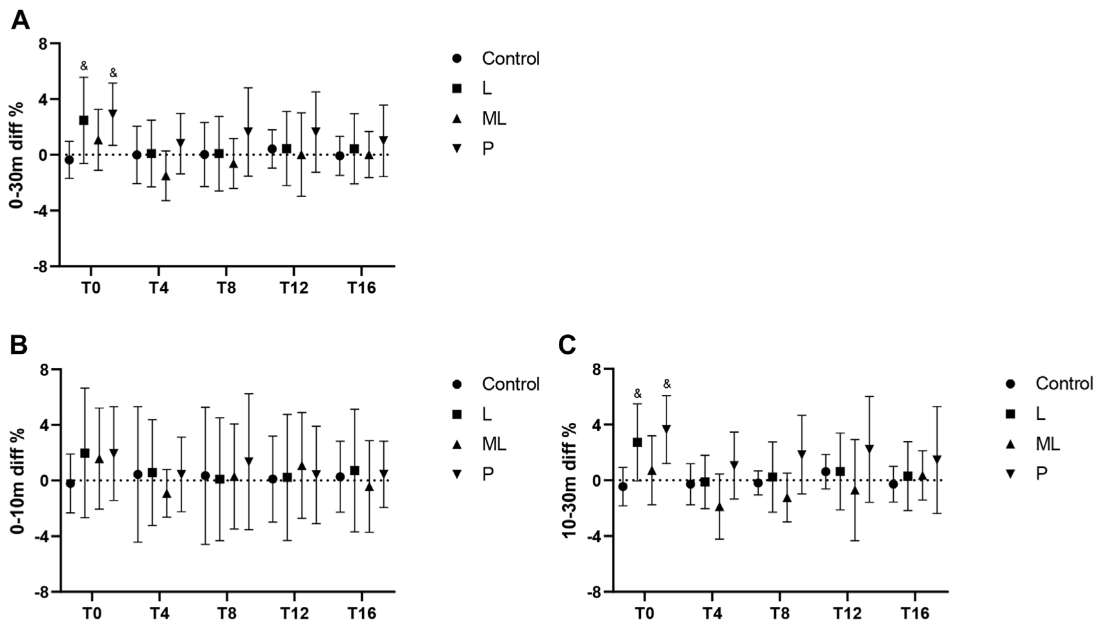
* Compared with Tb (p<0.05), # Compared with Tb (p<0.05).

FIGURE 4
Variation of PAPE from 0-10 m in 30 m sprint with time under different inertial loads.



*** Compared with Tb (p<0.05), # Compared with Tb (p<0.05).**

FIGURE 5
Variation of PAPE from 10-30 m in 30 m sprint with time under different inertial loads.



& Compared between the conditions (p<0.05).

FIGURE 6
Percentage change of PAPE with time under different inertial loads.

even adopting the cluster set configurations (e.g., intra-set rest) is the key to efficiently dissipating the fatigue and offsetting the residual dominant fatigue immediately after the FT implementation. Further studies in this regard are warranted to fully understand the rest configuration, FT-induced fatigue, and the immediate PAPE.

In addition, the aforementioned study by Beato et al. (Beato et al., 2021a) also supposed a superior effect of using a high inertial load over the medium one as theoretically, the eccentric overloaded method could better recruit higher order motor units, and induce greater postsynaptic potential and H-wave. Although their findings did not show a significant difference between high and medium load, it was proposed that a longer recovery interval (>6 min) may be required to support this supposition. In this regard, our study showed a larger magnitude of PAPE on CMJ tasks when the higher inertial load was used (P: 0.122 kg·m^2 > ML: 0.057 kg·m^2 > L: 0.041 kg·m^2) while the peak PAPE appeared within 6 min timeframe (i.e. 4 min in our study). It is noteworthy that our middle load (ML: 0.057 kg·m^2) approximated their high load (0.061 kg·m^2) while our largest one in the P condition was twice their high load. Despite the different findings in these two studies, our results supported their supposition. Considering that a 3-min inter-set rest is barely sufficient to eliminate all the cumulated fatigue and to maintain the repetition sustainability or the lifting performance in the continuous straight-set configuration (Ho et al., 2021), the shorter inter-set rest (2 min) adopted in the previous studies might therefore hinder the expression of the potential PAPEs in using high inertial load (Beato et al., 2019; Beato et al., 2020; Beato et al., 2021a). Therefore, we recommend that practitioners may use multiple sets of ML (0.057 kg·m^2) and P (0.122 kg·m^2) inertial loads of FT interspersed with 3-min inter-set rest meanwhile giving a 4-min post-FT recovery period to peak the PAPE before vertical jump-related activities or training. For shorter inter-set rest (e.g., 2 min) during EOL training, with the reference from previous findings, the inertial load should be adjusted to light and moderate (≤0.061 kg·m^2) while a 6-min post-FT recovery window is needed to achieve the peak PAPE. When considering the optimal balance between FT loading stimulation and induced fatigue, a recent study has shown a significantly higher concentric and eccentric peak power output in FT-assisted squat over the classic FT squat with an unassisted concentric phase (Wren et al., 2023). Therefore, it is an interesting question if FT-assisted squat can potentially yield a higher magnitude and longer duration of PAPE on jumping and sprinting tasks with the same or even lower FT volume.

Besides the interaction between loading and recovery period, the FT volume and intensity may also play a role in PAPE. A recent study has shown that multiset (at least two) FT half-squat exercises (light inertia with 0.029 kg·m^2) were required to elicit significant PAPE on jumping performance after 3 or 6 min (de Keijzer et al., 2020). Interestingly (Maroto-Izquierdo et al., 2020) have successfully demonstrated a single set of high-intensity FT (0.083 kg·m^2) that led to a peak PAPE with a small effect on CMJ enhancement after 12 min and meanwhile, a clear increase of peak concentric velocity was still observable after 20 min. It seems that proper dosage of FT exercises is essential to optimize the PAPE (maximize the magnitude and duration) of jumping performance. Given that a lower volume of FT might potentially decrease the magnitude and duration of fatigue while a sufficiently high intensity of stimulation is needed for maximizing the neuromuscular response, it is speculated that a lower volume of high-intensity FT (i.e., 2 sets of our P condition) may potentially achieve comparable jumping or sprinting enhancement meanwhile lengthen the duration of observable PAPE (e.g., only diminished after 16 or 20 min in CMJ or sprinting tasks). Future studies regarding the different combinations of intensity and volume to identify the optimal FT dosage on PAPE are indicated.

Regarding the horizontal explosive tasks, since PAPE using FT has the property of task-specific adaptations (Beato and Dello Iacono, 2020), the PAPE should only be maximized when the PAPE drill and the performing activities share similar biomechanical characteristics (e.g., vector force and joint movements) (Beato et al., 2020). Therefore, even though similar muscles were recruited in squat and sprint tasks, the FT drill using half squat might only yield sub-optimum PAPE on sprinting performance. In support of previous studies, our findings showed a similar trend in the expression of fatigue and PAPEs after FT exercises that the sprint performance decreased (longer sprint time) immediately (T0) in all conditions (Figures 3–5). From the magnitude perspective, modest beneficial PAPEs on 10–30 m sprint tasks were observed (only in ML condition at T4 with ES = −0.49), while both L and P yielded no or trivial effects in most sprint situations. It seems possible that the low inertial load in L did not provide sufficient stimulation, while the high load in P may induce too much fatigue and undermine the PAPE during the subsequent recovery period. Therefore, FT as a preload modality may induce the PAPE to different extents according to the nature of the subsequent training or performing activities, while the potential PAPE benefits can be retained in the recovery period depending on 1) the total amount of PAPE and fatigue produced during training and; 2) the residual PAPE and fatigue during a range of recovery period. Besides, the motor pattern interference effect, or called "perseveration" (Giannouli, 2013) that the initial task perseveres and leads to the perceived loss of coordination of the second similar task may have played an important role in hindering the post-FT PAPE. Apart from the biomechanical differences between squat, CMJ, and sprint, the long ground contact time of CMJ (>0.25 s) can be regarded as a slow stretch-shortening cycle (SSC) while the 30 m sprint is dominated by the fast SSC activities. Thus, this may further explain that the relatively slow FT squat without any SSC involvement did not maximize the PAPE in transferring to the sprinting activities. In this regard, the previous study showed a significant improvement in both the 10 and 20 m sprint performance (2.3%–2.6%) in the window between 4 and 8 min after weighted (10% of body mass) plyometric PAPE drills (Turner et al., 2015). Further studies to compare the actual PAPE differences on sprint tasks after FT, plyometric exercises, and the combined methods are required to provide more conclusive practical guidelines in this area.

This study has several strengths, including using a crossover randomized controlled trial that can eliminate the issues of between-subjects differences. At the same time, most previous studies adopted 2-min inter-set rest, which might have more prominent cumulated fatigue. In return, this might potentially mask the PAPE expression. The longer inter-set rest (3 min) used in our study seemed to be more capable of unmasking the PAPE potentials in wider perspectives and conditions.

Despite these strengths, major limitations of the present study included that only the vertical FT (parallel squat) was adopted. The optimum FT exercise format to maximize CMJ and sprint performance should be further determined by comparing the PAPEs with other movements (e.g., unilateral-based such as lunge and horizontal-based such as hip thrust). Meanwhile, our findings have included T0 (or within 15s after FT) and both PAP and PAPE probably co-existed in around 30 s (Blazevich and Babault, 2019). The current experimental design was not able to differentiate and explain the determinant effect (PAP vs. PAPE) of any observable performance change of this condition. In the future, muscle activity monitoring such as electromyography can also be used to evaluate the degree of motor unit recruitment and the biomechanical similarity. Moreover, given the fact that performance enhancements would not depend only on the fiber type II stimulation, another future study perspective is to test if light loads could trigger the same effects as heavy loads but with higher repetitions. Finally, further investigations can explore the use of assisted flywheel squats to determine if such an approach could be suitable for inducing PAPE.

5 Conclusion

In conclusion, this study shows that the multiple sets of FT method as the preloaded activity can acutely enhance the CMJ and 30 m sprint performance in trained individuals. With 3-min inter-set rest given during the preloaded activity, both P and ML inertial loads could produce the peak PAPE and CMJ performance at 4 min and the benefits gradually subsided after 12 min, whereas the 30 m sprint (especially the 10–30 m split) was enhanced via PAPE using ML inertial load at 4–8 min time points. Future research is encouraged to further explore the optimum FT exercise format to maximize the PAPEs on various exercise tasks.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by the Beijing Sport University's Research Ethics Committee has approved this study protocol (Registration number 2020008H). The patients/participants provided their written informed consent to participate in this study.

Author contributions

Conceptualization: KF, LC, QL, and HL. Data curation and writing–original draft: KF, LC, RW, and QL. Formal analysis and investigation: KF, LC, and HL. Writing–review, and editing: EP, QL, IH. All authors contributed to the article and approved the submitted version.

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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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Morphological and viscoelastic properties of the Achilles tendon in the forefoot, rearfoot strike runners, and non-runners *in vivo*

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The purpose of this study was to investigate the differences in the morphological and viscoelastic properties of the Achilles tendon (AT) among different groups (rearfoot strikers vs. forefoot strikers vs. non-runners). Thirty healthy men were recruited, including habitual forefoot strike runners ($n = 10$), rearfoot strike runners ($n = 10$), and individuals with no running habits ($n = 10$). The AT morphological properties (cross-sectional area and length) were captured by using an ultrasound device. The real-time ultrasound video of displacement changes at the medial head of the gastrocnemius and the AT junction during maximal voluntary isometric contraction and the plantar flexion moment of the ankle was obtained simultaneously by connecting the ultrasound device and isokinetic dynamometer via an external synchronisation box. The results indicated that male runners who habitually forefoot strike exhibited significantly lower AT hysteresis than male non-runners ($p < 0.05$). Furthermore, a greater peak AT force during maximal voluntary contraction was observed in forefoot strike male runners compared to that in male individuals with no running habits ($p < 0.05$). However, foot strike patterns were not related to AT properties in recreational male runners ($p > 0.05$). The lower AT hysteresis in male FFS runners implied that long-term forefoot strike patterns could enhance male-specific AT's ability to store and release elastic energy efficiently during running, resulting in a more effective stretch-shortening cycle. The greater peak AT force in male FFS runners indicated a stronger Achilles tendon.

KEYWORDS

Achilles tendon, foot strike patterns, cross-sectional area, hysteresis, running

1 Introduction

To adapt to bipedal running, humans have gradually evolved the Achilles tendon (AT), which serves as a crucial structure connecting the heel and the plantar flexor muscles of the foot. It plays a primary role in transmitting the muscular force generated by the calf muscles during the movement, enabling efficient force or energy storage (during contact) and release (during push-off) in the lower limb during running and jumping (Bramble and Lieberman, 2004; Lorimer and Hume, 2016). Achilles tendinopathy accounted for the highest proportion of injury incidence (10.3%) in runners (Davis et al., 2017), with a cumulative lifetime prevalence of 52% in endurance runners (Lorimer and Hume, 2016). Particularly, the running-related injury incidence proportion of Achilles tendinopathy is male-biased (Francis et al., 2019), and the majority of AT ruptures occurred in male compared with female patients, with an incidence rate ratio ranging from 5.5:1 to 30:1 (Möller et al., 1996; Longo et al., 2009; Lemme et al., 2018). Thus, understanding the biomechanical properties of the AT and its response to different running habits, particularly in the male-specific AT, is important for optimizing training strategies and minimizing the risk of injuries (Chen et al., 2023).

Running is a popular form of exercise that can significantly impact the musculoskeletal system, including AT. Different foot strike patterns, such as rearfoot strike (RFS) and forefoot strike (FFS), have been observed in runners. Rearfoot strikers primarily contact the ground on their heels, whereas forefoot strikers initially contact the ground with the ball of their foot before the heel comes down (Hayes and Caplan, 2012). The biomechanical implications of different foot strike patterns on the AT have been a topic of interest in the field of sports science, and most studies have investigated the effect of foot strike patterns on AT's morphological and mechanical properties as a primary outcome. However, previous studies have yielded controversial results. Some studies have found that FFS runners had a greater cross-sectional area (CSA) of the AT (Histen et al., 2017; Hirono et al., 2022), whereas others have not observed this significant difference (Kubo et al., 2015; Kernozek et al., 2018). Furthermore, whether the high AT load in FFS runners during running indicates improved running performance or increased risk of Achilles tendinopathy is currently a subject of debate (Rice and Patel, 2017; Kernozek et al., 2018).

Tendons are primarily composed of a collagenous matrix with elastic properties, which enable them to efficiently transmit force according to the amount of stretch they experience (Peltonen et al., 2013). However, viscoelasticity, an important characteristic, has often been overlooked in previous assessments comparing the AT mechanical properties of runners with different foot strike patterns. Currently, only a limited number of studies have investigated the *in vivo* viscoelasticity of the AT using ultrasound (Kubo et al., 2001; Lichtwark and Wilson, 2005; Peltonen et al., 2013; Suydam et al., 2015), suggesting that viscoelastic changes play a role in reducing the risk of AT injury (Wilson et al., 1991). Low hysteresis is advantageous for most tendons, indicating lower viscosity properties and excellent elastic properties that can effectively store and release elastic energy during activities, such as walking, running, and jumping (Peltonen et al., 2013). High hysteresis generates heat to increase temperature and may eventually lead to thermal injury and tendon degeneration during prolonged exercise (Wilson and Goodship, 1994). Given the importance of applied mechanical loading (stress and strain) on the adaptation of AT properties during running, exploring the effect of running exercise on the viscoelastic properties (e.g., hysteresis) of AT *in vivo* is crucial before exploring such effects in runners with different foot strike patterns.

Therefore, the objectives of this study are as follows: 1) to investigate the differences in male-specific AT morphological and viscoelastic properties between individuals with and without running exercise habits; 2) to examine the differences in male-specific AT morphological and viscoelastic properties between individuals with habitual foot strike patterns (RFS vs. FFS). We hypothesised that 1) runners had greater length, CSA, AT force, and lower hysteresis of AT than non-runners, and 2) FFS runners had greater length, CSA, force, and lower hysteresis of AT than RFS runners.

2 Materials and methods

2.1 Participants

The sample size was determined using G*Power software (3.0.1, Univ. Kiel, Kiel, Germany) through *a priori* power analysis based on preliminary data published by Intziegianni et al. (2016), which examined the differences in AT CSA between children, asymptomatic adults, and patients with Achilles tendinopathy (f = 0.63). The results indicated that a minimum sample size of 30 participants was required for a one-way analysis of variance (ANOVA) with a significance level α of 0.05 and a power β of 0.2. Therefore, this study recruited three groups consisting of 10 participants each: an RFS group, an FFS group, and a non-exercising control group (CG, Table 1). The runners in the RFS and FFS groups were required to have run a weekly mileage of more than 20 km in the past 4 weeks. The RFS group was accustomed to running with cushioned running shoes (featuring shock absorption and cushioning structures) in an RFS pattern, while participants in the FFS group were accustomed to running in an FFS pattern. The CG consisted of individuals who did not meet the minimum activity score in the International Physical Activity Questionnaire Short Form: i) engaging in vigorous physical activity for at least 20 min per day on at least 3 days or more in the past 7 days, ii) engaging in walking or moderate-intensity physical activity for at least 30 min per day on at least 5 days or more in the past 7 days or iii) engaging in a combination of walking, moderate-intensity, or high-intensity activities for at least 5 days or more in the past 7 days, with a minimum cumulative weekly total of 600 MET-minutes (Holler et al., 2019). All participants were males, right-leg dominant, and free from any lower limb injuries in the past year. They abstained from consuming caffeine and alcohol-containing food for 2 h prior to the tests, and they did not engage in vigorous or exhaustive exercise within 24 h preceding the tests. Participants were informed about the experimental procedures and objectives before testing and provided informed consent by signing a consent form. This study obtained ethical approval from the Ethics Committee of Shanghai University of Sport (approval no. 102772021RT085).

2.2 Procedure

Participants were instructed to change into experimental clothing consisting of a sports vest and shorts. They were asked to wear their own preferred running shoes and perform a 5-min warm-up exercise on the treadmill at a self-selected speed. At the beginning of the testing session, the initial length of the AT was measured using an ultrasound imaging device (uSmart 3300, Terason, United States). A detailed description of the model preparation was reported in our previous study (Zhang et al., 2021a). In brief, the following steps were performed: 1) participants were positioned in a prone position on the treatment table, the ankle joint was in a neutral position (90°), and the knee and hip joints were in an extended position (180°); 2) after the application of a coupling gel, a needle of size 25 was inserted between a 12L5A linear array probe (maximum frequency: 12 MHz; probe array length: 4.5 cm) and the skin surface to serve as a marker projection in the ultrasound image. The

TABLE 1 Basic information of subjects in the habitual rearfoot striker (RFS) group, habitual forefoot striker (FFS) group, and non-exercise control group (CG, $\bar{x}$ ± SD).

	CG (*n* = 10)	RFS group (*n* = 10)	FFS group (*n* = 10)
Age (years)	24.2 ± 2.9	33.1 ± 8.1	29.8 ± 9.5
Height (cm)	174.0 ± 3.4	174.1 ± 7.1	175.2 ± 5.4
Weight (kg)	71.9 ± 7.6	70.7 ± 9.7	71.2 ± 9.1

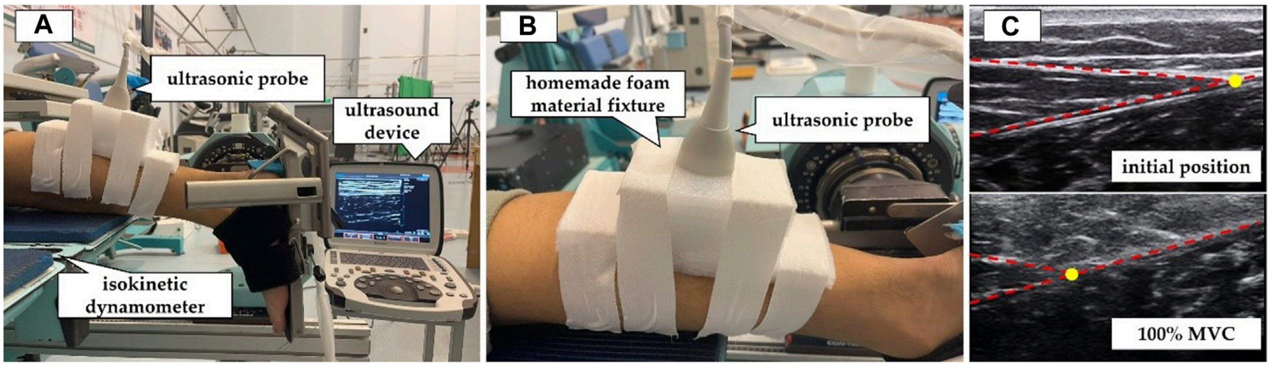

FIGURE 1
Measurement of mechanical properties of the Achilles tendon (AT) by synchronous ultrasound imaging with a maximum isometric contraction (MVC). **(A)** The participants were positioned prone on the CON-TREX isokinetic dynamometer. **(B)** The ultrasound probe was fixed at the junction between the AT and the medial head of the gastrocnemius muscle. **(C)** Ultrasound images of the AT in the resting position and during 100% MVC. The yellow circle indicated the location of the junction between the AT and the medial head of the gastrocnemius muscle.

intersection point of the marker needle and the ultrasound probe on the skin was marked as the junction of the medial head of the gastrocnemius muscle and the AT (MTJ_{GM_AT}); 3) the same procedure was repeated to mark the insertion point of the AT into the calcaneus; and 4) the distance between these two points was measured using a flexible ruler (Barfod et al., 2015). Subsequently, the ultrasound probe was positioned perpendicular to the skin surface to capture the AT CSA at a level consistent with the medial and lateral malleoli.

Participants were instructed to lie prone on the isokinetic dynamometer (CON-TREX MJ, PHYSIOMED, Schnaittach, Freistaat Bayern, Germany) with their chest against the bed, hands naturally placed by their sides, hip and knee joints fully extended, and ankle joint in a neutral position (Figure 1A). They were asked to gradually increase their ankle joint dorsiflexion maximum voluntary isometric contraction (MVC) from relaxation to the maximum within 5 s and then gradually relax within 5 s (Kubo et al., 2001). During the testing process, the ultrasound probe was fixed at MTJ_{GM_AT} using an elastic bandage (Figure 1B). The real-time ultrasound video of the *in vivo* displacement changes in MTJ_{GM_AT} (Figure 1C) and the plantar flexion moment of the ankle joint during MVC were acquired simultaneously by connecting the ultrasound device and the isokinetic dynamometer via an external synchronisation box (BIOPAC Systems Inc., Goleta, CA, United States). The ultrasound video was measured at a sampling rate of 35 Hz, and the isokinetic dynamometer was measured at a sampling rate of 256 Hz. Before the test, the participants were given sufficient time to become familiar with the target tasks. Three sets of valid data were obtained, meeting the following criteria: 1) the participants exerted maximum effort to perform the MVC and 2) the ultrasound video capturing the displacement of MTJ_{GM_AT} during the MVC was clear. In the preliminary pre-experiment, the intraclass correlation coefficient (ICC) was used to evaluate the reliability of measurements by different experimenters and the same experimenter on different days. The results showed excellent reliability of the AT morphological properties as obtained and calculated (ICC = 0.895–0.996).

2.3 Data processing

ImageJ software (version 1.46r, NIH, United States) was used to evaluate the CSA images of the AT measured by tracing the surrounding echogenic boundary of the AT. Changes in the displacement of MTJ_{GM_AT} during MVC were semiautomatically tracked using the Tracker video modelling software (Tracker 4.95, InstallBuilder, United States). The position of MTJ_{GM_AT} was tracked automatically according to the in-house scripts of Tracker video modelling. Then, data were checked manually frame by frame, and the offset points were moved to the correct position. The aforementioned process was repeated three times to reduce errors, and the average values were obtained. After the manually checked data were acquired, linear interpolation was applied to adjust the sampling rate of the ultrasound image data sequences. The sampling rate was then changed to 256 Hz, which

TABLE 2 Morphological properties of the Achilles tendon (AT) in the habitual rearfoot striker (RFS) group, habitual forefoot striker (FFS) group, and non-exercise control group (CG, $\bar{x} \pm$ SD).

Variable	CG (n = 10)	RFS group (n = 10)	FFS group (n = 10)	p-value	Partial η^2
AT length (cm)	20.3 ± 2.3	20.1 ± 3.3	20.6 ± 2.6	0.923	0.006
AT CSA (mm^2)	61.4 ± 12.1	60.8 ± 6.0	64.1 ± 10.4	0.721	0.024

was consistent with the sampling frequency of the CON-TREX isokinetic dynamometer.

The plantar flexion moment (M_{PF}) was obtained during MVC using the CON-TREX isokinetic dynamometer and normalised to the body weight (BW). Thus, F_{AT_peak} was calculated by deriving from the M_{PF} and moment arm (L_M) of the AT as follows (Suydam et al., 2015):

$$F_{AT\_peak} = \frac{M_{PF}}{L_M},$$

where F_{AT_peak} is normalised by the BW and L_M is defined as the vertical distance from the centre point of the ankle joint to AT, which is set to a fixed value of 0.05 m (Rice and Patel, 2017).

The peak AT stress was calculated by dividing F_{AT_peak} by the CSA of the AT. The peak AT strain was defined as the length in MVC relative to the initial length and divided by the initial length. AT stiffness was calculated as the slope of the least-squares line of the ascending limb of the force–elongation curve between 50% and 100% of MVC force (Kubo et al., 2015). Hysteresis was calculated by subtracting the area under the descending limb of the force–elongation curve from the area under the ascending limb and dividing the difference by the area under the ascending limb (Peltonen et al., 2010).

2.4 Statistical analysis

All data were expressed as the mean ± standard deviation. The Shapiro–Wilk test was used to assess the normality of the data. One-way ANOVA was used to compare differences between the morphological (length and CSA) and mechanical characteristics of the AT (AT force, stress peak, strain peak, stiffness, and hysteresis) among the RFS group, FFS group, and CG. *Post hoc* pairwise multiple comparisons were conducted, the alpha Bonferroni was corrected, and the partial eta-squared (η^2) was applied as a measure of effect size. SPSS statistical software (IBM SPSS v22.0, IBM Corp., Armonk, NY, United States) was used for all statistical procedures with $p < 0.05$ as the statistical significance criterion.

3 Results

No significant differences in AT length and CSA were found among the RFS group, FFS group, and CG ($p > 0.05$, Table 2).

Significant group differences were observed in the plantar flexion moment (p = 0.036 and η^2 = 0.219), F_{AT_peak} (p = 0.033 and η^2 = 0.223), and hysteresis of AT (p = 0.009 and η^2 = 0.297). *Post hoc* analysis revealed that the plantar flexion moment and F_{AT_peak} were significantly larger (21.4% and 17.2%, respectively) in the FFS group compared with the CG ($p < 0.05$, Figure 2). The AT hysteresis in the FFS group was significantly lower than that in the CG group by 68.4% ($p < 0.05$, Figure 2). However, no significant differences were observed between the FFS and RFS groups ($p > 0.05$, Table 3). Moreover, no significant differences in peak AT stress, peak AT strain, and stiffness were found among the three groups ($p > 0.05$, Table 3).

4 Discussion

The purpose of this study was to investigate the morphological and viscoelasticity properties of the AT in RFS runners, FFS runners, and non-exercising individuals. Consistent with our hypothesis, the results revealed that the ankle plantar flexion moment and AT force during MVC were significantly greater and AT hysteresis was significantly lower in the FFS group than that in the CG. However, on the contrary to our study hypothesis, no significant differences were found between the FFS and RFS groups.

No significant differences in the AT length and CSA were found among the RFS group, FFS group, and CG. This result supported the study by Kubo et al. (2015), who observed no significant differences in AT morphology among habitual FFS runners, habitual RFS runners, and habitually midfoot strike runners. Compared with other tissues, tendons are generally considered metabolically inert and less prone to morphological changes (Merza et al., 2021). However, the study used magnetic resonance imaging (MRI) to investigate a significantly larger AT CSA (95 ± 3 mm^2) in runners than in non-runners (73 ± 3 mm^2; (Rosager et al., 2002). Similarly, Devaprakash et al. (2020) found that elite or sub-elite long-distance runners had a larger CSA and shorter AT length than healthy controls according to MRI. Furthermore, Histen et al. (2017) observed that habitual FFS male runners wearing minimalist shoes had a larger CSA of the AT compared with the habitual RFS male runners. The increased AT CSA has been indicated to be related to the changes in fibre diameter, fibre density, collagen protein, and proteoglycan content (Magnusson and Kjaer, 2019). However, repetitive tendon loading associated with running not only stimulates the increase in collagen and other matrix components but also affects their redistribution within a tendon. Some regions of a tendon may contain more matrix components, whereas others may contain fewer, which are susceptible to injury (Merza et al., 2021). Based on this theory, one possible reason for the inconsistency between our study and previous studies was the difference in measurement location. Our study and the study by Kubo et al. (2015) measured the AT CSA at the same level as the medial and lateral malleoli, whereas Rosager et al. (2002) measured the CSA at a point of 3 cm above the calcaneus. The CSA in the study by Devaprakash et al. (2020) was obtained by dividing the volume of the free AT by the tendon length. Additionally, a positive correlation

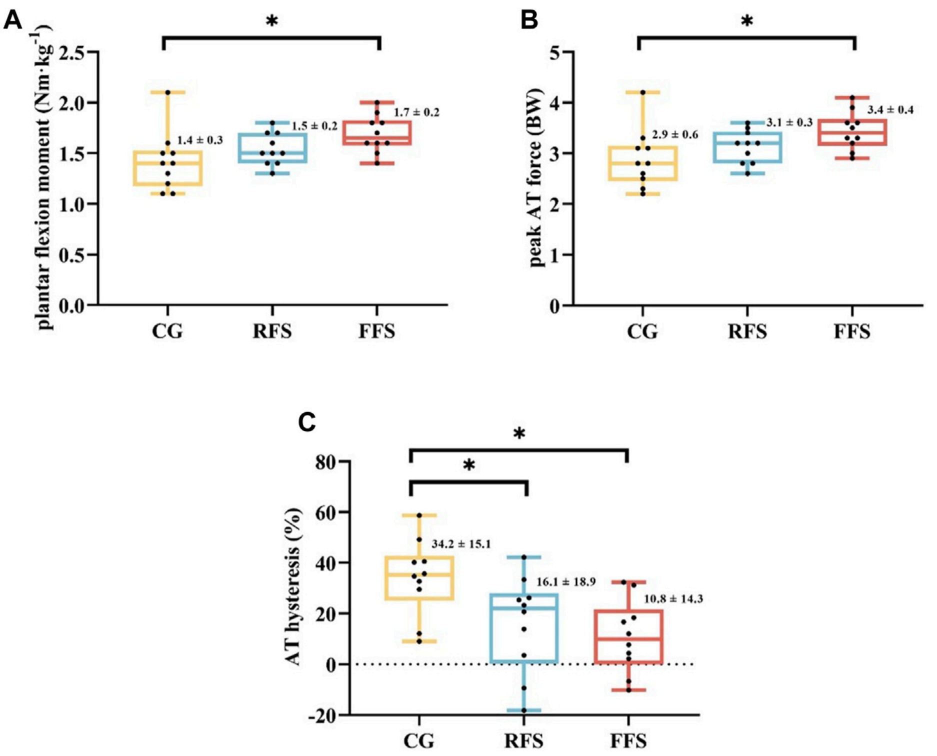

FIGURE 2
Differences in plantar flexor moment **(A)**, peak Achilles tendon (AT) force **(B)**, and AT hysteresis **(C)** at maximum isometric contraction among the habitual rearfoot striker (RFS) group, habitual forefoot striker (FFS) group, and non-exercise control group (CG). Scatter indicates individual data points for participants; * indicates $p < 0.05$.

TABLE 3 Mechanical and viscoelastic properties of the Achilles tendon (AT) in the habitual rearfoot striker (RFS) group, habitual forefoot striker (FFS) group, and non-exercise control group (CG, $\bar{x} \pm$ SD).

Variable	CG (n = 10)	RFS group (n = 10)	FFS group (n = 10)	p-value	Partial η^2
Plantar flexor moment ($Nm{\cdot}kg^{-1}$)	1.4 ± 0.3	1.5 ± 0.2	1.7 ± 0.2[a]	0.036	0.219
Peak AT force (BW)	2.9 ± 0.6	3.1 ± 0.3	3.4 ± 0.4[a]	0.033	0.223
Peak AT stress (MPa)	34.2 ± 9.9	35.8 ± 6.6	38.1 ± 7.4	0.563	0.042
Changes in AT elongation (cm)	2.0 ± 0.2	2.1 ± 0.6	2.1 ± 0.4	0.669	0.029
Peak AT strain (%)	10.0 ± 1.6	10.6 ± 2.8	10.6 ± 2.8	0.782	0.018
AT stiffness ($N{\cdot}mm^{-1}$)	146.2 ± 66.6	134.0 ± 39.5	155.5 ± 41.3	0.640	0.032
AT hysteresis (%)	34.2 ± 15.1	16.1 ± 18.9	10.8 ± 14.3[a]	0.009	0.297

[a]indicates significant differences between the FFS group and CG ($p < 0.05$) for *post hoc* tests.

between the AT CSA and body weight has been proposed (Magnusson et al., 2003; Kudron et al., 2020). Given that no significant difference in body weight was found among the participants in our study, there was no significant difference in the AT CSA among the groups, indicating that the AT CSA did not continuously increase within a certain range of body weight. The potential impact of body weight on different foot strike runners needs to be further explored in future research.

Stiffness was calculated from the linear portion of the force–elongation curve, and the selected region of the linear portion was currently inconsistent. In the present study, we elected 50%–100% regions, which were more appropriate for this study data (Kubo et al., 2007). Low AT stiffness has been shown to influence the speed of force transmission. Changes in energy expenditure are related to AT stiffness. The required AT stiffness during running was estimated to be approximately 250 $N\ mm^{-1}$, higher than that during walking. Accordingly, we hypothesized that the AT of FFS runners was stiffer than that of RFS runners. However, despite male runners having lower levels of energy consumption (i.e., hysteresis) than male non-runners, no significant differences in

AT stiffness were found among the three groups. Consistently, the previous study indicated no significant differences in AT stiffness among runners with different foot strike patterns [FFS vs. RFS vs. midfoot strike; (Kubo et al., 2015)]. Fletcher et al. (2013) investigated that energy expenditure measured using indirect calorimetry during running was only related to AT stiffness in females and not in male runners.

Mechanical loading produces adaptive changes in the AT, including increased morphological properties or mechanical properties (Devaprakash et al., 2020; Zhang et al., 2021b). Given the greater triceps muscle strength isrequired in habitual FFS runners during the stance phase, we hypothesized that the greater mechanical loading stimulated on the AT would be accompanied by an increase in the AT CSA and stiffness in the FFS group. However, our results indicated that the AT of FFS runners did not exhibit this adaptation, that is, no significant difference in AT morphological and viscoelastic properties between male runners with FFS and RFS were found. Only FFS male runners showed significantly higher AT force than male non-runners, and no differences were found between male runners with different foot strike patterns. Similar results were shown in the study by exploring AT loading in female runners (Kernozek et al., 2018). Greater AT force in FFS runners suggested more optimised athletic performance during the push-off phase of running, but asynchronous changes in mechanical and morphological properties may lead to a potential risk for Achilles tendinopathy.

Although the run itself did not affect the morphological properties of the AT, our study observed differences in the viscoelasticity properties of the AT among the three groups. In the cyclic force test (gradually increasing to 100% MVC over 5 s and gradually relaxing over 5 s), the loading and unloading curves produced a loop, which was defined as hysteresis. The area within this loop represented the heat loss due to internal damping, whereas the area under the unloading curve represented the energy restored during elastic recoil. The AT has good energy storage capacity and excellent elastic properties superior to its viscous properties (Peltonen et al., 2013), providing an energy-saving mechanism during human walking, running, and jumping. Furthermore, the results of this study showed that the FFS group had significantly lower AT hysteresis than the CG. The AT stored elastic energy during the early phase of support by elongation and released energy during the push-off phase of support to propel the body forward (Smith et al., 2022). A low hysteresis is advantageous for the AT because it indicates high elastic energy recovery and reduces energy loss during the movement while minimising heat-induced damage (Alexander, 2002). In the present study, the hysteresis values for the FFS group (10.8% ± 14.3%), RFS group (16.1% ± 18.9%), and CG (34.2% ± 15.1%) were consistent with the previous reports of hysteresis during running [2%–45% (Finni and Vanwanseele, 2023)] and during single-leg jumping [15%–39%; (Lichtwark and Wilson, 2005)]. The wide range of hysteresis variation may be attributed to several factors. First, it may be due to the anatomical structure of the tendon because the AT is a tendon shared by the three heads of the triceps surae. Each head can independently stretch the tendon, leading to regional strain variations. Despite efforts to reduce measurement errors by averaging multiple measurements, the uncertainty in measuring AT hysteresis is difficult to avoid when tendons are explored *in vivo* (Peltonen et al., 2013). Second, an individual's ability to control motion during the unloading phase contributes to possible errors (Finni and Vanwanseele, 2023). Ultrasound sampling frequency is usually much lower than that of force measurements. Although this study corresponded to two datasets by interpolation, the effect of desynchronisation of force and ultrasound image on AT hysteresis is sensitive (Finni et al., 2013).

This study had several limitations. First, owing to the low sampling frequency of the ultrasound images, errors in the result are inevitable. Although this error may be resolved by averaging multiple trials from each participant, AT hysteresis is higher *in vivo* than *in vitro* and may be addressed only by validation studies, where the same AT is measured separately *in vivo* and *in vitro*. Second, this study only measured the viscoelastic properties of the AT at 100% MVC, and whether this property changes with foot strike pattern during running remains unclear. Finally, the assessment of AT morphological and viscoelastic properties is influenced by several factors, for example, synergistic muscle activity, AT and foot moment arm, preconditioning of the tendon, and the rate of force development. Therefore, the influences of these factors need to be further analysed. In addition, all participants were male in the current study, and whether female runners would show the same results remains unclear. In future studies, we suggest including female participants to better reflect the diversity of runners in the target population.

5 Conclusion

Habitual FFS exhibited significantly lower AT hysteresis than non-runners in men. This result suggested that long-term FFS patterns could enhance the male-specific AT's ability to store and release elastic energy efficiently during running, resulting in a more effective stretch-shortening cycle. Furthermore, the peak AT force observed in the FFS group was greater than that in non-runners, suggesting that male FFS runners have a stronger Achilles tendon. However, foot strike patterns were not related to the morphological and viscoelastic properties of the AT in recreational male runners.

Data availability statement

The raw data supporting the conclusion 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 Shanghai University of Sport (Approval No. 102772021RT085). 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

XZ: Data curation, Investigation, Methodology, Software, Validation, Writing–original draft, Writing–review and editing. LD: Data curation, Investigation, Methodology, Writing–review and editing. SX: Methodology, Software, Writing–review and editing. WF: Conceptualization, Formal Analysis, Funding acquisition, Project administration, Resources, Supervision, Writing–review and editing.

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Conflict of interest

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

Publisher's note

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Respiratory muscle training induces additional stress and training load in well-trained triathletes—randomized controlled trial

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Background: Respiratory muscle training (RMT) has been investigated in the context of improved athletic performance and pulmonary function. However, psychophysiological costs of RMT remain understudied. Voluntary isocapnic hyperpnoea (VIH) and inspiratory pressure threshold loading (IPTL) are widely applied RMT methods. The main purposes of this study were to assess whether RMT induces additional load on well-trained triathletes and determine differences in RMT-induced load between sexes and applied methods.

Materials and Methods: 16 well-trained triathletes ($n = 16$, 56% males) underwent 6 weeks of VIH or IPTL program with progressive overload. Blood markers, subjective measures, cardiac indices, near-infrared spectroscopy indices, inspiratory muscle fatigue, and RMT-induced training load were monitored pre-, in and post-sessions. We used multiple ANOVA to investigate effects of sex, training method, and time on measured parameters.

Results: There were significant interactions for acid-base balance ($p = 0.04$ for sex, $p < 0.001$ for method), partial carbon dioxide pressure ($p = 0.03$ for sex, $p < 0.001$ for method), bicarbonate ($p = 0.01$ for method), lactate ($p < 0.001$ for method), RMT-induced training load ($p = 0.001$ for method for single session, $p = 0.03$ for method per week), average heart rate ($p = 0.03$ for sex), maximum heart rate ($p = 0.02$ for sex), intercostales muscle oxygenation ($p = 0.007$ for testing week), and intercostales muscle oxygenation recovery ($p = 0.003$ for testing week and $p = 0.007$ for method).

Conclusion: We found that RMT induced additional load in well-trained triathletes. Elicited changes in monitored variables depend on sex and training method. VIH significantly increased subjective training load measures. IPTL was associated with disbalance in blood gasometry, increase in lactate, and reports of headaches and dizziness. Both methods should be applied with consideration in high-performance settings.

KEYWORDS

respiratory muscle training, respiratory muscles, training load, triathlon, triathlete

Introduction

Thorough evidence of the crucial role of respiratory strength, endurance, and fatigue in athletic performance emerged in the last decades (Boutellier et al., 1992; Volianitis et al., 2001; Romer et al., 2002). Systematic reviews of literature found that respiratory muscle training (RMT) may improve specific performance during time trials, constant load tests, and intermittent incremental tests (González-Montesinos et al., 2012; Illi et al., 2012; HajGhanbari et al., 2013), enhance respiratory muscle strength and endurance (González-Montesinos et al., 2012; HajGhanbari et al., 2013; Salesdo et al., 2016), and reduce respiratory fatigue, perceived breathlessness, and exertion during exercise in normoxia and hypoxia (Klusiewicz, n.d.; HajGhanbari et al., 2013; Álvarez-Herms et al., 2018). High levels of respiratory muscle fatigue are known to limit exercise performance among different sports, conditions, and populations (Mador and Acevedo, 1991; Amann et al., 2007; Verges et al., 2007). Moreover, cardiorespiratory fitness and sports performance depend on the athlete's ventilation and lung function (Wiecha et al., 2023). RMT has received significant research attention beyond just the athletic community. It has been associated with improved balance and trunk control, endurance, pulmonary function, and quality of life in patients and the elderly (Keles et al., 2018; Ferraro et al., 2019; Zheng et al., 2021; Arslan et al., 2022). However, the traditional sport-specific training programs do not enhance the function of respiratory muscles (Coast et al., 1990; Eastwood et al., 2001; Klusiewicz et al., 2017), providing a rationale to introduce RMT.

The underpinning physiological mechanisms of the respiratory-related performance benefits are associated with delaying or attenuating of the respiratory metaboreflex (Dempsey et al., 2006; Witt et al., 2007; Illidi et al., 2023). The increased fatigue and accumulation of metabolites in respiratory muscles lead to a decrease in the blood flow of skeletal muscles and redirection of blood flow to respiratory muscles (Sheel et al., 2018). Consequently, the vasoconstriction in the exercising limbs may lead to increased local fatigue and limit performance (McConnell and Lomax, 2006; Romer et al., 2006). Therefore, due to improvement of mechanical efficiency and fatigue resistance of respiratory muscles, RMT is expected to constrain the accumulation of muscle metabolites triggered by exercise and mitigate its systemic repercussions (Sheel et al., 2018; Illidi et al., 2023). There are different RMT methods, techniques, devices, and protocols. The following study focuses on two methods that are widely used with athletes and general populations: voluntary isocapnic hyperpnoea (VIH), and inspiratory pressure threshold loading (IPTL). Both of them have been found effective (Illidi et al., 2023), however VIH is more associated with improving respiratory muscles endurance, and IPTL is more associated with improving respiratory muscles strength (McConnell and Romer, 2004; Illidi et al., 2023).

Limited research described VIH as time-consuming and physically demanding (McConnell, 2011; Bhammar et al., 2022) or reported sporadic complaints about side stitches and soreness of respiratory muscles (Boutellier and Piwko, 1992). Singular publications indicated that IPTL should not be considered as a significant training load (TL) and does not result in additional fatigue in trained individuals (McConnell and Lomax, 2006; Klusiewicz, 2007). RMT was previously investigated in regard to elicited performance changes, but not in regard to the psychophysiological cost. Monitoring and measuring TL enables coaches and support staff to adjust levels of physiological work to maximize performance, as well as reduce excessive levels of fatigue and the risk of injury or overtraining (Wing, 2018). However, to our knowledge, no study has examined the direct effects of RMT on TL measurements, and only a small number of studies evaluated the effects of RMT on stress- and fatigue-related indices (Foster et al., 2012; Sartorio et al., 2012; Briskey et al., 2020; Iqbal et al., 2023). The main purpose of this study was to comprehensively assess whether RMT puts extra load on athletes by assessing changes in blood markers, subjective measures, cardiac indices, and near-infrared spectroscopy (NIRS)-derived indices. The secondary aim was to determine if there are significant differences in RMT-induced load between sexes or the investigated training methods.

Materials and methods

The study design was reviewed and approved by the Institute of Sport - National Research Institute Ethics Committee (approval no KEBN-23-78-TK). Informed written consent was obtained from all study participants. All procedures were carried out in accordance with the Declaration of Helsinki. The study was registered at ClinicalTrials.gov as NCT05936398. CONSORT guidelines for reporting parallel group randomized trials were applied (Schulz et al., 2011) (Supplementary Table S1).

Participants

Sixteen well-trained triathletes (7 females and 9 males) volunteered to participate in the study in response to the invitation. The recruitment process occurred in January 2023 and February 2023. All the participants were classified in Tier 3 or Tier 4 according to the Participant Classification Framework (McKay et al., 2022), as highly trained or elite athletes. The inclusion criteria were: valid medical certificate to compete in triathlon, lack of previous experience with RMT, at least 6 years of triathlon training, average training volume over 12 h per week during last 6 weeks, performance caliber corresponding to at least medal placement during national multisport championship (any distance) during last 2 years. The exclusion criteria were: any chronic medical condition, any acute medical condition within last 3 months, any ongoing medication intake. Use of hormonal contraception and time since last menstruation were registered in females. All the study participants were in a similar training period (base training, after 10–14 weeks of structured training and few months before the competition season). The total required sample size was calculated with G* Power (version 3.1.9.2; Germany), with the level of significance set at $\alpha = 0.05$, power $(1 - \beta) = 0.80$, and effect size $f = 0.42$ (ANOVA with repeated measures, within-between interaction). According to the calculations, the required total sample size was 12 participants. To account for possible dropouts, 16 participants were recruited. All participants completed the study. Body composition was assessed with dual-energy x-ray absorptiometry using the Lunar Prodigy Pro DXA machine (GE Healthcare, Chicago, IL, United States). The participants' characteristics at baseline are presented in Table 1.

TABLE 1 Basic participant characteristics at baseline.

Variable/Group	VIH (n = 9)	IPTL (n = 7)
Age	30.2 ± 6.4	32.5 ± 4.3
Body mass	68.8 ± 10.42	67.3 ± 11.1
Body height	176.8 ± 10.9	173.3 ± 10.7
Body fat	14.6 ± 4.8	14.9 ± 4.5
Training experience	12.0 ± 3.6	15.6 ± 3.7
S-Index Test score	144.8 ± 41.7	151.4 ± 34.4

Values are mean ± standard deviation. VIH, voluntary isocapnic hyperpnoea; IPTL, inspiratory pressure threshold loading. Age is presented in [years], body mass is presented in [kg], body height is presented in [cm], body fat is presented as [percentage], training experience is presented in [years], S-Index Test score in [cmH2O]. In VIH, group were 4 (44.44%) females and 5 (55,56%) males, while in ITPL, group were 3 (42.86%) females and 4 (57.14%) males. All the participants were Caucasian. No statistically significant differences in any parameter were found between the groups ($p > 0.05$).

No statistically significant differences in any parameter were found between the groups ($p > 0.05$).

Study design

The study was conducted as a randomized controlled trial with two parallel groups. Whereas participants and data collectors were aware of the allocated training method, the data analysts and laboratory technicians performing biochemistry assays were kept blinded to the allocation. The participants were assigned at random to either VIH or IPTL training group to perform RMT with progressive overload for 6 weeks. Initially, the participants performed S-Index Tests to measure inspiratory muscle strength (Silva et al., 2018). Subsequently, according to the results achieved, they were classified into corresponding pairs with the same sex. One individual in each pair was assigned to either VIH or IPTL group with a coin toss. Due to the odd number of each sex, unpaired participants were assigned to the training group with a coin toss.

The measurements were taken in week 1 (session 3 for VIH group and session 5 for the IPTL group), week 4 (session 14 for VIH and session 20 for the IPTL group), and week 6 (session 21 for VIH and session 30 for the IPTL group). All the measurements were taken in a laboratory setting. All the participants were adapted to laboratory settings due to their previous testing experiences. However, the investigators invited participants for the initial familiarization visit, when S-Index Tests were performed, RMT instructional presentations were delivered and a supervised training session has been completed. Then, three laboratory visits were required to perform the training session with multidimensional monitoring and investigators' supervision. The participants were reminded weekly about executing prescribed training sessions via direct messages. During the study, 10 out of 16 participants were using TrainingPeaks App (TrainingPeaks LLC, Louisville, CO, United States) to plan and track training, including RMT sessions. Their personal accounts were attached to the investigators' coaching account, allowing for constant training monitoring. All the participants were approached with regular follow-up at least once a week. According to self-declared reports, all of them meticulously followed the prescribed training program with a minimal number of minor changes to the planned workouts.

Training protocols

VIH requires intentional, vigorous, paced ventilation for up to 30–40 min and uses partial rebreathing circuits to prevent hypocapnia. The training is based on hyperventilation at an intensity from 60% to 90% of maximal voluntary ventilation, with little or no external resistance (McConnell, 2011). The VIH group trained every second day with gradual progression based on session length and breathing frequency. Participants began with 3 min of exercise with a frequency of 20 breaths min^{-1} during the first session and added no more than 1 min or 2 breaths min^{-1} with each consecutive session. The course of the VIH training progression is presented in Table 2.

IPTL uses breathing trainers with a spring-loaded inspiratory valve and an unloaded expiratory flap valve. During inspiration maneuvers participants must overcome the pressure load to open the valve and generate airflow, whereas no additional resistance during expiration is applied (Hart et al., 2001). Popular IPTL protocols are based on 30 full vital capacity inspirations from the residual volume level, against a resistance corresponding to 30%–50% of maximal inspiratory pressure (Illi et al., 2012; HajGhanbari et al., 2013). However, higher resistance may be successfully applied by elite endurance athletes (Klusiewicz et al., 2008). The IPTL group trained 5 days a week, twice a day, with at least 6 h break between sessions. The session consisted of 30 dynamic inspiratory maneuvers. The IPTL group was instructed to perform full vital capacity inspirations from residual volume level, against a resistance allowing them to perform 28–34 dynamic and powerful breaths. The IPTL group was instructed to increase the resistance periodically to account for training improvement.

Testing design

Testing was performed in the morning, between 8:30 and 10:30 a.m., to minimize potential physiological diurnal variation. The experimental data were gathered in the laboratory of the Department of Nutrition Physiology and Dietetics, Institute of Sport - National Research Institute, Warsaw, Poland. Repeatable testing conditions were provided with laboratory temperature varying from 20.7°C to 22.1°C, and humidity varying from 44% to 56%. The participants rested in a seating position for 15 min

TABLE 2 The voluntary isocapnic hyperpnoea (VIH) group 6-week training protocol progression.

Session number	Session length	Breathing frequency	Session number	Session length	Breathing frequency
1	3	20	12	13	22
2	4	20	13	14	24
3	5	20	14	15	24
4	5	20	15	16	24
5	6	22	16	17	24
6	7	22	17	18	44
7	8	22	18	18	26
8	9	22	19	19	26
9	10	22	20	20	26
10	11	22	21	20	26
11	12	22			

Length of the session in [minutes], breathing frequency in [breaths·min^{-1}].

after entering the laboratory. At this point, McGill Pain Questionnaire (MPQ) was presented for the purpose of familiarization. Subsequently, the participant performed the S-Index Test. Then the HR chest strap and the near-infrared spectroscopy devices were fitted. Next, the participants sat for an additional 5 min to gather the baseline data for cardiac and near-infrared spectroscopy indices. All pre-session capillary blood samples were taken 1 min before the start of the RMT session. The session was performed in a seating position. VIH sessions consisted of 5 min of exercise in week 1, 15 min in week 4, and 20 min in week 6. The breathing frequency was 20 breaths min^{-1} in week 1, 24 breaths min^{-1} in week 3, and 26 breaths min^{-1} in week 6. Isocapnic BreathWayBetter device (Isocapnic Technologies Inc., Kelowna, Canada) with 6-L bags was used. IPTL sessions consisted of 2 min of dynamic and powerful breathing exercises with a Powerbreathe Plus - Medium Resistance device (POWERbreathe International Ltd., Southam, United Kingdom). The resistance was selected by the participants based on the instructions given before the start of training and corresponded to the resistance used during the regular IMT sessions in the current week. The average resistance used in week 1 was 39.50 cm H_2O with an average of 31.43 breaths, in week 4 was 58.90 cm H_2O with an average of 30.89 breaths, and in week 6 was 81.00 cm H_2O with an average of 30.42 breaths. After the RMT sessions, the participant sat for another 5 min to gather the post-exercise data. Blood samples used for acid-base balance (pH), partial pressure of oxygen (pO_2), partial pressure for carbon dioxide (pCO_2), partial pressure for bicarbonate ion (HCO_3^-), and blood lactate (bLa) were collected immediately after cessation of the exercise and MPQ was presented 1 min after cessation of the exercise. Blood samples for cortisol (C) and testosterone (T) were collected 5 min after cessation of the exercise. The second S-Index Test was performed between minute 5 and minute 7 after cessation of the exercise. Rate of perceived exertion (RPE) was assessed 10 min after cessation of the exercise. The participants again answered MPQ after 24 and 48 h after the monitored RMT sessions. The detailed testing timeline is presented in Figure 1.

Measured blood markers

Radiometer™ ABL90 FLEX blood gas analyzer (Radiometer Medical ApS, Brønshøj, Denmark) was used to measure pH, HCO_{3-}, pO_2, and pCO_2. Super GL2 analyzer (Dr. Muller Geratebau GmbH, Freital, Germany) was used to measure bLa. Roche Cobas E 411 analyzer (Roche Diagnostics at F. Hoffmann-La Roche Ltd., Basel, Switzerland) was used to measure T and C with ElectroChemiLuminescence (ECL) technology for assay analysis. All the indices mentioned in this section were measured in capillary blood samples (45 µL for blood gas analysis, 20 µL for bLa analysis, and 300 µL for hormone analysis) taken from the fingertip before and after the monitored RMT sessions. Blood gas analysis and bLa analysis were performed immediately after RMT cessation. The samples for hormone measurements underwent centrifugation at 5,000 rpm for a duration of 10 min at a temperature of 4°C. Then, the serum was aliquoted and stored at a temperature of −20°C until the assays were performed during the next 24 h.

Subjective measures

The Borg CR-10 Scale was presented to the participants and the assessment was made 10 min after the cessation of exercise (Scherr et al., 2013). Borg CR-10 Scale is widely used to assess RPE and prescribe training and monitor intensity (Thompson et al., 2013). In the past, all the participants utilized the scale to evaluate their athletic training. The session's TL (sRPE) was calculated with a session RPE method (Foster et al., 2001). The method has demonstrated its validity, good reliability, and internal consistency across a variety of sports and physical activities, and has been utilized with individuals of different ages (children, adolescents, and adults) and skill levels (novices to experts), regardless of sex (Haddad et al., 2017). The average weekly TL induced by RMT (sRPEweek) was calculated with the assumption that VIH group performed RMT 3.5 times per week and IPTL group

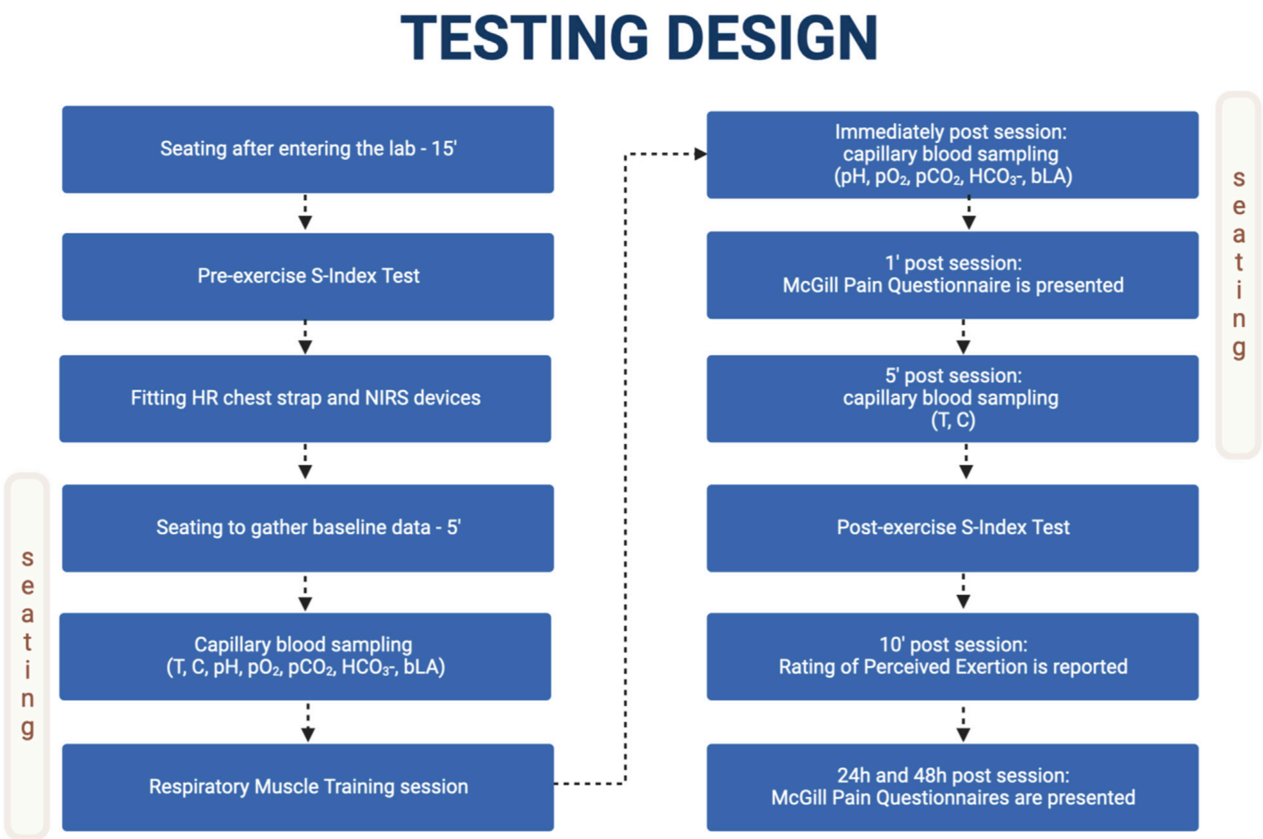

FIGURE 1
Testing design timeline. Adapted from "Flowchart Template", by BioRender.com (2023). Retrieved from https://app.biorender.com/biorender-templates.

performed RMT 10 times per week. Calculations are presented below:

$$\text{sRPE} = \text{RPE x length of RMT session in minutes}$$

$$\text{sRPEweek} = \text{sRPE x average number of RMT sessions during the week}$$

MPQ is based on self-reported measures of pain and it assesses both the quality and intensity of subjective pain (Melzack, 1975). MPQ was selected due to its validated usefulness in pain research, including delayed onset muscle soreness (Melzack, 1975; Cleather and Guthrie, 2007), and psychometric properties (Graham et al., 1980). The Polish adaptation of the questionnaire developed by Kazimierz Sedlak was presented to the participants. The instrument comprises 78 adjectives categorized into twenty subcategories, with ten representing the sensory dimension of pain, five representing the affective dimension, one representing the evaluative dimension, and four miscellaneous subcategories. Participants were asked to choose words that best described their pain, resulting in a collection of descriptors that characterize an individual's pain when the MPQ is completed. Each word in the MPQ is assigned a numerical value on a 0 to 5 scale based on its relative strength compared to predetermined anchor words. The total scale values of all the chosen words and the descriptive summary of words chosen most often were included in the analysis. Additionally, participants reported accompanying symptoms with an optional MPQ section, and the descriptive summary of symptoms chosen most often was included in the analysis.

Cardiac indices

Heat rate (HR) and Heart Rate Recovery (%HRR) were monitored during and after RMT sessions with a Polar H10 chest strap (Polar Electro Oy, Kempele, Finland) paired with HRV Logger app (A.S.M.A. B.V., Marco Altini, Version 5.1.0, dowloaded from Mac App Store on 3 Feb 2022). %HRR was calculated as below.

$$\%\text{HRR}\ (\%) = (\text{HR at1 min afterthe cessation of exercise}/\text{maximal HR during RMT session}) \times 100$$

NIRS-derived indices

Two NIRS monitors (Moxy monitors; Fortiori Design LLC, Hutchinson, MN, United States) were used to measure local muscle oxygenation (SmO2). The first device was fitted on the right vastus lateralis, approximately 13 ± 2 cm above the proximal border of the patella and 4 ± 2 cm lateral to the midline of the thigh. The skinfold tissue thickness was measured in the same place with Harpenden Skinfold Caliper (Baty International, Burgess Hill, West Sussex, United Kingdom). The obtained values (7.39 ± 2.97 mm) allowed for physiologically credible SmO_2 measurements (McManus et al., 2018). The second monitor was fitted on the right intercostales, at the seventh intercostal space, at the anterior axillary line. Dark dynamic tape of 7.5 cm width was used to provide a repeatable testing environment and hypoallergenic skin tape was used to fix devices to the skin. A computation window of 2 s was used. SmO_2 changes during RMT session (ΔSMO_2B) and SmO_2 recovery after RMT session (ΔSMO_2A) were recorded to assess exercise intensity (Contreras-Briceño et al., 2022) as below:

$$\Delta SMO_2B = \text{average } SMO_2 \text{ concentration during 2-minute period before RMT-minimal } SMO_2 \text{ concentration during RMT session}$$

$$\Delta SMO_2A = \text{maximal } SMO_2 \text{ concentration during 2-minute period after RMT-minimal } SMO_2 \text{ concentration during RMT session}$$

Other measured variables

Inspiratory muscle fatigue (IMF) was measured by performing pre- and post-training sessions S-Index Tests. S-Index Test is a dynamic spirometry assessment used to evaluate inspiratory muscle strength (Silva et al., 2018). POWERbreathe K5 device was used (POWERbreathe International Ltd., Southam, United Kingdom).

TL produced by RMT (%TTL) was assessed in the context of overall TL and calculated as below:

$$\%TTL = (\text{sRPEweek produced by RMT} / \text{overall weekly sRPE produced by all training sessions}) \times 100$$

Statistical analysis

The normality of the distribution was tested visually with Q-Q plot figures and the Shapiro-Wilk test.

Independent t-tests were used to assess the differences in participant characteristics between groups. The main effects for type of training method, time of measurement (testing week), sex, and interaction of main effects were assessed by repeated-measures analysis of variance (ANOVA) with additional covariate assessment for training experience, age, and somatic indices, and body composition. Additionally, homogeneity was assessed with Levene's test, and sphericity of variance using Mauchly's test for spherical Greenhouse-Geisser correction, was applied. In significant main effects, a *post hoc* assessment was performed using Bonferroni correction. Significance was set at $p < 0.05$. Results are presented as mean and standard deviation. The effect size was determined by partial eta squared (ηp^2) and omega squared (ω^2) (Sullivan and Feinn, 2012; Lakens, 2013).

All statistical analyses were performed using the JASP Team statistical package JASP (Amsterdam, Netherlands, Version 0.17.2).

Results

Blood markers

Measurements for blood markers stratified by testing week, sex, and training method are presented in Table 3.

There was a statistically significant interaction between ΔpH and sex (F (1, 2) = 5.428, p = 0.04, η_p^2 = 0.31) or training method (F (1, 2) = 55.438, p < 0.001, η_p^2 = 0.82). The mean value of ΔpH was significantly higher for IPTL than VIH (Mean Difference = −1.23, SE = 0.17, d = −2.78) and for females than males (Mean Difference = 0.38, SE = 0.17, d = 0.87).

There was also a statistically significant interaction between ΔpCO_2 and sex (F (1, 2) = 6.45, p = 0.03, η_p^2 = 0.35, ω^2 = 0.15) or training method (F (1, 2) = 34.77, p < 0.001, η_p^2 = 0.74, ω^2 = 0.68). The mean value of ΔpCO_2 was significantly higher for VIH than IPTL (Mean Difference = 20.64, SE = 3.50, d = 2.17) and for males than females (Mean Difference = −8.89, SE = 3.50, d = −0.94).

Another significant interaction has been found between ΔpHCO3- and the training method (F (1, 2) = 8.17, p = 0.01, η_p^2 = 0.41, ω^2 = 0.22). The mean value of $\Delta pHCO_3^-$ was significantly higher for VIH than IPTL (Mean Difference = 4.95, SE = 1.73, d = 0.97).

The last significant interaction occurs between ΔbLa and the training method (F (1, 2) = 39.37, p < 0.001, η_p^2 = 0.77, ω^2 = 0.60). The mean value of ΔbLa was significantly higher for IPTL than VIH (Mean Difference = −43.33, SE = 6.91, d = −1.72).

Subjective measures

Subjective measures stratified by testing week, sex, and training method are presented in Table 4.

There was a statistically significant interaction between sRPE and training method (F (1, 2) = 16.81, p = 0.001, η_p^2 = 0.58, ω^2 = 0.38). The mean value of sRPE was significantly higher for VIH than IPTL (Mean Difference = −42.11, SE = 10.27, d = 1.65).

There was also a statistically significant interaction between sRPEweek and training method (F (1, 2) = 6.48, p = 0.03, η_p^2 = 0.35, ω^2 = 0.17). The mean value of sRPEweek was significantly higher for IPTL than VIH for first round and lower for IPTL than VIH for second and third round (Mean Difference = 94.49, SE = 37.11, d = 1.03).

The following pain descriptors in MPQI were chosen more than once. For IPTL during the first round: boring (1 time for male and 1 time for female), pressing (1 time for male and 1 time for female), tight (1 time for male and 1 time for female). For VIH during the first round: tender (2 times for male and 1 time for female), pressing (1 time for male and 1 time for female). For VIH during the third round: tiring (2 times). No pain descriptors were chosen in MPQ24 and MPQ48. The following accompanying symptoms in MPQI were chosen more than once. For IPTL during the first round: headache (1 time for males and 3 times for females), dizziness (1 time for males and 3 times for females). For IPTL during the second round: headache (3 times for females), dizziness (2 times for females). For IPTL during the third round: headache (3 times for females), dizziness (2 times for females). No accompanying symptoms were chosen in MPQ24 and MPQ48.

Cardiac indices

Cardiac indices stratified by testing week, sex, and training method are presented in Table 5.

There was a statistically significant interaction between HRavg and sex (F (1, 1.18) = 5.71, p = 0.03, η_p^2 = 0.32, ω^2 = 0.15). The mean

TABLE 3 Differences in blood markers for respiratory muscle training.

Testing week	Sex	Training method	ΔpH†*	ΔpCO_2†*	ΔpO_2	ΔHCO_{3^-}†	ΔbLa†	ΔC	ΔT
1st	F	VIH	0.14 (0.19)	−3.85 (3.62)	23.09 (13.00)	−1.73 (0.98)	−18.96 (9.08)	1.29 (5.29)	−0.46 (6.38)
		IPTL	1.53 (0.16)	−27.39 (2.95)	5.73 (19.14)	−6.82 (1.32)	38.27 (36.23)	−6.44 (3.39)	−5.53 (15.14)
	M	VIH	−0.16 (0.29)	4.10 (6.49)	7.28 (8.17)	0.44 (1.65)	−2.55 (17.18)	−3.47 (6.83)	8.33 (13.21)
		IPTL	1.14 (0.50)	−21.44 (9.58)	15.19 (19.42)	−4.77 (4.23)	23.90 (18.52)	−3.93 (4.10)	7.81 (4.77)
4th	F	VIH	−0.03 (0.43)	−10.74 (7.86)	23.87 (7.15)	1.26 (2.73)	−37.55 (11.26)	−8.84 (8.63)	2.46 (3.47)
		IPTL	1.57 (0.55)	−30.66 (10.04)	15.43 (10.51)	−10.00 (4.00)	34.16 (38.31)	−4.55 (1.81)	19.94 (22.36)
	M	VIH	−0.03 (0.51)	2.32 (10.34)	9.12 (16.48)	1.00 (2.80)	−21.81 (21.67)	−3.36 (13.40)	12.82 (12.52)
		IPTL	0.71 (0.42)	−12.74 (9.81)	8.15 (5.76)	−2.61 (4.31)	8.68 (20.60)	2.79 (15.94)	9.19 (9.41)
6th	F	VIH	−0.03 (0.23)	−0.25 (2.54)	16.41 (11.27)	−0.80 (0.92)	−7.28 (15.46)	−1.41 (8.80)	2.52 (28.70)
		IPTL	1.57 (0.87)	−23.53 (22.83)	19.77 (27.15)	−2.22 (17.80)	26.84 (3.67)	−8.52 (6.04)	4.32 (38.55)
	M	VIH	0.03 (0.39)	0.57 (8.33)	11.88 (13.64)	0.76 (3.19)	−7.47 (33.93)	−7.24 (8.95)	2.86 (8.61)
		IPTL	0.74 (0.50)	−15.90 (10.12)	17.95 (18.09)	−4.87 (3.91)	32.52 (44.69)	−2.54 (7.10)	1.76 (15.84)

Abbreviations: ΔpH, difference in acid-base balance before and after session; ΔpCO_2, difference in partial pressure for carbon dioxide before and after session [percentage]; ΔpO_2, difference in partial pressure of oxygen before and after session [percentage]; $\Delta pHCO_3^-$, difference bicarbonate ion concentration before and after session [percentage]; ΔbLA, difference in blood lactate concentration before and after session [percentage]; ΔC, difference in blood cortisol concentration before and after session [percentage]; ΔT, difference in blood testosterone concentration before and after session [percentage]; SD, standard deviation; F, females; VIH, voluntary isocapnic hyperpnoea; IPTL, inspiratory pressure threshold loading; M, males. Athletes underwent respiratory muscle training three times: in first, fourth and sixth week. Data are presented as mean with (standard deviation). Significant interactions between variables and training method were marked with †, while significant interactions with sex were marked with *.

TABLE 4 Differences in subjective measures for respiratory muscle training.

Testing week	Sex	Training method	sRPE†	sRPEweek†	MPQI	MPQ24	MPQ48
1st	F	VIH	16.25 (8.54)	56.88 (29.89)	2.00 (2.16)	0.00 (0.00)	0.00 (0.00)
		IPTL	6.67 (1.16)	66.67 (11.55)	8.00 (7.94)	0.00 (0.00)	0.00 (0.00)
	M	VIH	15.00 (7.07)	52.50 (24.75)	2.40 (2.30)	0.00 (0.00)	0.00 (0.00)
		IPTL	8.50 (4.12)	85.00 (41.23)	4.25 (7.18)	0.00 (0.00)	0.00 (0.00)
4th	F	VIH	71.25 (43.08)	249.38 (150.80)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
		IPTL	8.00 (3.46)	80.00 (34.64)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
	M	VIH	57.00 (22.25)	199.50 (77.87)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
		IPTL	7.50 (2.52)	75.00 (25.17)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
6th	F	VIH	70.00 (52.92)	245.00 (185.20)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
		IPTL	6.67 (4.62)	66.67 (46.19)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
	M	VIH	72.00 (41.47)	252.00 (145.16)	0.20 (0.45)	0.00 (0.00)	0.00 (0.00)
		IPTL	11.50 (4.44)	115.00 (44.35)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

Abbreviations: sRPE, declared rating of perceived exertion for one session; sRPEweek, sum of rating of perceived exertion for all respiratory muscles training sessions in a week; MPQI, total scale values of all the chosen words in McGill Pain Questionnaire declared immediately after session; MPQ24, total scale values of all the chosen words in McGill Pain Questionnaire declared 24 h after session; MPQ48, total scale values of all the chosen words in McGill Pain Questionnaire declared 48 h after session; SD, standard deviation; F, females; VIH, voluntary isocapnic hyperpnoea; IPTL, inspiratory pressure threshold loading; M, males. Athletes underwent respiratory muscle training three times: in first, fourth and sixth week. Data are presented as mean with (standard deviation). Significant interactions between variables and training method were marked with †.

value of HRavg was significantly higher for females than males (Mean Difference = −13.04, SE = 5.46, d = 0.97).

Another significant interaction has been found between HRmax and sex (F (1, 1.39) = 6.81, $p = 0.02$, $\eta_p^2 = 0.36$), $\omega^2 = 0.18$). The mean value of HRmax was significantly higher for females than males (Mean Difference = 16.51, SE = 6.33, d = 1.12).

NIRS-derived indices

NIRS-derived indices stratified by testing week, sex, and training method are presented in Table 6. Exemplary time course of muscle oxygenation for intercostales is presented in Figure 2.

TABLE 5 Differences in cardiac indices for respiratory muscle training.

Testing week	Sex	Training method	HRavg*	HRmax*	%HRR
1st	F	VIH	79.00 (7.35)	86.25 (7.32)	74.26 (8.91)
		IPTL	107.33 (22.90)	119.68 (22.81)	54.08 (8.12)
	M	VIH	76.00 (4.72)	84.20 (6.91)	71.84 (8.46)
		IPTL	77.75 (17.23)	83.75 (20.53)	70.91 (11.46)
4th	F	VIH	87.00 (16.83)	93.25 (20.04)	82.52 (6.08)
		IPTL	92.00 (4.58)	108.68 (7.02)	64.96 (6.58)
	M	VIH	84.20 (15.96)	92.00 (15.81)	78.49 (5.55)
		IPTL	69.50 (16.98)	75.25 (19.76)	76.35 (17.02)
6th	F	VIH	82.00 (6.98)	94.25 (8.26)	72.04 (5.41)
		IPTL	95.00 (7.00)	102.00 (5.00)	69.12 (6.71)
	M	VIH	80.40 (10.36)	87.80 (11.26)	84.27 (7.95)
		IPTL	76.25 (16.66)	82.00 (18.06)	76.94 (16.66)

Abbreviations: HRavg, average heart rate during session [beats·min^{-1}]; HRmax, maximal heart rate during session [beats·min^{-1}]; %HRR, post-exercise heart rate recovery [percentage]; SD, standard deviation; F, females; VIH, voluntary isocapnic hyperpnoea; IPTL, inspiratory pressure threshold loading; M, males. %HRR, was calculated as (heart rate at first minute after the cessation of exercise/maximal heart rate during session) × 100. Athletes underwent respiratory muscle training three times: in first, fourth and sixth week. Data are presented as mean with (standard deviation). Significant interactions between variables and sex were marked with *.

TABLE 6 Differences in NIRS-derived indices for respiratory muscle training.

Testing week	Sex	Training method	ΔSMO_2BI‡	ΔSMO_2BV	ΔSMO_2AI†‡	ΔSMO_2AV
1st	F	VIH	6.65 (27.97)	10.47 (28.31)	12.75 (12.18)	7.75 (9.64)
		IPTL	31.71 (16.48)	8.82 (24.40)	−22.33 (4.62)	−5.67 (17.24)
	M	VIH	−24.78 (24.28)	−10.65 (15.90)	21.03 (15.13)	16.40 (5.90)
		IPTL	5.67 (45.77)	4.39 (17.82)	2.00 (26.73)	−5.50 (20.66)
4th	F	VIH	−7.73 (6.06)	−8.37 (7.09)	14.25 (3.30)	14.50 (9.04)
		IPTL	−2.49 (0.90)	−2.82 (1.16)	24.93 (8.97)	12.64 (5.51)
	M	VIH	−15.39 (14.42)	−2.32 (11.33)	16.80 (4.60)	13.40 (5.41)
		IPTL	−8.33 (8.35)	−7.49 (5.40)	12.25 (6.40)	11.00 (1.63)
6th	F	VIH	−24.60 (21.73)	−4.87 (7.34)	28.50 (13.30)	16.00 (7.07)
		IPTL	−14.46 (14.40)	−3.95 (2.58)	24.67 (10.12)	14.33 (5.51)
	M	VIH	−19.48 (11.25)	−3.23 (2.50)	25.00 (12.17)	12.20 (3.49)
		IPTL	−15.54 (10.85)	−4.21 (7.15)	18.50 (8.43)	14.00 (7.70)

Abbreviations: ΔSMO2BI, difference in local muscle oxygen saturation before session for intercostales [percentage]; ΔSMO2BV, difference in local muscle oxygen saturation before session for vastus lateralis muscle [percentage]; ΔSMO2AI, difference in local muscle oxygen saturation after session for intercostal muscles [percentage]; ΔSMO2AV, difference in local muscle oxygen saturation after session for vastus lateralis muscle [percentage]; SD, standard deviation; F, females; VIH, voluntary isocapnic hyperpnoea; IPTL, inspiratory pressure threshold loading; M, males. Athletes underwent respiratory muscle training three times: in first, fourth and sixth week. Data are presented as mean with (standard deviation). Significant interactions between variables and training method were marked with †, while significant interaction with testing week were marked with ‡.

There was a statistically significant interaction between ΔSMO_2B for intercostales and testing week (F = 6.27, p = 0.01, η_p^2 = 0.34, ω^2 = 0.21). The mean value of ΔSMO_2B was decreasing with each testing session (Mean Difference = −7.09 SE = 3.95, d = 0.63 between first and fourth week, Mean Difference = −6.91 SE = 3.95, d = 0.28 between fourth and sixth week).

There was also a statistically significant interaction between ΔSMO_2A for intercostales and testing week (F = 9.57, p = 0.003, η_p^2 = 0.44, ω^2 = 0.35). The mean value of ΔSMO_2A was increasing with each testing session (Mean Difference = 14.97 SE = 4.90, d = 1.20 between first and fourth week, Mean Difference = 5.86 SE = 4.90, d = 0.47 between fourth and sixth week).

Another significant interaction has been found between ΔSMO_2A for intercostales and method (F (1, 2) = 10.79, p = 0.007, η_p^2 = 0.47, ω^2 = 0.27). The mean value of ΔSMO_2A was higher for VIH than IPTL for first and third round and lower for

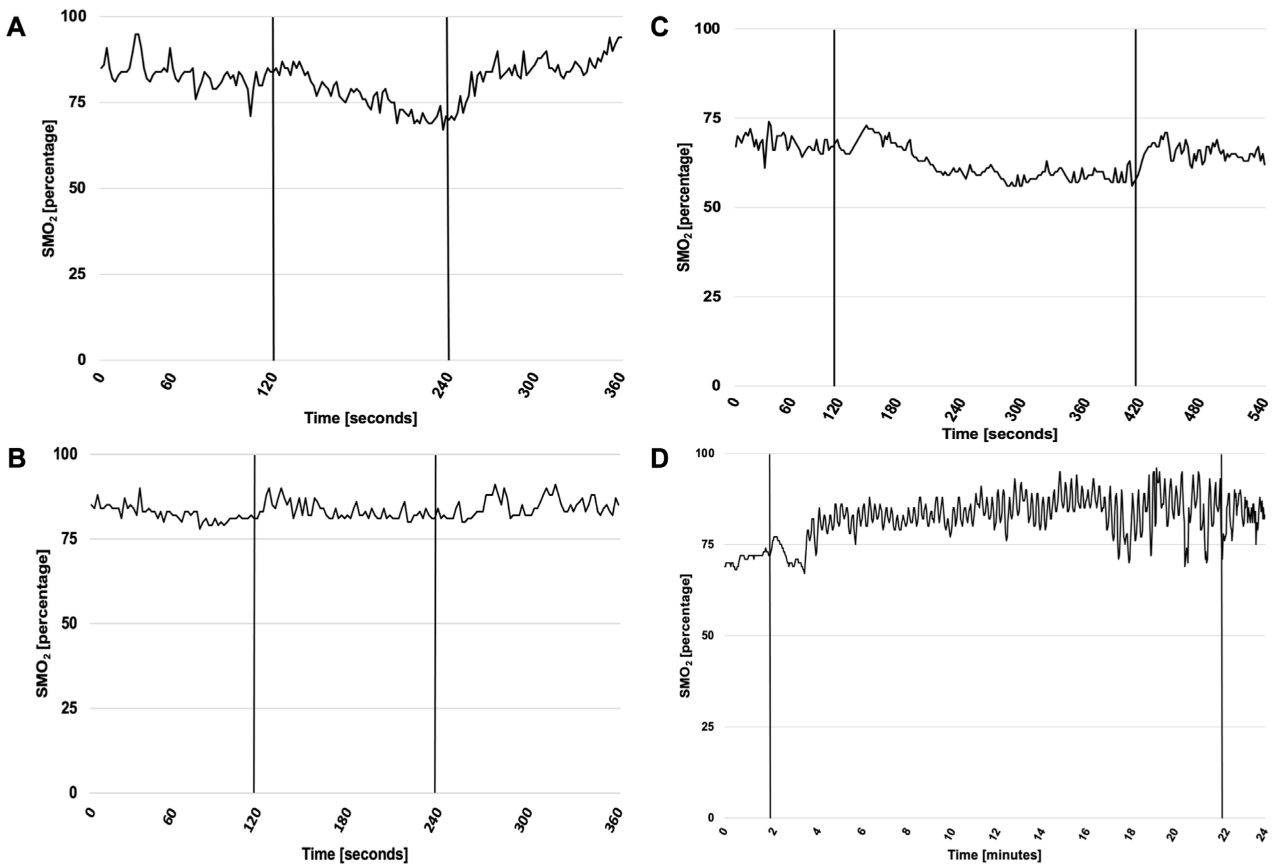

FIGURE 2
Exemplary time course of muscle oxygenation for intercostales during RMT in first and sixth testing week. Abbreviations: SMO_2, local muscle oxygenation. **(A)** presents SMO_2 for ITPL in first week, **(B)** for ITPL in sixth week, **(C)** for VIH in first week and **(D)** for VIH in sixth week. ITPL lasted 2 min both in first and sixth week, while VIH lasted 5 min in first week and 20 min in sixth week. Vertical lines represent start and cessation of RMT. The exemplary plots (male participant for ITPL, female participant for VIH) illustrate time course of SMO_2 changes for intercostales. Throughout the monitored sessions, SMO_2 usually increased during first respiratory maneuvers during all monitored sessions. In first testing week muscle deoxygenation was usually observed, however in sixth testing week no muscle deoxygenation was noticed during RMT for intercostales, suggesting RMT-related adaptation of muscle function.

VIH than IPTL for second round (Mean Difference = 8.89 SE = 2.71, d = 0.72).

Other measured variables

Other measured variables stratified by testing week round, sex, and training method are presented in Table 7.

Discussion

To our knowledge, this is the first study to assess comprehensively psychophysiological cost of RMT. The main objective of our study was to assess whether RMT puts extra load on athletes and to determine if there are significant differences in RMT-induced load between sexes or applied training methods. Using multiple objective and subjective exertion measures we were able to capture multidimensional fatigue, stress, and TL induced by popular RMT training methods. As in many studies, the magnitude of observed changes significantly varies between the participants. However, inter-individual variability exhibits similar level in both investigated methods. We found that VIH and IPTL contribute to overall TL, therefore should be applied with consideration. The investigated methods differ in eliciting changes in monitored variables. Moreover, RMT induced larger changes in blood gasometry and cardiac indices in females rather than in males.

Blood markers

Blood gas analysis showed larger post-RMT differences in females rather than in males, and VIH induced smaller changes in blood gasometry compared to IPTL. In literature, RMT was associated with mild hypocapnia (McConnell and Griffiths, 2010) and respiratory alkalosis due to hyperventilation resulting in pH and pO_2 increase and pCO_2 decrease (Djarova et al., 1986; Brown et al., 2010). However, according to our results, the extent of blood gasometry changes elicited by RMT may depend on the method

TABLE 7 Differences in other measured variables for respiratory muscle training.

Testing week	Sex	Training method	%TTL	%ΔS-index
1st	M	VIH	0.83 (0.41)	1.64 (12.30)
		IPTL	1.69 (0.28)	4.15 (7.22)
	F	VIH	1.37 (1.01)	−2.17 (4.50)
		IPTL	1.69 (0.71)	2.21 (4.63)
4th	M	VIH	3.52 (2.08)	1.61 (2.76)
		IPTL	1.99 (0.67)	3.47 (3.62)
	F	VIH	5.14 (3.47)	−0.66 (3.59)
		IPTL	1.57 (0.76)	−0.35 (1.15)
6th	M	VIH	3.50 (2.67)	1.57 (5.84)
		IPTL	1.63 (0.95)	3.03 (4.06)
	F	VIH	6.61 (5.51)	4.63 (8.77)
		IPTL	2.29 (0.70)	2.97 (4.19)

Abbreviations: %TTL, part of total training load induced by respiratory muscle training [percentage]; ΔS-Index, difference in S-Index Test before and after session [percentage]; SD, standard deviation; F, females; VIH, voluntary isocapnic hyperpnoea; IPTL, inspiratory pressure threshold loading; M, males. %TTL, was calculated as (sRPE, for RMT/sRPE, for all activities) × 100. Athletes underwent respiratory muscle training three times: in first, fourth and sixth week. Data are presented as mean with (standard deviation).

of RMT or sex. Since IPTL training protocols are usually based on multiple (10–12) sessions per week, significant changes in blood gasometry also occur multiple times per week. However, the short- or long-term influence of such changes in athletes is an understudied area and the relevance of the aforementioned findings require further investigation. The differences in RMT-induced blood gasometry changes between males and females may be associated with functional consequences of sex-differences in the structure of respiratory system. The difference in lungs and rib-cage shape between the sexes, and proportionally smaller airways and lungs in women than man have been reported in the literature. In consequence, lungs' volume and pressure, flow characteristic and regulation of blood gas homeostasis exhibit different patterns in man and women during exercise (Molgat-Seon et al., 2018; Archiza et al., 2021). ΔbLa was significantly higher for IPTL than VIH, with increased bLa after IPTL and decreased bLa after VIH. It confirms the theory that respiratory muscles may act as net consumers of lactate during recovery from intense exercise and the possibility of a decrease in bLa concentration after RMT (Spengler et al., 1999; Chiappa et al., 2008). Although it may seem otherwise, our findings that IPTL increased bLa concentration are not contrary to findings from Chiappa et al., 2008, where the bLa decreased after IPTL. In the mentioned study IPTL was introduced after intense exercise, whereas in our investigations we operated on relatively lower bLa concentration. Despite the potential usefulness of both methods, we speculate that VIH may be more appropriate as an active recovery protocol compared to IPTL. Implementing RMT as a recovery protocol requires further investigation with emphasis on the choice of method, timing, length, and intensity of RMT. No significant differences for ΔC and ΔT between groups were found. However, we noticed a trend for acute pre- and post-session changes in C and T concentration in both groups. Our results are inconclusive about the direction and extent of induced changes in first and second rounds. However, in third round, after a 6-week training program and improved RMT status, all groups noted decrease in C and increase in T. Therefore, we do not consider observed hormonal changes as noteworthy fatigue or stress effects after RMT.

Subjective measures

sRPE was significantly higher for VIH than IPTL and the difference increased with the applied progressive overload. In IPTL, progressive overload comes from increase in resistance, but there is no increase in duration of exercise. In VIH, progressive overload comes from both increases in breathing frequency and duration of exercise. Consequently, as VIH training sessions significantly increased in duration from 5 min in first week to 20 min in sixth week, the sRPE also significantly increased. sRPE calculated for IPTL was more stable since there was no increase in duration and perceived exertion associated with increased resistance. We conclude that the main sRPE contributor during RMT is duration, rather than intensity coming from resistance or breathing frequency. Hence, the RMT based on longer exercise duration, such as VIH, tend to generate higher sRPE scores. However, since the number of sessions per week was different, sRPEweek was higher for IPTL than VIH in first week and lower for IPTL than VIH in fourth and sixth week. MPQI scores showed few measures of pain with very limited exertion and high individual variation. MPQ24 and MPQ48 results showed that no measures of pain were reported 24 and 48 h after the RMT session. Based on the reported measures, RMT did not deliver significant acute pain or heavy fatigue resulting in delayed onset muscle soreness. Noteworthy, headache or dizziness were reported in MPQI by many participants from the IPTL group in all three monitored training rounds. Both symptoms may be explained by blood gasometry changes associated with IPTL, as described before, which may be interpreted as hypercapnia. Hypercapnia causes vasodilation of cerebral arteries and contributes to an increase in cerebral blood flow (Ainslie and Duffin, 2009). As a result, elevated intracranial pressure may lead to headaches and dizziness (Ramadan, 1996). Both gasometry changes and the mentioned symptoms were larger for females than males. The latter may be associated with higher cerebral blood flow in females (Rodriguez et al., 1988), which potentially overlaps with RMT effects. The symptoms tend to lessen in frequency and severity with the progression of the training program, which confirms the findings of McConnell (McConnell, 2011). However, they were still reported by study participants in the third round, after almost 6 weeks of regular RMT. The reported dizziness decreased to a larger extent than the reported headache. Interestingly, the reduction of pain measures and accompanying symptoms with time was not associated with the reduction in blood gasometry changes. Overall, the subjective negative effects of RMT sessions are temporary rather than chronic.

Cardiac indices

Both HRavg and HRmax were significantly higher for females than males. Interestingly, higher HR values were not reflected in sRPE assessment. Larger cardiac response to RMT may be associated with sex-differences in the structure and function of respiratory system, as pulmonary function and exercise capacity differ in females and males. Therefore, the increased work of breathing during exercise may lead to higher cardiac load in females (Harms, 2006; Archiza et al., 2021). It may suggest that women are predisposed to increased respiratory muscle fatigue, however after exercising to exhaustion the diaphragm fatigue is smaller in woman then man (Guenette et al., 2010), possibly due to extra-diaphragmatic inspiratory muscle recruitment (Molgat-Seon et al., 2018). This may partially explain higher HR values, since more muscles are engaged in the work of breathing. We also speculated that the level of motivation and engagement might have been lower in male compared to female participants, resulting in lower HR. Such interpretation may indicate possible challenges of implementing RMT in real-life environment.

NIRS-derived indices

No significant differences in ΔSMO_2BV, and ΔSMO_2AV were noted in the context of training methods, sex, and testing week. There were significant differences in ΔSMO_2BI between testing week and ΔSMO_2AI between testing week and methods. Noteworthy patterns in local muscle oxygen saturation were observed. The extent of muscle deoxygenation during RMT became smaller with time, resulting in negative ΔSMO_2BI and ΔSMO_2BV for fourth and sixth week. That means that after the initial daptation period, local oxygenation tends to increase during RMT session. The increase in oxygenation was higher in intercostales compared to vastus lateralis. The difference between muscle groups is consistent with the observation of Espinoza-Ramirez et al. (2023), who showed decreased deoxygenation of intercostales during exercise after RMT program, with no effect of vastus lateralis oxygenation (Espinoza-Ramírez et al., 2023). High values of ΔSMO_2AI and ΔSMO_2AV show fast recovery and do not indicate any type of significant fatigue. Post-training SMO_2 values are usually higher than pre-training SMO_2 values, which suggests a possible value of RMT as an active recovery protocol.

Other measured variables

TL produced by RMT was assessed in the context of overall TL. Despite noting no significant statistical differences between training methods, sex, and time we found important practical differences. As mentioned earlier, the main sRPE contributor during RMT is its duration. Therefore, after the introduction period, with increased session length, VIH tends to generate higher sRPE week scores and higher %TTL compared to IPTL. Whereas %TTL calculated for IPTL is in 1.69%–2.29% range for the whole studied period, %TTL calculated for VIH for fourth week is 3.52% and 5.14% for males and females respectively, and for sixth week is 3.50% and 6.61% for males and females respectively. In our opinion, the mentioned values are noticeable and must be taken into account during training programming to establish an adequate level of physiological work and limit the risk of overreaching or overtraining. Suggestions that RMT sessions develop IMF may be found in the literature (Briskey et al., 2020; Iqbal et al., 2023). However, both the implemented RMT protocols and the methods of IMF assessment were different in each study. The findings of Briskey et al. (2020) indicate that systemic oxidative stress, as indicated by increased plasma F2-isoprostanes, occurs only during strenuous inspiratory flow-resistive breathing. Interestingly, the stress response was not associated with a decrease in transdiaphragmatic twitch pressures (Briskey et al., 2020). Iqbal et al. (2023) investigated the response of biomarkers, including fast skeletal troponin I, slow skeletal troponin I, creatine kinase-MB, fatty acid binding protein 3, myosin light chain 3, and myoglobin, in order to assess the presence of respiratory muscle damage in response to RMT. Although the presence of muscle damage was noted, the study informed more about the application of biomarker assessment of RMT-related muscle damage and fatigue, rather than the extent of the fatigue for different methods and loads of RMT (Iqbal et al., 2023). Moreover, the participants' characteristics were different, since in both studies they were not highly-trained athletes and all the participants were males. There is no consensus on the percentage drop in measured values defined as IMF. However many studies use a 10% or 15% threshold in function decline (Luo et al., 2001; Mador et al., 2002) or statistically significant mean fall from baseline (McConnell et al., 1997; Lomax and McConnell, 2003). Therefore, assessing changes between pre- and post-RMT S-Index Tests, we did not observe RMT-induced IMF during our investigation independently on method, sex, and time. However, in many cases, the inspiratory muscle strength was improved post-RMT. Whereas the aforementioned studies investigated IMF in healthy subjects, only our study investigated IMF in well-trained athletes. Knowing that characteristics of inspiratory muscle strength depend on training level (Klusiewicz et al., 2014), we speculate that also the magnitude of IMF following RMT sessions may depend on the training status, fitness level, and pulmonary function level. Therefore, the investigated RMT protocols may potentially serve as an efficient respiratory warm-up in well-trained triathletes. Our finding also provides scientific background to the recommendations of Shei et al. about moving beyond a "One-Size Fits All" approach to RMT (Shei et al., 2022). The introduction of individualized training protocols that match athletes' level of performance and competition demands should be the next step in developing RMT. We speculate that after the initial adaptation period, well-trained athletes may require a larger RMT stimulus to provide desirable adaptation, compared to less athletic populations. However, with pulmonology patients (Gosselink et al., 2011) or athletes recovering from illnesses affecting cardiopulmonary performance (Śliż et al., 2022; 2023) the same mechanism indicates that smaller RMT dose may elicit desirable adaptations.

Strengths and limitations

The study investigated a homogeneous group of well-trained athletes. Therefore, the findings should not be extrapolated to different populations, such as sedentary subjects or patients. Despite the required sample size, relatively low number of participants may be considered a study limitation. Therefore, a replication study is required for the confirmation of the findings. Moreover, lack of sham-control group and spirometry measurements may be considered as a study limitations. Measurement of IMF was based on maximal maneuvers. Although this approach may be found in the literature, it requires a high level of participants' motivation and therefore is prone to associated limitations. We acknowledge that phrenic nerve stimulation to assess diaphragmatic fatigue should be a valuable contribution to the study design, as it minimizes the influence of central nervous system and participants' motivation on the IMF assessment. Response to RMT may depend on swim training characteristics in terms of both performance and induced stress. We did not monitor the swim training load in study participants, which may be an important consideration for their responses to RMT, as respiratory muscle adaptation to swim training is dose-dependent (Lomax et al., 2019). Novelty, larger female participation, applying the wide range of measurement methods and blinding the data analysts and laboratory technicians may be considered strengths of the study.

Recommendations for further research

TL induced by RMT may differ depending on the chosen training method and investigated populations. Further research with different RMT methods and activity profiles, physical fitness, age, race, sex, and health status of participants are required. Specifically, the performance-oriented studies on RMT application in swimmers indicate that swim training may already be a significant stimulus for developing endurance and strength of respiratory muscles (Shei, 2018). Therefore, even in well-trained athletes there may be differences in RMT-induced stress and TL between populations that swim and do not swim in training or between athletes with different swimming TL. Moreover, with the advancement of training individualization, coaches and practitioners can offer athletes personalized RMT related to their individual profiles and sport-specific performance determinants. Hence, research should be carried out to develop measurement protocols that can effectively assess the individual TL induced by RMT and its influence on athletes.

Conclusion

RMT induced larger changes in blood gasometry and cardiac indices in females rather than in males. VIH induced additional training load in well-trained triathletes. Despite the traditional objective indices such as T, C, and bLa concentrations, changes in blood gasometry, HR and local SMO_2 did not suggest that VIH is a significant source of load for well-trained athletes, %TTL based on subjective assessments suggested that VIH was a relevant component of the training program and substantially contributes to overall TL. On the other hand, IPTL was associated with a disbalance in blood gasometry variables, an increase in bLa, and reports of headaches and dizziness. Although, the subjective assessments suggested the relatively low perceived impact of IPTL on well-trained athletes. Both methods of RMT should be applied with consideration, especially in the context of demanding training programs and athletes already training close to their personal capabilities. In such scenarios, common in high-performance environments, a few percent increase in TL might lead to excessive levels of fatigue, unnecessary risk of injury, or overtraining.

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 Institute of Sport - National Research Institute Ethics Committee; 2 Trylogii Street, 01-982, Warsaw, Poland. 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

TK: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. PK: Conceptualization, Data curation, Formal Analysis, Methodology, Visualization, Writing–original draft, Writing–review and editing. KR: Conceptualization, Investigation, Methodology, Resources, Validation, Writing–original draft. AK: Conceptualization, Funding acquisition, Project administration, Supervision, Writing–review and editing, Resources. DG: Methodology, Writing–review and editing, Investigation. SW: Conceptualization, Data curation, Formal Analysis, Project administration, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

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

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2023.1264265/full#supplementary-material

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Hip thrust and back squat training elicit similar gluteus muscle hypertrophy and transfer similarly to the deadlift

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We examined how set-volume equated resistance training using either the back squat (SQ) or hip thrust (HT) affected hypertrophy and various strength outcomes. Untrained college-aged participants were randomized into HT (n = 18) or SQ (n = 16) groups. Surface electromyograms (sEMG) from the right gluteus maximus and medius muscles were obtained during the first training session. Participants completed 9 weeks of supervised training (15–17 sessions), before and after which gluteus and leg muscle cross-sectional area (mCSA) was assessed via magnetic resonance imaging. Strength was also assessed prior to and after the training intervention via three-repetition maximum (3RM) testing and an isometric wall push test. Gluteus mCSA increases were similar across both groups. Specifically, estimates [(–) favors HT (+) favors SQ] modestly favored the HT *versus* SQ for lower [effect ±SE, –1.6 ± 2.1 cm^2; $CI_{95\%}$ (–6.1, 2.0)], mid [–0.5 ± 1.7 cm^2; $CI_{95\%}$ (–4.0, 2.6)], and upper [–0.5 ± 2.6 cm^2; $CI_{95\%}$ (–5.8, 4.1)] gluteal mCSAs but with appreciable variance. Gluteus medius + minimus [–1.8 ± 1.5 cm^2; $CI_{95\%}$ (–4.6, 1.4)] and hamstrings [0.1 ± 0.6 cm^2; $CI_{95\%}$ (–0.9, 1.4)] mCSA demonstrated little to no growth with small differences between groups. mCSA changes were greater in SQ for the quadriceps [3.6 ± 1.5 cm^2; $CI_{95\%}$ (0.7, 6.4)] and adductors [2.5 ± 0.7 cm^2; $CI_{95\%}$ (1.2, 3.9)]. Squat 3RM increases favored SQ [14 ± 2 kg; $CI_{95\%}$ (9, 18),] and hip thrust 3RM favored HT [–26 ± 5 kg; $CI_{95\%}$ (–34, –16)]. 3RM deadlift [0 ± 2 kg; $CI_{95\%}$ (–4, 3)] and wall push strength [–7 ± 12N; $CI_{95\%}$ (–32, 17)] similarly improved. All measured gluteal sites showed greater mean sEMG amplitudes during the first bout hip thrust *versus* squat set, but this did not consistently predict gluteal hypertrophy outcomes. Squat and hip thrust training elicited similar gluteal hypertrophy, greater thigh hypertrophy in SQ, strength increases that favored exercise allocation, and similar deadlift and wall push strength increases.

KEYWORDS

hip thrust, back squat, gluteus maximus, strength, hypertrophy

Introduction

Resistance training (RT) presents potent mechanical stimuli that produce robust biological responses (Egan and Sharples, 2023; Roberts et al., 2023). However, RT responses vary considerably depending on several training variables. One such variable is exercise selection; specifically, different exercises have varying mechanical demands that can lead to differences in muscle growth, strength, and other related outcomes (Waters et al., 1974; Maeo et al., 2021; Zabaleta-Korta et al., 2021; Maeo et al., 2022). Practitioners and researchers often rely on functional anatomy, basic biomechanics, and acute physiological measurements to surmise what adaptations different exercises may elicit. The degree to which such surmises can meaningfully predict outcomes remains an open question, and recent work casts some doubt on their fidelity.

The reliance on theory and acute measures to guide exercise selection is especially evident in the hip extension exercise literature, an area of particular interest with applications in rehabilitation (Collings et al., 2023a), aging (Kulmala et al., 2014), performance (Miller et al., 2021), and bodybuilding. The roles of various hip extensor muscles during different hip extension tasks have been studied in several ways, including surface electromyography (sEMG), nerve blocks, and musculoskeletal modeling (Boren et al., 2011; Brazil et al., 2021; Collings et al., 2023b). Based on these acute measures, investigators infer stimulus potency or exercise superiority. For instance, previous work investigated sEMG amplitudes during two common and contentiously contrasted hip extension exercises—the hip thrust and squat—to compare muscle function, implying that this relates to subsequent adaptations (Contreras et al., 2015; Delgado et al., 2019; Williams et al., 2021). Although mean and peak sEMG amplitudes favored hip thrusts, the ability of sEMG to predict longitudinal strength and hypertrophy outcomes from resistance training interventions was recently challenged (Vigotsky et al., 2022). To help overcome some sEMG limitations, more sophisticated investigations integrate excitation into musculoskeletal models (Collings et al., 2023b). Yet, more comprehensive analyses of muscle contributions are still limited by their underlying assumptions (Herzog and Leonard, 1991), and even perfect modeling of muscle contributions presumes a one-to-one relationship between tension and adaptations.

Muscle tension is the primary driver of muscle hypertrophy but is unlikely to be its sole determinant. Recent evidence demonstrates that RT at long muscle lengths and long-duration static stretching can augment hypertrophic outcomes (Warneke et al., 2023), suggesting other factors may modulate anabolic signaling. It is unknown to what extent muscle tension may interact with position-specific anabolic signaling and other variables to contribute to the anabolic response and how this interaction may change under different conditions. Regarding the squat and hip thrust, the former has a steeper hip extension resistance curve with a relatively greater emphasis in hip flexion (Lahti et al., 2019; Brazil et al., 2021), which may confer a more potent gluteal training stimulus. However, this notion assumes proportional force sharing among the hip extensors, but contributions shift throughout the range of motion, clouding inferences. This highlights that longitudinal predictions necessitate assumptions about how motor systems satisfy the mechanical constraints imposed by each exercise and subsequent biological responses, it is difficult to infer the potency of the hypertrophic stimulus using indirect measures. We ultimately need longitudinal data to understand and accurately forecast longitudinal outcomes from individual movements.

Direct evidence is presently needed to compare the outcomes of various exercises. Therefore, the purpose of this study was to examine how RT using either the barbell squat or barbell hip thrust on a set-volume equated basis affected gluteus maximus, medius, and minimus muscle hypertrophy (determined by MRI) and various strength outcomes including the back squat, hip thrust, deadlift, and isometric wall push. As a secondary outcome, we sought to determine how these exercises affected gluteus maximus/medius muscle excitation patterns using sEMG and if sEMG amplitudes forecasted hypertrophy.

Materials and methods

Ethical considerations and participant recruitment

Before commencing study procedures with human participants, this study was approved by the Auburn University Institutional Review Board (protocol #: 22-588). All approved study procedures followed the latest revisions to the Declaration of Helsinki (2013) except for being pre-registered as a clinical trial on an online repository. Inclusion criteria were as follows: (a) between the ages of 18–30 years old with a body mass index (body mass/height^2) of less than 30, have minimal experience with resistance training, averaging less than or equivalent to 1 day per week for the last 5 years; (c) have not been actively participating in any structured endurance training program (e.g., running or cycling) for more than 2 days per week over the past 6 months; (d) free of any known overt cardiovascular or metabolic disease; (e) have not consumed supplemental creatine, and/or agents that affect hormones (testosterone boosters, growth hormone boosters, *etc.*) within the past 2 months, f) free of any medical condition that would contraindicate participation in an exercise program, (g) do not have conditions which preclude performing an MRI scan (e.g., medically-implanted devices), h) and free of allergies to lactose or intolerances to milk derived products that would contraindicate ingestion of whey protein. Eligible participants who provided verbal and written consent partook in the testing and training procedures outlined in the following paragraphs.

Study design overview

An overview of the study design can be found in Figure 1. Participants performed two pre-intervention testing visits, one in a fasted state for body composition and MRI assessments and the other in a non-fasted state for strength assessments. These visits occurred in this sequence ~48 h apart; after the pre-intervention strength visit, participants were randomly assigned to one of two

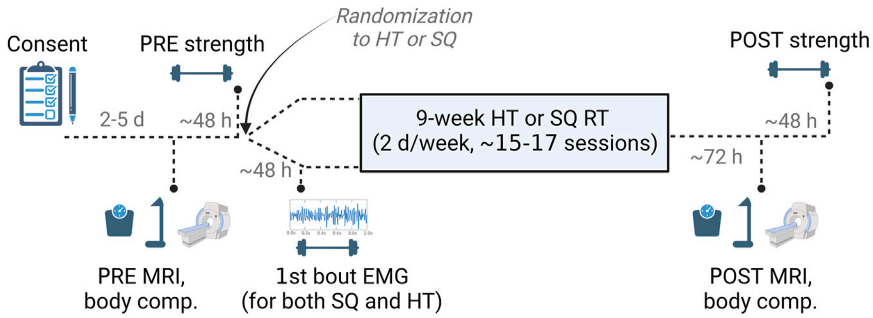

FIGURE 1
Study design overview Legend: Figure depicts study design overview described in-text. Abbreviations: PRE, pre-intervention testing visit; POST, post-intervention testing visit; HT, barbell hip thrust; SQ, barbell squat; body comp., body composition testing using bioelectrical impedance spectroscopy; MRI, magnetic resonance imaging; sEMG, surface electromyography.

experimental groups, including the barbell back squat (SQ) or barbell hip thrust (HT) groups. Two days following the pre-intervention strength testing, all participants partook in their first workout, which served to record right gluteal muscle excitation via sEMG during one set of 10 repetitions for both the SQ and HT exercises. Thereafter, participants engaged in 9 weeks of resistance training (2 days per week). Seventy-2 hours following the last training bout, participants performed two post-intervention testing visits with identical timing and protocols as pre-testing.

Body composition and MRI assessments

Body composition

Participants were told to refrain from eating for 8 h prior to testing, eliminate alcohol consumption for 24 h, abstain from strenuous exercise for 24 h, and to be well hydrated for testing. Upon arrival participants submitted a urine sample (~50 mL) for urine specific gravity assessment (USG). Measurements were performed using a handheld refractometer (ATAGO; Bellevue, WA, United States), and USG levels in all participants were ≤1.020, indicating sufficient hydration. Participants' heights were measured using a stadiometer and body mass was assessed using a calibrated scale (Seca 769; Hanover, MD, United States) with body mass being collected to the nearest 0.1 kg and height to the nearest 0.5 cm. Body composition was then measured by bioelectrical impedance spectroscopy (BIS) using a 4-lead (two hands, two feet) SOZO device (ImpediMed Limited, Queensland, Australia) according to the methods described by Moon et al. (Moon et al., 2008). Our laboratory has previously shown these methods to produce test-retest intraclass correlation coefficients ($ICC_{3,1}$) >0.990 for whole body intracellular and extracellular water metrics on 24 participants (Haun et al., 2018), and this device provided estimates of fat free mass, skeletal muscle mass, and fat mass.

MRI measurements

MRI testing assessed the muscle cross-sectional area (mCSA) of both glutei maximi. Upon arriving to the Auburn University MRI Research Center, participants were placed onto the patient table of the MRI scanner (3T SkyraFit system; Siemens, Erlangen, Germany) in a prone position with a ~5-min latency period before scanning was implemented. A T1-weighted turbo spin echo pulse sequence (1,400 m repetition time, 23 ms echo time, in-plane resolution of 0.9 × 0.9 mm^2) was used to obtain transverse image sets. 71 slices were obtained with a slice thickness of 4 mm with no gap between slices. Measurements were taken by the same investigator (R.J.B.) for all scans who did not possess knowledge of the training conditions for each participant.

Following the conclusion of the study, MRI DICOM files were preprocessed using Osirix MD software (Pixmeo, Geneva, Switzerland), and these images were imported into ImageJ (National Institutes of Health; Bethesda, MD, United States) whereby the polygon function was used to manually trace the borders of muscles of interest to obtain mCSA. For all participants, image standardization was as follows: (a) the middle of the gluteus maximus was standardized at the image revealing the top of the femur, (b) the image that was 10 slices upward from this mark was considered to be the upper gluteus maximus, (c) the image that was 18 slices downward from the top of the femur was considered lower gluteus maximus, (d) gluteus medius and minimus mCSAs were ascertained at the upper gluteus maximus image, and (e) combined quadriceps (vastii and rectus femoris), adductors (brevis, longus, and magnus), and combined hamstrings (biceps femoris, semitendinosus, semimembranosus) mCSAs were ascertained at the first transverse slice distal to the last portion of the lower gluteus maximus. When drawing borders to quantify muscles of interest, care was taken to avoid fat and connective tissue. Certain muscles were grouped (i.e., gluteus medius + minimus, combined quadriceps muscles, combined adductor muscles, combined hamstrings muscles) due to inconsistent and poorly delineated muscle borders within participants. All left- and right-side gluteus muscles were summed to provide bilateral mCSA values at each site. Alternatively, thigh musculature mCSA values were yielded from the averages of the left and right legs. This method was performed on the thigh because ~10% of participants yielded either left or right thigh images that presented visual artifacts from the edge of the MRI receiving coil. In these situations, thigh musculature from only one of the two legs was quantified.

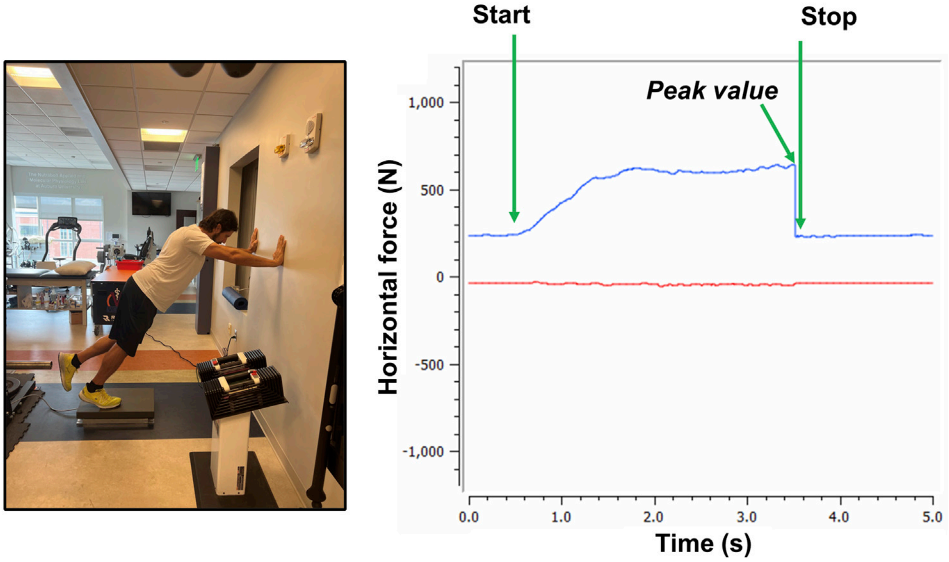

FIGURE 2
Wall push demonstration. Legend: Figure depicts the wall push test with one of the co-authors (M.D.R.) and shows force tracing.

Strength assessments

Isometric muscle strength (wall push)

Participants reported to the laboratory (non-fasted) having refrained from any exercise other than activities of daily living for at least 48 h before baseline testing. A tri-axial force plate (Bertec FP4060-10-2000; Columbus, OH, United States) with an accompanying amplifier (Bertec model # AM6800) sampling at 1,000 Hz was used to measure horizontal force production in newtons N) during a wall push test. The distance from the force plate to the wall was positioned such that when the subjects' forearms were parallel with the ground, the torso was at a ~45° angle with the ground and one rear foot was in contact with the force plate. Hand placement was standardized by distance from the ground and foot placement was standardized by distance from the wall. The subject was instructed to push, using the dominant leg, as hard as possible into the wall while keeping the torso at 45° (Figure 2). Two wall pushes were performed for 3 s each, with each repetition being separated by 2 m of rest. The highest peak horizontal force from these two tests was used for analysis.

Dynamic muscle strength

Following wall push testing, dynamic lower body strength was assessed by three-repetition maximum (3RM) testing for the barbell back squat, barbell hip thrust, and barbell deadlift exercises. Notably, our laboratory has extensively performed 3RM dynamic strength testing on numerous occasions in untrained and trained participants (Mobley et al., 2018; Vann et al., 2020; Godwin et al., 2023; Smith et al., 2023). Briefly, specific warm-up sets for each exercise consisted of coaching participants through the movement patterns and gauging comfort and movement proficiency. Subsequent warm-ups for each exercise were chosen with an attempt at approximating 5 repetitions at ~50% 1RM for one set and 2–3 repetitions at ~60–80% 1RM for two additional sets. Participants then performed sets of three repetitions with incremental increases in load for 3RM determinations for each exercise and 3 m of rest was given between each successive attempt. For all exercises, participants were instructed to perform repetitions in a controlled fashion, with a concentric action of approximately 1 s and an eccentric action of approximately 2 s. All three exercises were performed with feet spaced 1–1.5-times shoulder width apart. For the barbell squat, depth was set to when the femur was parallel to the floor, with all but one participant achieving a depth at or below this point. For the barbell hip thrust, the hip thrust apparatus (Thruster 3.0, BC Strength; San Diego, CA, United States) was set to a height at which participants could make brief contact with the ground with the weight plate (21") and hips at the bottom of each repetition. Repetitions were considered properly executed when the participant's tibia was perpendicular to the floor and the femur was parallel to the floor. Torso position was sufficiently maintained to avoid excessive motion through the pelvis. For the barbell deadlift, participants began repetitions from the floor and were prompted to maintain the torso position throughout the execution of the lift. A lift was deemed successful once participants stood upright with full knee and hip extensions.

sEMG measurements during the first training bout

Subjects were asked to wear loose athletic attire to access the EMG electrode placement sites. Before placing the electrodes on the skin, if necessary, excess hair was removed with a razor, and the skin was cleaned and abraded using an alcohol swab. After preparation, double-sided adhesives were attached to wireless sEMG electrodes (Trigno system; Delsys, Natick, MA, United States), where were placed in parallel to the fibers of the right upper gluteus maximus, mid gluteus maximus, lower gluteus maximus, and gluteus medius (see Figure 4A in *Results*). Upper and middle gluteus maximus electrodes were placed based on the recommendations of Fujisawa and others (Fujisawa et al., 2014), albeit we considered the lower gluteus maximus as middle. The upper gluteus maximus electrodes were placed superior and lateral to the shortest distance between the posterior superior iliac spine (PSIS) and the posterior greater trochanter, and the middle gluteus maximus electrodes were placed inferior and medial to the shortest distance between the PSIS and the posterior greater trochanter. Lower gluteus maximus electrodes were placed one inch (2.54 cm) above the most medial presentation of the gluteal fold. If it was ambiguous as to whether an appreciable amount of muscle tissue existed in this lower region, the participant was asked to contract the area and palpation was used to confirm proper placement. Gluteus medius electrodes were placed over the proximal third of the distance between the iliac crest and the greater trochanter. After the electrodes were secured, a quality check was performed to ensure sEMG signal validity. Following electrode placement, maximum voluntary isometric contraction (MVIC) testing was performed immediately prior to 10RM testing. For the gluteus maximus, the MVIC reference was a prone bent-leg hip extension against manual resistance applied to the distal thigh, as used by Boren and others (Boren et al., 2011). For the gluteus medius MVIC, participants laid on their side with a straight leg and abducted against manual resistance. Care was taken not to depress the joint of interest during manual testing. In all MVIC positions, participants were instructed to contract the tested muscle as hard as possible. After 5 m of rest following MVIC testing, all participants performed one set of ten repetitions utilizing estimated 10RM loads for both the barbell back squat and the barbell hip thrust exercises. The exercise form and tempo used were the same as described in the strength testing section above. During both sets, muscle excitation of the upper/middle/lower gluteus maximus and gluteus medius were recorded with the wireless sEMG system whereby electrodes were sampled at 1,000 Hz. Participants allocated to HT training performed the squat set first followed by the hip thrust set. Participants allocated to SQ training performed the hip thrust set first followed by the back squat set. Following these two sEMG sets, the wireless sEMG electrodes were removed. Participants finished the session with two more sets of 8–12 repetitions using the calculated 10RM load for the exercise allocated to them for the intervention.

Signal processing was performed using software associated with the sEMG system (Delsys EMGworks Analysis v4.7.3.0; Delsys). sEMG signals from the MVICs and 10RM sets of back squat and hip thrust were first rectified. Signals were then processed with a second-order digital low-pass Butterworth filter, with a cutoff frequency of 10 Hz, and further smoothed using a root mean square moving window of 250 m. The average of the middle 3 s of the filtered MVIC time series was then used to normalize the squat and hip thrust data for each site. Data were then visually inspected for fidelity before calculating the mean and peak sEMG values. Partial sequences of sEMG data were removed in the rare event that tempo was irregular or not maintained, or if a brief artifact was introduced. Final EMG data are presented as mean and peak sEMG amplitudes during the hip thrust and back squat 10RM sets. sEMG issues were only evident for a small portion (see *Results*) of the 34 participants who finished the intervention. Data were dropped from analyses due to artifacts produced through either electrode slippage or sEMG electrode jarring during the 10RM sets, leading to persistent distortion. In this regard, sample sizes for each muscle site are presented in the results section.

Resistance training procedures

The RT protocol consisted of 3–6 sets per session of barbell hip thrusts for HT participants or barbell back squats for SQ participants. Excluding the first week, which consisted of one session, all remaining weeks consisted of two sessions per week on non-consecutive days for 9 weeks. Week-to-week set schemes per session were as follows: week 1, 3 sets; week 2, 4 sets; weeks 3–6, 5 sets; weeks 7–9, 6 sets. The repetition range was set to 8–12 repetitions; if a participant performed less than 8 repetitions or more than 12 repetitions, the load was adjusted accordingly. D.L.P. and 1–2 other co-authors supervised all sessions, during which participants were verbally encouraged to perform all sets to the point of volitional muscular failure, herein defined as the participants being unable to volitionally perform another concentric repetition while maintaining proper form. Again, the exercise form and tempo used were the same as described in the strength testing section above; however, squat repetitions were not limited to a depth corresponding to the femur parallel to the floor but rather the lowest depth achievable. Outside of these supervised training sessions, participants were instructed to refrain from performing any other lower-body RT for the duration of the study. Participants could miss a maximum of 2 sessions and still be included in the analysis.

Dietary instructions during the study

Participants were given containers of a whey protein supplement (Built with Science; Richmond, BC, Canada) and were instructed to consume one serving per day (per serving: 29 g protein, 1 g carbohydrate, 0.5 g fat, 130 kcal). This was done in the hope of diminishing inadequate protein intake as a confounding variable. Other than this guidance, participants were advised to maintain their customary nutritional regimens to avoid other potential dietary confounders.

All participants were instructed to provide 4-day food logs (2 weeks days, 2 weekend days) during the first and last weeks of the intervention. A registered dietician (A.D.R.) oversaw food log analyses using The Nutrition Data System for Research (NDSR; NDSR 2014; University of Minnesota) food log entry and analyses (Schakel, 2001). Calories and macronutrients from each time point represent the 4-day average for the respective food log dates.

Notes on randomization and blinding

Investigators were blinded to group allocation during the MRI scan and its analysis. Participants were not blinded to group allocation as exercise comparisons were not amenable to blinding. Due to logistical constraints investigators were not blinded to group allocation during strength testing and, thus, bias cannot be completely ruled out in this context. Randomization into SQ and HT groups was performed via a random number generator in blocks of 2 or 4 as participants consented.

Statistics and figure construction

Data were analyzed in Jamovi v2.3 (https://www.jamovi.org) and R (version 4.3.0). We performed three different sets of analyses.

First, we compared mean and peak HT and SQ sEMG amplitudes from the first training session, for which we performed paired *t*-tests.

Second, we compared the longitudinal effects of HT and SQ training on mCSA and strength. Notably, baseline and within-group inferential statistics were not calculated, as baseline significance testing is inconsequential (Senn, 1994) and within-group outcomes are not the subject of our research question (Bland and Altman, 2011). However, we descriptively present within-group changes to help contextualize our findings. The effect of group (SQ *versus* HT) on each outcome variable was estimated using linear regression, in which post-intervention scores were the response variable, group was dummy-coded 0 for SQ and 1 for HT, and the pre-intervention score was included as a covariate of no interest (Vickers and Altman, 2001). The model output can thus be interpreted as the expected difference in post-intervention (or mathematically equivalently, change) scores between the SQ and HT groups for a given pre-intervention score. We used the bias-corrected and accelerated stratified bootstrap with 10,000 replicates to calculate 95% compatibility intervals (CIs).

Third, we investigated the extent to which sEMG amplitudes from the first session forecasted growth. There are multiple ways this question could be posed, and since claims surrounding sEMG amplitude's predictive power are ambiguous, we addressed each of the following questions: i) Do individuals with greater sEMG amplitudes grow more than individuals with lower sEMG amplitudes? For this, we calculated a Pearson correlation for each muscle using changes in mCSA and the sEMG amplitudes. ii) Do regions or muscles with greater sEMG amplitudes grow more than regions or muscles with lower sEMG amplitudes? For this, we used a linear mixed-effects model in which ln ($mCSA_{post}$/$mCSA_{pre}$) was the response variable; sEMG amplitude, group, and their interaction were fixed effects; and we permitted intercepts and slopes for sEMG amplitude to vary across subjects. Since we are interested in generalizable predictions, we calculated prediction intervals for the slopes by calculating a Wald interval using the sum of the parameter variance and random effects variance. iii) Can the differences in growth elicited from different exercises be accounted for by sEMG amplitude? For this, we calculated the so-called "indirect effect" of sEMG amplitude, which represents the extent to which the group effect on hypertrophy can be explained by sEMG amplitudes. This was done the same way a typical "mediation analysis" is done (although, this should not be viewed as causal here)—we bootstrapped the difference between the group effect (SQ vs HT) when sEMG was not in the model and when sEMG was added to the model. If group-based sEMG differences accounted for group-based hypertrophy differences, then the effect of group on growth would shrink towards 0 and sEMG would absorb the variance in growth.

Finally, self-reported food log data (kcal/d, protein g/d, carbohydrate g/d, and fat g/d) were analyzed using two-way repeated measures ANOVAs.

Figures were constructed using Microsoft PowerPoint and through paid site licenses for BioRender (https://www.biorender.com), GraphPad Prism v9.2.0 (San Diego, CA, United States), and ggplot2.

Results

Consort and general baseline participant characteristics

The CONSORT diagram is presented in Figure 3. In total, 18 HT and 16 SQ participants completed the study and were included in data analyses unless there were technical issues precluding the inclusion of data (e.g., sEMG signal distortion).

General baseline characteristics of the 18 HT participants who finished the intervention were as follows: age: 22 ± 3 years old, 24 ± 3 kg/m^2, 5 M and 13 F. Baseline characteristics of the 16 SQ participants who finished the intervention were as follows: age: 24 ± 4 years old, 23 ± 3 kg/m^2, 6 M and 10 F. Also notable, the HT participants missed an average of 0.8 ± 0.4 workouts during the study, and the SQ participants missed 0.8 ± 0.5.

Self-reported food log data between groups

Most participants reported 4 days at during the first and last weeks of the study with the following exceptions: i) two SQ participants reported 3 days only with the first food log, ii) two SQ participants were missing last-week food logs, and iii) one HT participant did not turn in the first food log. Thus, food log data were analyzed for n = 15 SQ and n = 16 HT participants. No group x time (G x T) interactions were evident for any of the assessed variables (data not shown).

First bout sEMG results

sEMG data obtained from the right gluteus muscles during the first workout bout, based on one set of 10RM hip thrust and one set of 10RM squat, are presented in Figure 4. All sites showed greater mean sEMG values during the hip thrust *versus* squat set ($p < 0.01$ for all; Figure 4B). Peak sEMG values were greater for the upper and middle gluteus maximus ($p < 0.001$ and $p = 0.015$, respectively), whereas small differences existed for the lower gluteus maximus or gluteus medius sites (Figure 4B). The number of repetitions completed during the 10RM sets used for sEMG recordings were not different between exercises (back squat: 9 ± 1 repetitions, hip thrust: 9 ± 2 repetitions).

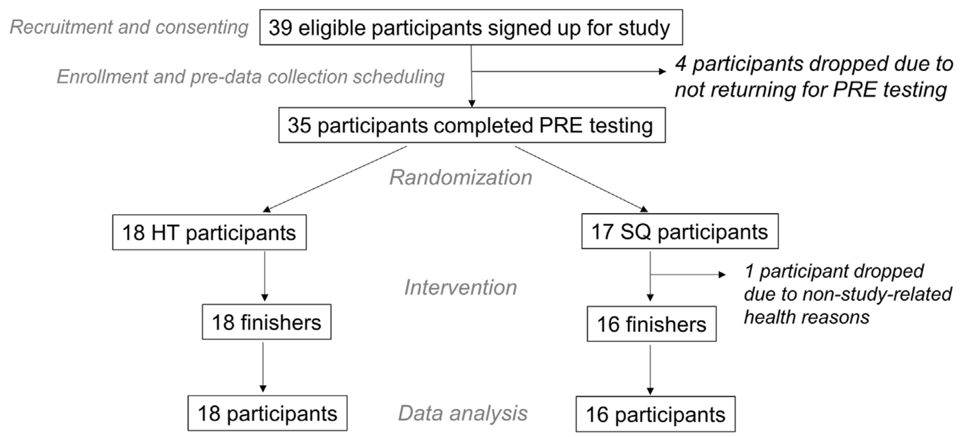

FIGURE 3
CONSORT diagram Figure depicts participant numbers through various stages of the intervention. All participants were included in data analysis unless there were technical issues precluding the inclusion of data (e.g., EMG distortion).

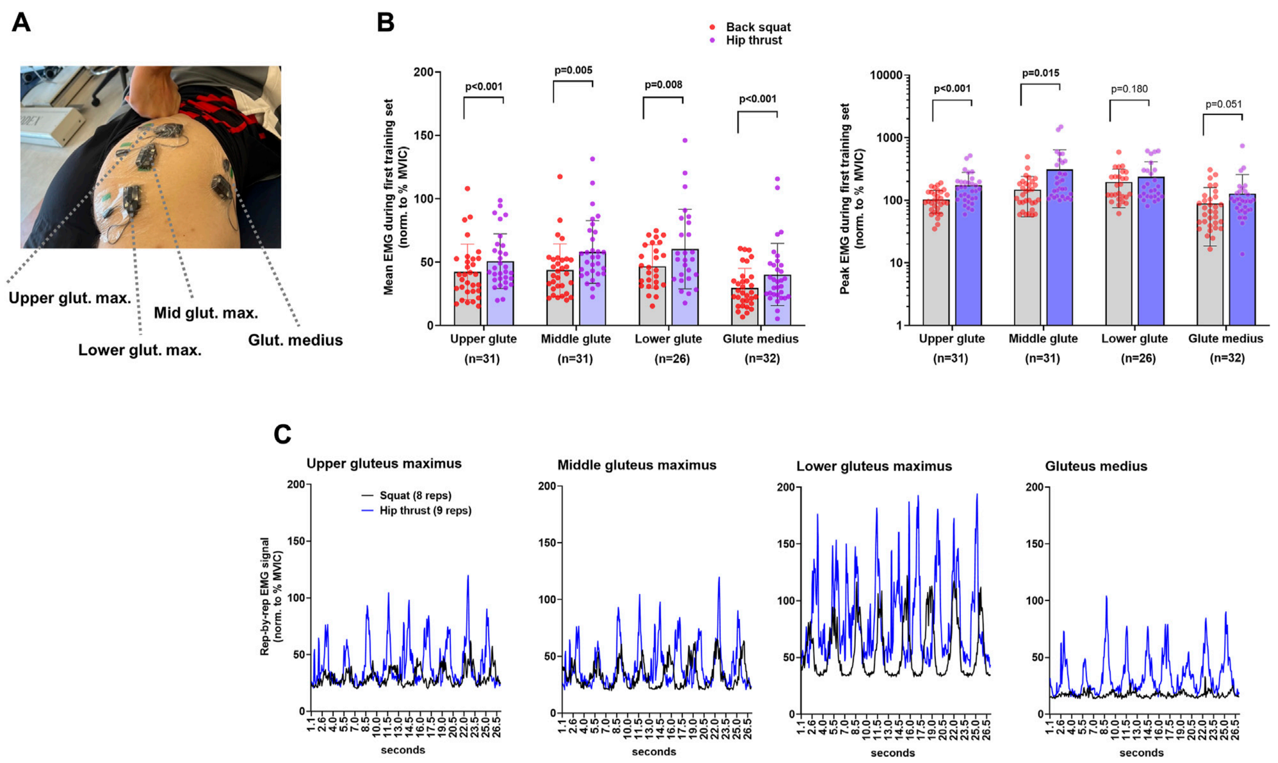

FIGURE 4
Surface electromyography (sEMG) amplitudes during the back squat and barbell hip thrust. Legend: During the first session, all participants performed both back squats and barbell hip thrusts while we recorded sEMG amplitudes. **(A)** Representative sEMG electrode placement is depicted on a co-author in panel. **(B)** Data depict mean (left) and peak (right) sEMG amplitudes during one 10RM set of hip thrusts and one 10RM set of back squats. As 34 participants partook in this test, sample sizes vary due to incomplete data from electrode slippage or distortion. Bars are mean ± SD, and individual participant values are depicted as dots. **(C)** Representative data from one participant.

Gluteus musculature mCSAs according to MRI

The effect of SQ relative to HT for left + right mCSA was negligible across gluteal muscles (Figures 5A–D). Point estimates modestly favored HT for lower [effect ±SE, −1.6 ± 2.1 cm^2; $CI_{95\%}$ (−6.1, 2.0)], mid [−0.5 ± 1.7 cm^2; $CI_{95\%}$ (−4.0, 2.6)], and upper [−0.5 ± 2.6 cm^2; $CI_{95\%}$ (−5.8, 4.1)] gluteal mCSAs; these point estimates were dwarfed by the variance. Left + right mCSA values for the gluteus medius + minimus demonstrated a lesser

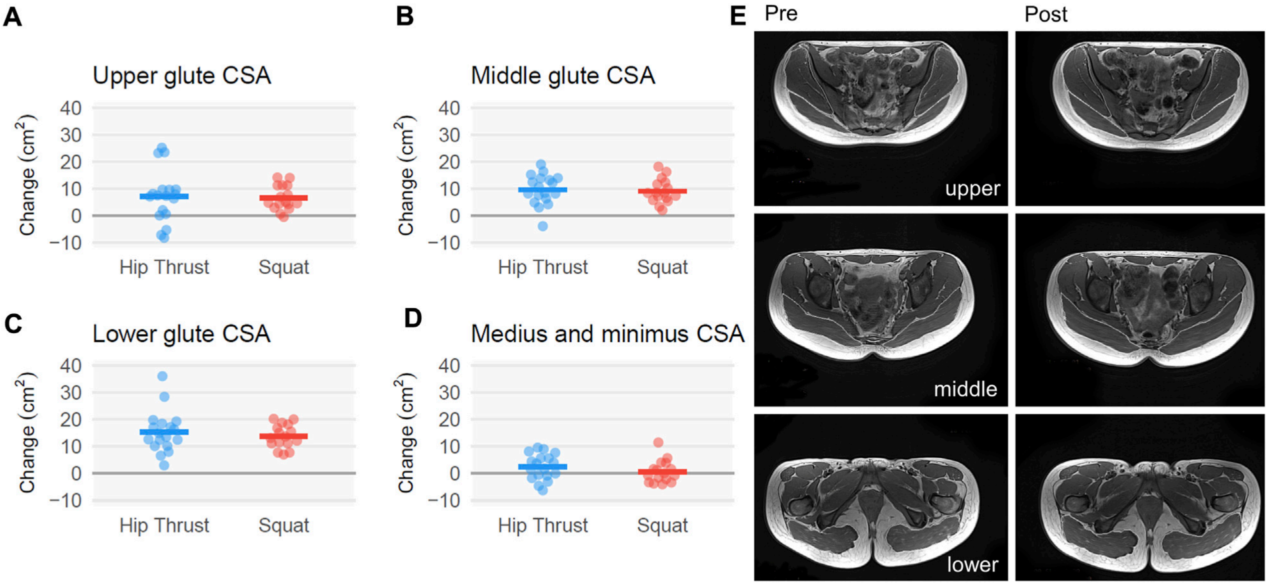

FIGURE 5
Gluteus musculature mCSA changes following back squat and barbell hip thrust training, assessed using MRI. Legend: Figure depicts change adjusted for pre-intervention scores for MRI-derived muscle cross-sectional area (mCSA). **(A)** left + right (L + R) upper gluteus maximus, **(B)** L + R middle gluteus maximus, **(C)** L + R lower gluteus maximus, and **(D)** L + R gluteus medius + minimus. Data include 18 participants in the hip thrust group and 16 participants in the back squat group. Graphs contain change scores with individual participant values depicted as dots. **(E)** Three pre and post representative MRI images are presented from the same participant with white polygon tracings of the L + R upper gluteus maximus and gluteus medius + minimus (top), L + R middle gluteus maximus (middle), and L + R lower gluteus maximus (bottom).

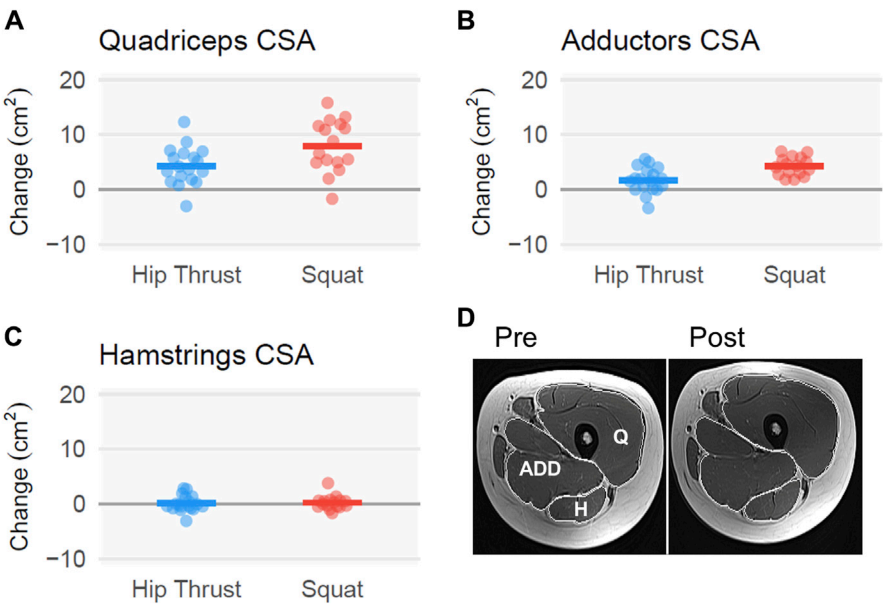

FIGURE 6
Thigh musculature mCSA changes following back squat and barbell hip thrust training, assessed using MRI. Legend: Figure depicts change adjusted for pre-intervention scores for MRI-derived muscle cross-sectional area (mCSA). Left and/or right **(A)** quadriceps, **(B)** adductors, and **(C)** hamstrings. Data include 18 participants in the hip thrust group and 16 participants in the back squat group. Bar graphs contain change scores with individual participant values depicted as dots. **(D)** A representative pre- and post-intervention MRI image is presented with white polygon tracings of the quadriceps (denoted as Q), adductors (denoted as ADD), and hamstrings (denoted as H).

FIGURE 7
Strength outcomes following back squat and barbell hip thrust training. Legend: Figure depicts change adjusted for pre-intervention scores for **(A)** 3RM barbell back squat values, **(B)** 3RM barbell hip thrust values, **(C)** 3RM barbell deadlift values, and **(D)** wall push as demonstrated in Figure 2. Data include 18 participants in the hip thrust group and 16 participants in the back squat group.

magnitude of growth, with a point estimate that also modestly favored HT albeit with appreciable variance [−1.8 ± 1.5 cm^2; $CI_{95\%}$ (−4.6, 1.4)].

Thigh musculature mCSAs according to MRI

Compared to HT, SQ produced greater mCSA growth for quadriceps [3.6 ± 1.5 cm^2; $CI_{95\%}$ (0.7, 6.4), Figure 6A] and adductors [2.5 ± 0.7 cm^2; $CI_{95\%}$ (1.2, 3.9), Figure 6B]. However, hamstrings growth was equivocal across both conditions, yielding negligible between-group effects [0.1 ± 0.6 cm^2; $CI_{95\%}$ (−0.9, 1.4), Figure 6C].

Strength outcomes

Strength outcomes of SQ relative to HT favored respective group allocation for specific lift 3RM values. Specifically, Squat 3RM favored SQ [14 ± 2 kg; $CI_{95\%}$ (9, 18), Figure 7A], and hip thrust 3RM favored HT [−26 ± 5 kg; $CI_{95\%}$ (−34, −16), Figure 7B]. Results were more equivocal for the deadlift 3RM [0 ± 2 kg; $CI_{95\%}$ (−4, 3), Figure 7C] and wall push [−7 ± 12 N; $CI_{95\%}$ (−32, 17), Figure 7D].

Forecasting training-induced gluteus muscle mCSA changes with sEMG amplitudes

Across-subject correlations

sEMG amplitude's ability to forecast muscle growth across-subjects was generally poor and variable. Mean sEMG amplitudes produce negligible to moderate correlations for lower [*r* = 0.18 (−0.30, 0.57)], middle, [*r* = −0.03 (−0.32, 0.25)], upper [r = 0.50 (0.03, 0.81)], and medius + minimus [*r* = 0.28 (0, 0.53)]. We observed similar results for peak sEMG amplitudes from the lower [r = 0.13 (−0.16, 0.46)], middle [*r* = −0.03 (−0.33, 0.21)], upper [r = 0.32 (−0.05, 0.62)], and medius + minimus [r = 0.24 (−0.02, 0.48)].

Across-region correlations

We fit two linear mixed-effects models to assess how differences in sEMG amplitudes across muscles can account for regional growth. Since the response variable was change in muscle size on the log scale, the exponentiated coefficients can be interpreted as the increase in muscle relative to baseline for each additional %MVIC; notably, this effect is multiplicative rather than additive. The first model, which used mean sEMG amplitudes, produced small and variable estimates for both SQ [1.003, $PI_{95\%}$ (0.998, 1.008)] and HT [1.002, $PI_{95\%}$ (0.997, 1.006)] groups. The second model, which used peak sEMG amplitudes, produced even more modest results for both the SQ [1.0003, $PI_{95\%}$ (0.9997, 1.0009)] and HT [1.0002, $PI_{95\%}$ (0.9996, 1.0007)] groups.

Across-exercise variance

Mean sEMG amplitude's ability to capture the group effects was inconsistent for lower [indirect effect = −0.55, $CI_{95\%}$ (−3.87, 0.58)], middle [0.06, $CI_{95\%}$ (−0.82, 1.56)], upper [−2.98, $CI_{95\%}$ (−8.73, −0.38)], and medius + minimus [−0.73, $CI_{95\%}$ (−2.70, 0.14)]. We observed similar results for peak sEMG amplitudes for lower [−0.08, $CI_{95\%}$ (−2.27, 0.59)], middle [0.22, $CI_{95\%}$ (−1.63, 1.89)], upper [−3.04, $CI_{95\%}$ (−8.32, 0.15)], and medius + minimus [−0.86, $CI_{95\%}$ (−2.47, 0)]. These estimates can be compared to the group effects ("total effects") earlier in the Results.

Discussion

To further our understanding of hip extensor exercises and the validity of relying on theory and acute physiological measures for exercise selection, here we acutely (sEMG) and longitudinally (hypertrophy, strength) compared two common hip extension exercises: the back squat and barbell hip thrust. Acutely, HT sEMG amplitudes were generally greater for the HT. However, this did not appear to translate and accurately capture longitudinal adaptations. Across all gluteus muscle hypertrophy outcomes, SQ and HT training yielded modest differences but meaningful growth occurring, except in the gluteus medius and minimus. Thigh hypertrophy outcomes favored SQ in the adductors and quadriceps, with no meaningful growth in either group in the hamstrings. Strength outcomes indicated that hip thrust 3RM changes favored HT, back squat 3RM changes favored SQ, and other strength measures similarly increased in both groups. sEMG amplitudes could not reliably predict hypertrophic outcomes across several analytical approaches. In the following paragraphs, we discuss these results in the context of available evidence and speculate on their potential implications for exercise prescription.

Hypertrophy outcomes

The primary finding of interest was that upper, middle, and lower gluteus maximus muscle hypertrophy was similar after 9 weeks of training with either the squat or hip thrust. This may seem to run counter to the notion that muscle tension in lengthened positions augments growth (Kassiano et al., 2023b), since the sticking region for the squat occurs in greater hip flexion as compared to the hip thrust. Importantly, much of the previous work on this topic is in muscles being worked in a more isolated fashion (Maeo et al., 2021; Maeo et al., 2022). Thus, the equivocal findings may suggest that the context in which the muscle is experiencing lengthened loading critically determines subsequent adaptations. Muscle contributions, and not just positions, may need to be jointly considered in determining whether superior hypertrophy outcomes would be achieved. This idea is loosely supported by sEMG and musculoskeletal modeling research, suggesting the gluteus maximus may not be strongly recruited toward the bottom of the squat (Contreras et al., 2015; Chiu et al., 2017; Kassiano et al., 2023a). This notion would suggest the nervous system may not strongly recruit the gluteus maximus while at its longest length in the squat, and synergist muscle involvement could be precluding the maximum benefits of stretch-augmented hypertrophy.

In addition to motor control governing how the gluteus maximus contributes to and adapts from the squat, there are study-specific considerations. Both exercises may stimulate similar muscle hypertrophy in untrained populations given that RT in general elicits rapid growth early on, potentially creating a ceiling effect on growth rate and thus observed growth. Alternatively stated, skeletal muscle hypertrophy in novice trainees may be less influenced by nuances in exercise selection. Notwithstanding, our results suggest that a 9-week set-equated training program with either the hip thrust, or squat elicits similar gluteal muscle hypertrophy in novice trainees.

Finally, our data show that thigh hypertrophy favored the squat, whereas thigh hypertrophy was minimal in the hip thrust. This is perhaps unsurprising and is consistent with previous literature. The adductors, particularly the adductor magnus, have the largest extension moment contribution at the bottom of a squat. Thus, the nervous system may favor its recruitment for this purpose. In line with this finding, adductor magnus mCSA changes favor a greater squat depth (Kubo et al., 2019). Hamstring mCSA changes did not occur in either group, in accordance with previous work (Kubo et al., 2019). Critically, these data imply that the hip thrust exercise primarily targets gluteus muscle hypertrophy while limiting non-gluteal thigh muscle hypertrophy; in other words, the hip thrust appears to be more gluteus maximus-specific.

Strength outcomes

Both groups effectively increased strength outcomes for all exercises tested, with magnitudes in accordance with previous strength literature (Lacio et al., 2021). However, HT RT better increased hip thrust strength and SQ RT better increased back squat strength, which is to be expected due to training specificity (Morrissey et al., 1995). Back squat 3RM increased by 17% in the HT group and 44% in the SQ group, while hip thrust strength increased by 63% in HT group and 34% in SQ group. In contrast, deadlift and wall push outcomes increased similarly in both groups. Deadlift increased by 15% in SQ and 16% in HT, and wall push increased by 7.6% in SQ and 10% in HT.

Using acute first bout sEMG to predict hypertrophy

Our secondary aim was to evaluate the ability of sEMG to forecast longitudinal adaptations. In agreement with previous work (Contreras et al., 2015), gluteus muscle sEMG amplitudes during the hip thrust exercise were greater across all measured gluteal sites. However, these sEMG amplitude differences did not reliably translate to greater hypertrophy, no matter what analytical approach we took. Specifically, i) individuals with greater sEMG amplitudes did not consistently experience greater growth; ii) regions with greater sEMG amplitudes did not consistently experience greater growth; iii) differences in sEMG amplitudes between exercises could not consistently explain differences in growth, in large part since the hypertrophy results were equivocal. This finding implies that acute sEMG readings during a workout bout are not predictive of hypertrophic outcomes, and this viewpoint is supported by a recent review by Vigotsky et al. (Vigotsky et al., 2022). As indicated by the authors, inconsistent relationships between EMG amplitudes and muscle growth have been previously reported, which may be due to one or several reasons, ranging from biases in the sEMG recordings to assumptions about how adaptations occur (Vigotsky et al., 2022). Evidently, the reliance on acute sEMG measurements may in fact be an over-reliance, but more work is needed in this realm.

Finally, we also verbally asked participants which exercise they “felt more” in the gluteal muscles after testing both exercises. All participants indicated they felt the hip thrust more in the gluteal region. However, these data were not quantified and, despite these anecdotal sensations and sEMG differences indicating more gluteus muscle excitation during HT, hip thrust RT and squat RT elicited similar applied outcomes. These findings highlight the importance of longitudinal investigations.

Limitations

Our study has a few limitations to consider. First, our participants were young untrained men and women; thus, results cannot necessarily be generalized to other populations including adolescents, older individuals, or trained populations. Additionally, like most training studies, this study was limited in duration. It should also be noted that gluteal hypertrophy was the main outcome, and the MRI coil was placed over this region as subjects were lying prone. Thus, compression may have affected the thigh musculature, and distal measures were not obtained for the thigh. Finally, training volume was equated, and frequency was set at two training days per week. Therefore, results can only be generalized to this protocol.

Although we did not consider female participants' menstrual cycle phase or contraceptive usage, we do not view this as a limitation. In this regard, several reports indicate that contraceptives have no meaningful impact on muscle hypertrophy in younger female participants during periods of resistance training (Ruzic et al., 2003; Dalgaard et al., 2019; Romance et al., 2019; Dalgaard et al., 2020; Oxfeldt et al., 2020; Riechman and Lee, 2021). Likewise, well-controlled trials indicate that the menstrual cycle phase does not affect strength characteristics (Romero-Moraleda et al., 2019), and that variations in female hormones during different phases do not affect muscle hypertrophy and strength gains during 12 weeks of resistance training (Sakamaki-Sunaga et al., 2016).

Future directions

Future research should aim to examine a group that performs both exercises on a volume-equated basis to determine if there are synergetic effects. Comparing these exercises with different volumes/frequencies is also warranted as exercises may have differing volume tolerances. From a mechanistic standpoint, future studies should characterize anabolic signaling between different points on the length-tension curve as well as ascertain where a muscle exists on this curve with more clarity.

Conclusion

Squat and hip thrust RT elicited similar gluteal hypertrophy, whereas quadriceps and adductors hypertrophy was superior with squat training. Further, although strength increases were specific to exercise allocation, both forms of RT elicited similar strength transfer to the deadlift and wall push. Importantly, these results could not be reliably predicted from acute data (sEMG). These current data provide trainees with valuable insight concerning two widely popular hip-specific exercise modalities, and this information can be leveraged for exercise selection based on specific structural or functional goals.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Auburn University Institutional Review Board. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

DP: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Writing–original draft, Writing–review and editing. MR: Investigation, Methodology, Supervision, Writing–review and editing. AV: Data curation, Formal Analysis, Methodology, Software, Validation, Writing–review and editing. MM: Investigation, Methodology, Writing–review and editing. EB: Methodology, Writing–review and editing. RU: Investigation, Methodology, Writing–review and editing. CR: Methodology, Writing–review and editing. A-AB: Methodology, Writing–review and editing. MM: Investigation, Methodology, Writing–review and editing. MM: Investigation, Methodology, Writing–review and editing. NK: Investigation, Methodology, Writing–review and editing. SL: Data curation, Formal Analysis, Methodology, Writing–review and editing. AF: Formal Analysis, Investigation, Methodology, Writing–review and editing. CW: Data curation, Formal Analysis, Investigation, Methodology, Resources, Writing–review and editing. WW: Data curation, Methodology, Resources, Software, Writing–review and editing. AB: Data curation, Investigation, Methodology, Resources, Writing–review and editing. RB: Data curation, Methodology, Resources, Software, Writing–review and editing. MH: Conceptualization, Funding acquisition, Writing–review and editing. BC: Conceptualization, Funding acquisition, Writing–review and editing. MR: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Project administration, Supervision, Writing–review and editing.

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Conflict of interest

BC and MH disclose that they sell exercise-related products and services. However, neither was involved in any aspect of the study beyond assisting with the study design and providing funds to partially cover participant and MRI costs through a gift to the laboratory of MR. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

The remaining 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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Muscle synergies in joystick manipulation

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Extracting muscle synergies from surface electromyographic signals (sEMGs) during exercises has been widely applied to evaluate motor control strategies. This study explores the relationship between upper-limb muscle synergies and the performance of joystick manipulation tasks. Seventy-seven subjects, divided into three classes according to their maneuvering experience, were recruited to perform the left and right reciprocation of the joystick. Based on the motion encoder data, their manipulation performance was evaluated by the mean error, standard deviation, and extreme range of position of the joystick. Meanwhile, sEMG and acceleration signals from the upper limbs corresponding to the entire trial were collected. Muscle synergies were extracted from each subject's sEMG data by non-negative matrix factorization (NMF), based on which the synergy coordination index (SCI), which indicates the size of the synergy space and the variability of the center of activity (CoA), evaluated the temporal activation variability. The synergy pattern space and CoA of all participants were calculated within each class to analyze the correlation between the variability of muscle synergies and the manipulation performance metrics. The correlation level of each class was further compared. The experimental results evidenced a positive correlation between manipulation performance and maneuvering experience. Similar muscle synergy patterns were reflected between the three classes and the structure of the muscle synergies showed stability. In the class of rich maneuvering experience, the correlation between manipulation performance metrics and muscle synergy is more significant than in the classes of trainees and newbies, suggesting that long-term training and practicing can improve manipulation performance, stability of synergy compositions, and temporal activation variability but not alter the structure of muscle synergies determined by a specific task. Our approaches and findings could be applied to 1) reduce manipulation errors, 2) assist maneuvering training and evaluation to enhance transportation safety, and 3) design technical support for sports.

KEYWORDS
muscle synergy extraction, muscle synergy similarity, joystick manipulation, maneuvering, electromyography, EMG

1 Background

Fine manipulation refers to the ability to perform precise actions or delicate tasks using hands or tools, presented as coordination and precision of movements (Tang et al., 2017; Tang et al., 2021). In the training and selection of pilots, evaluating the control ability of the joystick is critical, as the joystick is one of the primary control devices in an aircraft and common interactive tools applied with muscle synergy. In (Bezerra et al., 2019), the mean and peak electromyographic activation values during joystick operation have been studied for favorable pilot load conditions. Previous research also revealed that muscle coordination changes during motor adaptation to the viscous force field generated by haptic interface (Fabio et al., 2016) or visuomotor rotation (Gentner et al., 2013).

Joystick manipulation is a multi-joint coordinated motion for which numerous control modes exist in the motion control of the musculoskeletal system. Movements are inherently variable and can be as consistent as possible by repetition of professional athletes. Various studies have evidenced that the central nervous system (CNS) can generate motor commands through a series of synergistic combinations of muscles (d'Avella et al., 2003; Bizzi et al., 2008; Bizzi and Cheung, 2013), known as muscle synergy. Muscle synergy has recently been considered a common method for studying complex motor control patterns, applied to research fields of nerve damage effects (Roh et al., 2013; Tang et al., 2017), human posture control (Torres-Oviedo and Ting, 2007; Robert and Latash, 2008; Asaka et al., 2011), and locomotion of robot-assisted technology (Pham et al., 2011; Salman et al., 2010; Wang et al., 2021a; Wang et al., 2021b; Scano et al., 2019). Muscle contractions during exercise can be divided into isometric and isotonic. In isometric tasks, the module structures of muscle synergies are robust to changes in speed, and the neural commands to muscle synergies change in response to speed changes (Kojima et al., 2017). The motor control strategy can be modified depending on the accuracy requirement of the isometric reach task (Ettema et al., 2005a; Sano et al., 2020). In joystick isometric dual degree-of-freedom torque tasks, the torque history affects coordination patterns, and the motor system controls different orthogonal combinations of torque oscillations and constant torques employing a single oscillating muscle synergy (Ettema et al., 2005b). In joystick isometric force feedback tasks (Camardella et al., 2021), divided muscle synergies into groups with specific motor strategies and the same global groups for all subjects, confirming that muscle sets can be reduced to achieve comparable hand force estimation performances. For isotonic contraction tasks, the literature shows that the CNS can perceive the relationship between stiffness level and the size of the endpoint deviation (Gribble et al., 2003; Osu et al., 2004) and alter the mechanical impedance of the limb through the simultaneous activation of antagonist muscle groups (Feldman and Levin, 1995; Burdet et al., 2001), revealing the critical role of co-contraction in arm movement performance.

In addition to co-contraction indices, inter- and intra-subject similarities are hotspots in motor coordination (Alnajjar and Shimoda, 2017; Barnamehei et al., 2018b; Esmaeili and Maleki, 2020). Studies have indicated that muscle synergies are a valuable tool for quantifying variability at the muscle level and reveal that intra-subject variability is lower than inter-subject variability in synergy modules and related temporal coefficients, and both intra-subject and inter-subject similarities are higher than random synergy matching, confirming shared underlying control structures (Zhao et al., 2021). During specific movements, two indices of muscle cooperative stability and cooperative space are introduced for the CNS, characterized by the best recruitment mechanism in the process of balance behavior proficiency (Alnajjar and Shimoda, 2017). Taking kicking as an example, elite players have a high similarity in the stability of muscle synergies (Barnamehei et al., 2018b). In a controlled experiment with overhead shots, individual muscle patterns ranged from moderate to highly similar between elite and non-elite groups (Barnamehei et al., 2018a). These results suggest that the CNS can create optimal sets of efficient behaviors by optimizing the size of the synergy space in the appropriate region by interacting with the environment (Alnajjar et al., 2013). However, the group comparison did not correlate muscle synergy results with the performance of each exercise.

Training is hypothesized to change manipulation performance and muscle synergies, and there is a specific correlation between them. Subjects with different maneuvering experiences are selected to perform the rocker manipulation task. This study explores an objective and effective method to explore the relationship between muscle synergy and manipulation performance, providing theoretical support for sports science and scientific training methods. To the best of our knowledge, this article is the first to study the relationship between muscle synergy and joystick manipulation position accuracy. This fine activity is practical and essential for sports and transportation, rather than the broader sense movements of the limb or joint, often studied in related fields.

2 Data preparation: subjects, hardware, and setup

2.1 Subjects, classes, and ethics

Seventy-seven healthy right-handed male subjects, detailed in Table 1, aged 17–55 (25.18 ± 13.73) years, volunteered to participate in this study and were divided into three classes according to their maneuvering experience.

- Class Experts consists of professional pilots with over 1,000 h of flight time;
- Class Trainees is formed by short-haul experienced pilots who have completed 7–8 h of flight time in the company of professionals;
- Class Newbies contains high school students without experience in flying missions or joystick operations.

All subjects were informed of the experiment procedure approved by the Ethics Review Committee of Fudan University (No. FE22064R).

TABLE 1 Grouping and information of the 77 subjects.

Class	Number	Age	Maneuvering experience (flight time)
Experts	19	40–55	≥3,000 h
Trainees	30	18–19	7–8 h
Newbies	28	17–19	0
All	77	17–55	—

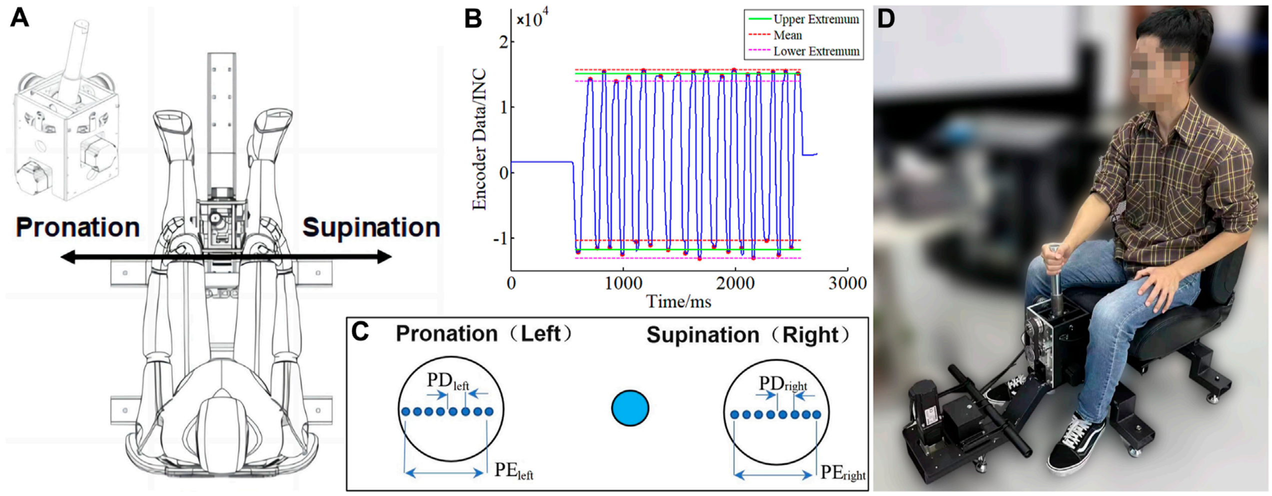

FIGURE 1
Self-developed experimental device and software interface. **(A)** Top view of the device for experiments; **(B)** An exemplar result record. PD: position deviation; PE: extreme range of the position. **(C)** A screenshot of the software interface; **(D)** Schematic experimental scene.

2.2 Experimental apparatus

Figure 1A exhibits our self-developed experimental apparatus achieving rocker X/Y operation in two directions, for which the motor encoder recorded the position of the joystick in real-time. Users operate the experimental apparatus, interacting with an upper computer interface. Figures 1B,C exemplify one record of a trail.

The angle of the joystick ranges from ±15°, normalizing the angle to the spacing of the two black circles on the screen. The precision of the joystick is determined by the clearance of the planetary reducer, which has a backlash of two arc minutes, that is, 0.03 mm on the screen. The sensitivity of the device is determined by the resolution of the motor encoder, 0.005 mm. The self-implemented prototype acquired position data with a position sampling frequency of 200 Hz.

The coordination of the shoulder, elbow, wrist, and fingers enables the manipulation of the joystick. The reciprocating motion in this study is designed under a constant load condition (see Figure 1B). The internal and external rotation of the shoulder and the pronation/supination of the forearm were performed during the experiment, while the elbow joint was retracted in the coronal plane and flexed/extended in the sagittal plane. The range of motion of the forearm was more evident than that of the elbow and shoulder joints.

Figure 1D illustrates the schematic experimental scene. All subjects carried out experiments in their own habitual postures that remained consistent and could have a slight forward lean. The base of the experimental apparatus was fixed, and the seat backrest was lowered backward to maintain enough space for the human body. Therefore, no contact between the electrodes and the backrest was observed or detected in the experiment.

2.3 Acquisition details

For convenience in the discussion, the entire experimental procedure was described in terms of *supination* and *pronation*. During the experiment, subjects were asked to sit upright on the chair. The joystick moved back and forth along the X-axis, as depicted in Figure 1A. The blue ball (10 mm) and the black circle (20 mm) were initialized in the center and on the left/right sides, respectively (see Figure 1C); the joystick moved right along the $+X$-axis, while the blue ball synchronized with the right circle and *vice versa*.

Subjects were asked to maintain a certain distance between their elbows and thighs, thus exerting force with the upper limbs. They were required to place the blue ball precisely in the circle center as quickly as possible while maintaining accuracy. The blue ball reciprocated between the black circles, providing instant feedback on user operations while prioritizing accuracy. All participants performed 16 repetitions in each test to ensure that at least 14 were completed. The manipulation procedures and the corresponding sEMG data were recorded simultaneously.

Operating the rocker arm requires rotation of the forearm and the shoulder. The internal rotation of the shoulder mainly involves the anterior deltoid (DA), the pectoralis major (PM), the latissimus dorsi, and the teres minor (TM), while the external rotation involves the infraspinatus (INF), the teres minor (TM), and the posterior deltoid (DP). The energy of inner rotation is much higher than that of outer rotation (Ijiri et al., 2020). The biceps brachii (short/long head) can be used as a supinator muscle, where the biceps play a role in the activity of medium or high-power supination. The triceps brachii (long/lateral head) can be activated by the same length and neutralize the tendency of the biceps to bend the elbow (Soubeyrand et al., 2017). The pronator muscle consists of the pronator muscle and the pronator teres muscle. The brachioradialis (BRAD) is used primarily for elbow flexion but can also be used for pronation.

As exhibited in Figure 2, a DELSYS Trigno system was used to collect sEMG and acceleration data from 10 muscles of the upper arm and shoulder, including BRAD, short head of the biceps (BICS), long head of the biceps (BICL), PM, DA, long head of the triceps (TRIL), lateral head of the triceps (TRILA), INF, TM, and DP.

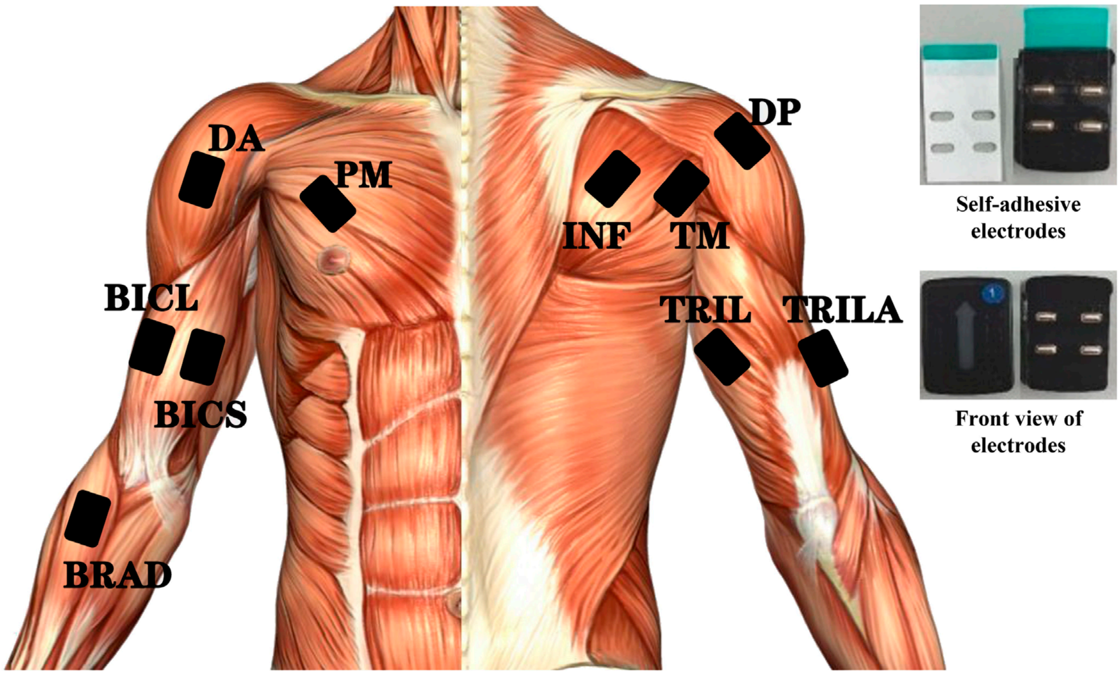

FIGURE 2
Placement and sensing muscles of sEMG sensors. Top right: self-adhesive electrodes. BRAD: brachioradialis; BICS: the short head of biceps; BICL: the long head of biceps; PM: pectoralis major; DA: anterior deltoid; TRIL: the long head of triceps; TRILA: the lateral head of triceps; INF: infraspinatus; TM: teres minor; DP: posterior deltoid.

The placement of the sEMG electrodes follows the guidelines for noninvasive electromyographic assessment of muscles, as shown in Figure 2, at a sampling rate of 1,249 Hz, while the acceleration was sampled at 149 Hz. The acquired signals were processed by *MATLAB* (R2017b, MathWorks Natick, United States).

3 Methodology

3.1 Processing of motion encoder data

The position data were derived from the motor encoder (see Figure 1C) and processed in the following steps to provide valid manipulation performance data.

- Normalization and median filtering: Normalized values within the $(-1, 1)$ interval of the raw data were filtered in the median to eliminate interference noise from abnormal burrs. The filter used 30 points and a window length of 150 ms.
- Indexing: Each successive data portion that contains all values (above a threshold T or below $-T$) was indexed, resulting in no fewer than 14 valid manipulation data partitions, as instantiated by the red dots in Figure 1B. T defaulted to 0.8 and was manually adjusted in a few cases to obtain the correct number of manipulation repetitions.
- Averaging and deviation: The position deviation (PD) is the deviation between the mean value of all actual positions on all trails, as instantiated by the green baselines in Figure 1B and the theoretical value of the black circle, indicating the precision of the position. The repeatability of the position (PR) represents the standard deviation of all actual positions. The extreme range of the position (PE) means the range of operation on each side.

3.2 Preprocessing of sEMG data

Before extracting muscle synergies, the acquired sEMG signal was pre-processed.

- A mean shift procedure eliminated baseline shifts caused by trial or subject electrode displacements.
- A Butterworth filter of 20–250 Hz removed high-frequency noise, with which motion artifacts were also significantly eliminated.
- Fixed band-stop filters removed the frequencies of 50 Hz and 150 Hz.
- A full-wave rectification flipped the negative EMG signal above the baseline to ensure positive values.
- A Butterworth filter of 20 Hz filtered the rectified signal to provide a smooth envelope (Kieliba et al., 2018).
- Min-Max scaling normalized the signal.

The simultaneous use of sEMG and ACC signals is a paradigm often adopted for human activity studies (Liu and Schultz, 2022; Liu. et al., 2023). A single extraction have been performed over the whole trips (Oliveira et al., 2014). The acceleration signal (ACC) was interpolated due to different sampling rates and filtered from median to segment the results of muscle synergy activation. Pre-processed signals $V_{m\times t}$ (m is the channel of muscles) are decomposed:

$$V_{m\times t} \cong W_{m\times n} \times H_{n\times t}, \tag{1}$$

where W is the basis matrix for muscle activation, n is the number of muscle synergies, and H holds the coefficients of the activation of the n muscle synergies. W_i $(i = 1, 2, \ldots, n)$ is a vector of the muscle synergy matrix, each element of which takes a value between 0 and 1. W_is, specifying the participation level of each muscle in each synergy and forming a muscle synergy, are activated by the activation coefficient matrix H_i, which represents the neural command of the CNS and determines the relative contribution of the muscle synergy matrix (Tang et al., 2017).

The reconstructed matrix $V'_{m\times t}$ is assumed to be

$$V'_{m\times t} = W_{m\times n} \times H_{n\times t}, \tag{2}$$

which is directly related to the value of n. Variability accounted for (VAF) is defined as

$$\mathrm{VAF} = 1 - \frac{\left(V_{m\times t} - V'_{m\times t}\right)^2}{V^2_{m\times t}} \tag{3}$$

which could be used to decide the value of n. VAF quantifies the percentage of muscle cooperativity extracted relative to the original EMG signal. The literature shows that the signal is considered successfully reconstructed when the VAF is greater than 90% or until the addition of synergy does not further increase the VAF by an amount greater than 5% (Clark et al., 2010). The number of muscle synergies $n \in [1, 10]$ is selected as the minimum number that could adequately reconstruct pre-processed signals in all trials (Tang et al., 2017).

3.3 Quantitative muscle synergy similarity

3.3.1 Muscle synergy spaces

SCI (synergy coordination index) is used to evaluate the size of the resulting synergy space, in other words, the coordination between the synergies utilized. In class $c \in$ Experts, Trainees, Newbies, the subject k's synergy matrix $M(c,k)$ and $H(c,k)$ are extracted from the sEMG signals of all the corresponding trials. Each segmented ACC signal for muscle synergy activation is regarded as a circle, interpolated to 100 data points based on time.

$$M(c,k) = \begin{bmatrix} W_1(c,k) \\ W_2(c,k) \\ \vdots \\ W_n(c,k). \end{bmatrix} \tag{4}$$

$$H(c,k) = \begin{bmatrix} H_1(c,k) \\ H_2(c,k) \\ \vdots \\ H_n(c,k) \end{bmatrix} = \left[\begin{bmatrix} H_{1_m}(c,k) \\ H_{2_m}(c,k) \\ \vdots \\ H_{n_m}(c,k) \end{bmatrix} \begin{bmatrix} H_{1_m}(c,k) \\ H_{2_m}(c,k) \\ \vdots \\ H_{n_m}(c,k) \end{bmatrix} \cdots \begin{bmatrix} H_{1_m}(c,k) \\ H_{2_m}(c,k) \\ \vdots \\ H_{n_m}(c,k) \end{bmatrix} \right]. \tag{5}$$

Only positive vector components have a cooperative space before the non-negative matrix decomposition for the estimation of W, Furthermore, the vectors W_i $(i = 1, 2, \ldots, n)$ are generally not orthogonal to each other. The size of the cooperative space depends on the relative angle of the vector W_i. To quantify the size of the collaborative space, we define SCI in terms of the inner product of W_i:

$$\mathrm{SCI}(c,k) = \frac{2}{n(n-1)} \sum_{i\neq j} W_i(c,k) \cdot W_j(c,k). \tag{6}$$

SCI values range from 0 to 1. An SCI of 1 means that all vectors W_i are identical, while 0 means that all vectors W_i are orthogonal. The larger the SCI, the smaller the synergy space. The median and standard deviation values of SCI describe the synergy space of the group.

3.3.2 Variability of muscle activation

In addition to computing the variability of W, an evaluation was also performed on the relationship between the variability of performance and the variability of synergy recruitment through the analysis of H, with the variability of the center of activity (CoA) in the form of standard deviation. The CoA of class c is defined as

$$\mathrm{CoA}(c) = \left[\mathrm{CoA}(c,1) \quad \mathrm{CoA}(c,2) \quad \cdots \quad \mathrm{CoA}(c,K_c)\right], \tag{7}$$

where K_c denotes the number of subjects in class c $(k = 1, 2, \ldots, K_c)$ and

$$\mathrm{CoA}(c,k) = \begin{bmatrix} \mathrm{CoA}_{H_1}(c,k) \\ \mathrm{CoA}_{H_2}(c,k) \\ \vdots \\ \mathrm{CoA}_{H_n}(c,k) \end{bmatrix}. \tag{8}$$

$\mathrm{CoA}_{H_i}(c,k)$ is calculated as the mean of 14 cycles cut from the ACC signal:

$$\mathrm{CoA}_{H_i}(c,k) = \frac{1}{14} \sum_{t=1}^{14} \left(\mathrm{CoA}_{H_{i_m}}(c,k)\right), \tag{9}$$

where the CoA during the mth part of $H_i(c,k)$, $\mathrm{CoA}_{H_{i_m}}(c,k)$, was calculated using circular statistics (Watson, 1982; Kibushi et al., 2018a) and plotted in polar coordinates with polar directions of 0°–360° and radii denoting the mean activities of the muscle:

$$\mathrm{CoA}_{H_{i_m}}(c,k) = tan^{-1} \frac{\sum_{t=1}^{100} \left(sin\,\theta \times H_{i_m}(t)\right)}{\sum_{t=1}^{100} \left(cos\,\theta \times H_{i_m}(t)\right)}. \tag{10}$$

$\mathrm{CoA}_{H_{i_m}}(c,k)$ was calculated as the vector angle, the first trigonometric moment that points to the center of mass of that circular distribution using the following formulas. Variability is reflected in the standard deviation (STD):

$$\mathrm{STD}_{H_{i_m}}(c,k) = \sqrt{\frac{1}{13} \sum_{i=1}^{14} \left(\mathrm{CoA}_{H_i}(c,k) - \overline{\mathrm{CoA}_{H_i}(c,k)}\right)^2}. \tag{11}$$

3.4 Statistical analysis

The descriptive statistics in this work involve mean values and standard deviations. Four one-way repeated analyses of variance (ANOVA) were performed on the synergy similarity

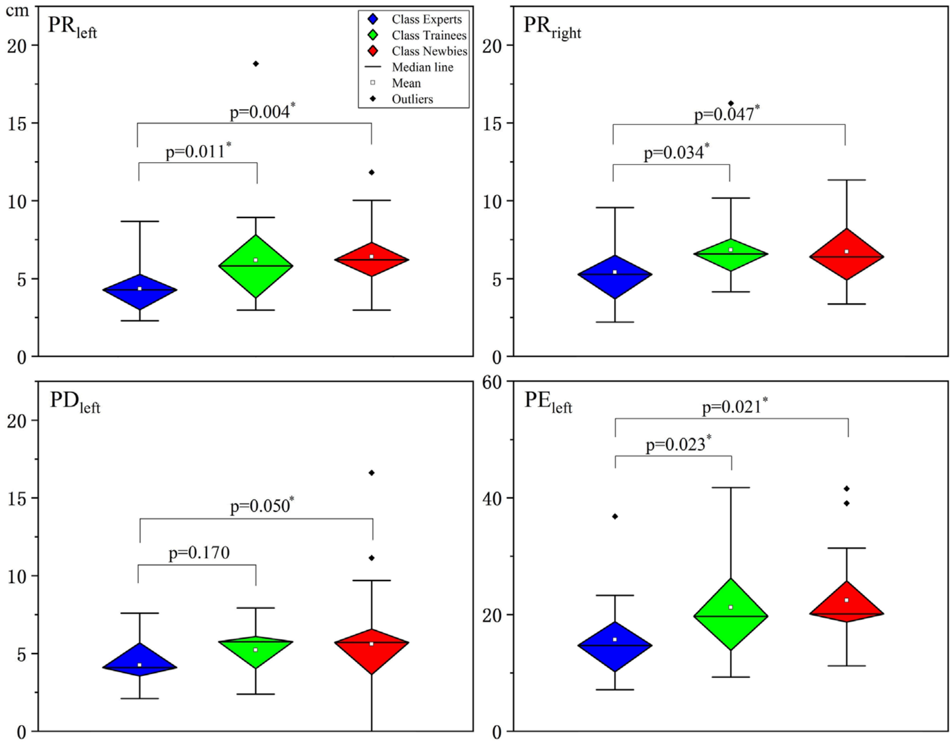

FIGURE 3
Significant results of the three classes' manipulation performance metrics analyzed by one-way analyses of variance (ANOVA). The vertical axes indicate the error value. All data passed the homogeneity of variance test. The asterisks indicate high significance ($p < 0.05$). PR: repeatability of the position; PD: position deviation; PE: extreme range of the position. Note that PE_{left} differs from the other three subplots in the vertical axis range.

and manipulation performance metrics (PR, PD, PE) among the three classes. In addition, the Pearson correlation coefficient r was analyzed through the manipulation performance (PR_{left}, PR_{right}, PD_{left}, PD_{right}, PE_{left}, and PE_{right}), SCI, $CoA_{H_{im}}$, and $STD_{H_{im}}$. The significance level was set as $p < 0.05$ for the statistical analysis implemented by *SPSS* (version 26.0, SPSS Inc. Chicago, IL, United States).

4 Results

4.1 Statistical analysis of manipulation performance metrics

The performance metrics for the manipulation of the three classes, PR, PD, and PE, are analyzed by one-way ANOVA in Figure 3, where all data passed the homogeneity of variance test. Significant differences were discovered in the values of PR_{left} ($F = 4.955$; $p = 0.010$), PR_{right} ($F = 2.735$; $p = 0.071$), and PE_{left} ($F = 3.415$; $p = 0.038$) between the three classes. Note that the asterisk indicates high significance ($p < 0.050$), as does the following. Comparing each pair of classes yields the following findings.

PR_{left} and PR_{right}

Compared to Experts, Trainees ($\Delta = -1.80 \pm 0.70$; $p = 0.011$) and Newbies ($\Delta = -2.07 \pm 0.70$; $p = 0.004$) have larger PR-left values; However, Figure 3(PR_{left}) shows no significant difference between Trainees and Newbies. The case of PR_{right} is similar: Trainees ($\Delta = -1.43 \pm 0.66$; $p = 0.034$) and Newbies ($\Delta = -1.32 \pm 0.62$; $p = 0.047$) are not significantly different, while both are larger than Experts, as diagnosed in Figure 3(PR_{right}).

PD_{left}

Newbies' PD_{left} ($\Delta = -1.35 \pm 0.70$; $p = 0.050$) is significantly larger than Experts' PD_{left}. At the same time, Trainees' PD_{left} did not show a significant difference ($\Delta = -0.96 \pm 0.70$; $p = 0.177$) compared to Newbies' and Experts' results, as reflected in Figure 3(PD_{left}).

PE_{left}

The relationship of the PE_{left} difference between Experts, Trainees ($\Delta = -6.95 \pm 2.90$; $p = 0.021$), and Newbies ($\Delta = -6.70 \pm 2.90$; $p = 0.023$) is the same as in the case of $PR_{left/right}$, which can be verified by Figure 3(PE_{left}).

4.2 Muscle synergy extraction

Figure 4 instantiates the non-negative matrix factorization (NMF) decomposition process of ten upper limb muscles. The basis matrix of muscle activation W and the activation coefficient matrix H are shown in Figure 4A.

Figure 4B evinces that the synergy W_1 between the muscle synergy vectors W mainly reflects the activation of BRAD, BICS, and BICL, whose synergies are greater than 0.3. W_2 primarily comprises DP, TM, INF, TRIL, TRILA, BICL, and BRAD. The dominant composition elements of W_3's are DA, PM, TRILA, and TRIL. The sEMG could be reconstructed by H and W, as manifested with the

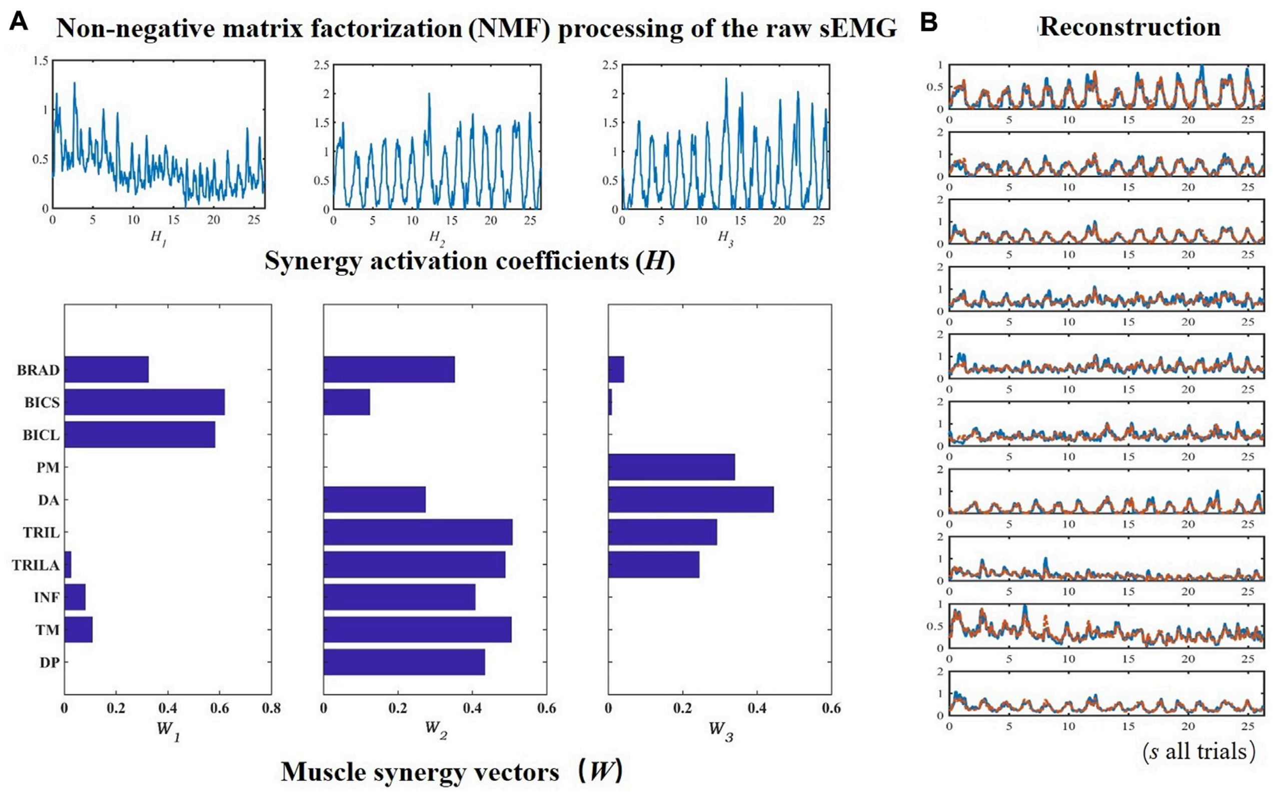

FIGURE 4
An example of extracting muscle synergies on ten upper limb muscles from Trainees. The sEMG data from ten upper limb muscles were processed by non-negative matrix factorization **(A)**, based on which synergy activation coefficients and muscle synergy vectors were used to reconstruct the sEMG **(B)**.

raw sEMG of ten muscles of the upper limbs in Figure 4B. Figure 5 revealed that after the number of synergies reaches three, the mean VAF of each class exceeds 95%.

4.3 Intraclass muscle synergy extratcion

The colorized bars in Figure 6 indicate different subjects in classes Experts (19 subjects), Trainees (30 subjects), and Newbies (28 subjects), and the black bars represent the mean values among each class for each muscle. PM has a low proportion in both INF W_1 and W_2, while DP, TM, INF, and TRIL exhibit low values in W_3, found in all three classes. Figure 7 embodies the Pearson correlation coefficients among the three classes for synergies W_1, W_2, and W_3. Figures 6, 7 show that the three classes have the same muscle synergies patterns, occurring in the same order.

4.4 Muscle synergy space

In addition to the three extracted muscle synergies elucidated in Figure 6, Figure 8 presents the SCI values of the three classes, where SCI(Experts) is 0.419 ± 0.138, SCI(Trainees) is 0.290 ± 0.070, and SCI(Newbies) is 0.270 ± 0.087, respectively. The SCI value of experts was significantly higher ($p = 0.000, p = 0.001$) than the values of trainees and newbies, between which no significant difference ($p = 0.608$) can be concluded.

4.5 The center of synergistic activities

Figure 9 exhibits the resulting CoA values and the interclass comparison. CoA_{H_1}, related to the flexion and extension of the elbow, shows no significant differences between the three classes. A similar case is CoA_{H_3}, recruited during the pronation of the forearm and shoulder. It should be noted that for CoA_{H_2}, recruited during supination of the forearm and shoulder, the activation of experts changed to an earlier phase ($p = 0.012, p = 0.011$).

Figure 10 provides a variability comparison between the three classes by STD values. Experts' intraclass variability of CoA_{H_3}, that is, standard deviation, is more pronounced than Trainees' ($p = 0.022$) and Newbies' ($p = 0.002$), while there is no significant difference between the latter two. As a point of comparison, in CoA_{H_1}, Experts' STD is more evident than Newbies' ($p = 0.005$), while an insignificant difference is shown between Experts and Trainees.

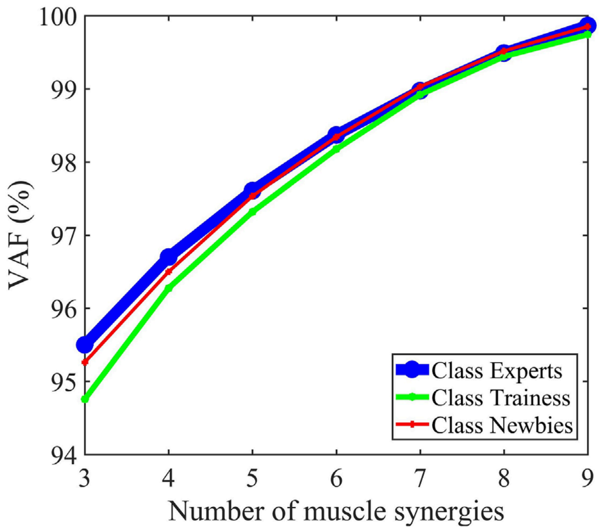

FIGURE 5
Mean percentage of variability accounted for (VAF) as a function describing the number of extracted synergies. Three synergies were identified for the three classes.

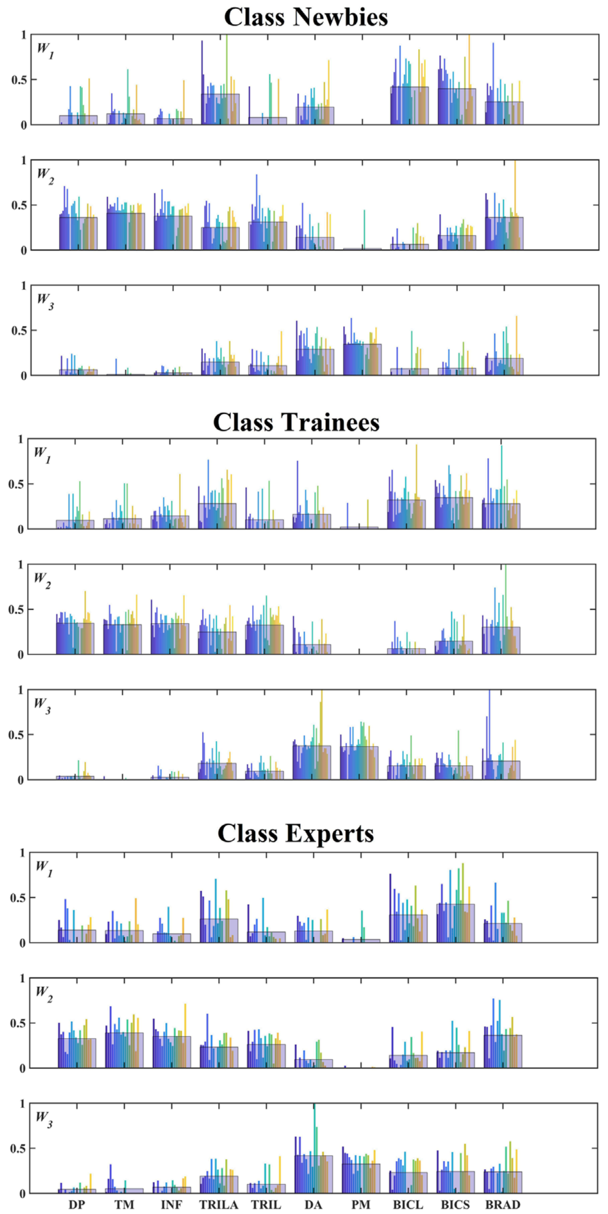

FIGURE 6
Composition of muscle synergies for the three classes. Three synergies were extracted from all subjects and matched among the classes. The colorized bars indicate different subjects. Note that the numbers of subjects in the three classes are 19 (Experts), 30 (Trainees), and 28 (Newbies). The black-bordered wide bar for each muscle indicates the mean value.

4.6 Correlation between manipulation performance and analytical metrics

Figure 11 details the Pearson correlation coefficients between manipulation performance metric and SCI/CoA/STD. In general, the results of Experts often show significant negative correlation values between the manipulation performance metrics $PR_{left}/PR_{right}/PE_{left}/PE_{right}$ and SCI/CoA.

4.6.1 Manipulation performance *versus* SCI

For Experts, PR_{left}, PR_{right}, and PE_{Left} in manipulation performance metrics show high negative correlations with SCI (−0.3823, −0.4128, and −0.3960), and PD_{left} has a positive, close to zero correlation with SCI (0.0096). On the contrary, newbies collectively have high positive correlations between $PR_{left}/PR_{right}/PD_{left}/PE_{Left}$ and SCI (0.3630, 0.4697, 0.4071, and 0.3397). The absolute correlations of the trainees are low (−0.005, −0.1142, −0.0739, −0.0405). The experimental results are consistent with the important muscle learning methodology (Alnajjar et al., 2013). Newbies' muscle status *W*) shows variability, which SCI reflects, whereas Experts tend to stabilize.

4.6.2 Manipulation performance *versus* CoA

Newbies show negative correlations between the CoA_{H_2}/CoA_{H_3} values and the four manipulation performances, of which the *r* values fell between −0.5718 and −0.1452, while the correlations between CoA_{H_1} and the four manipulation performances are positive. Trainees' manipulation-CoA_{H_1} correlations are significantly lower than Newbies, except for PR_{right}, though still all positive. Experts' manipulation-CoA_{H_1} correlations go the opposite, all negative ($r = -0.3200$–-0.1663). No general pattern was found in the remaining comparisons.

4.6.3 Manipulation performance *versus* STD (standard deviation of CoA)

The manipulation performance of Experts is positively correlated with the standard deviation of CoA in H_1–H_3 ($r =$ 0.0897–0.3609). Trainees' STD values are essentially similar to Experts', except that the PD_{left}-STD_{H_3} correlation is negative. For Newbies, the correlations are a mixture of positive and negative values, generally lower than Experts' and Trainees' values, except for two PD_{left}-related correlations.

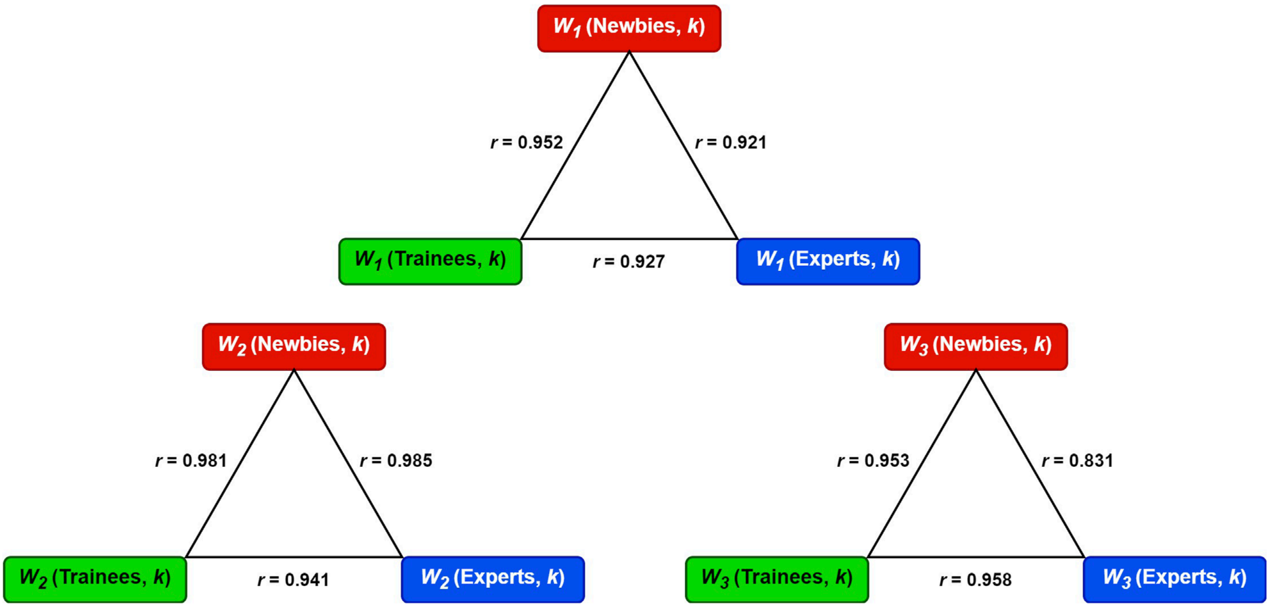

FIGURE 7
The Pearson correlation coefficients (r) among the three classes for synergies W_1, W_2, and W_3.

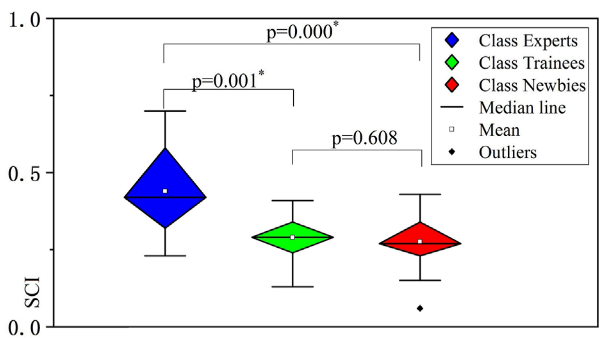

FIGURE 8
Significance results of the three classes' spaces of muscle synergies analyzed by nonparametric test. The vertical axes indicate the synergy coordination index (SCI) values. The asterisks indicate high significance ($p < 0.05$).

5 Discussion

Variability is a natural component of human movement. The notion of muscle synergy variability contains a lower-dimensional synergy space and time-dependent variables. Oriented towards better operation, variability affects the performance of motor tasks. As muscle synergy spaces are gradually optimized, movement performance will improve.

Based on the muscle synergy analysis of joystick manipulation in three classes of maneuvering experience, this study reveals the correlation between manipulation performance and muscle synergy variability, reflected by SCI and the standard deviation of CoA.

5.1 Structure of muscle synergies

The synergy structure corresponds to the synergy number, of which the patterns are related to the task. Consistency is demonstrated in different individuals. In this study, three muscle synergies were investigated, consistent with previous studies. Three to five muscles work together in the three-dimensional force generation of the upper extremity (Coscia et al., 2014). Four to five synergies can reconstruct the activation patterns of up to 19 muscles recorded during point-to-point reaching movements or forearm postures with different loads (d'Avella et al., 2003). In comparison, three synergies are sufficient to reconstruct multijoint movements performed in the horizontal plane (Roh et al., 2012). The consistency of the synergy number could be affected by individual differences such as muscle size, strength, subcutaneous fat thickness, and measurement electrode position, which is also in line with previous work. In addition to the physiological factors mentioned above, the synergy number may also be influenced by sEMG pre-processing. The variance accounted for (VAF) criterion is sensitive to the low-pass cut-off frequency, with higher cut-offs resulting in lower VAF (Kieliba et al., 2018).

The pattern of muscle synergies studied in this work is qualitatively similar to those underlying three-dimensional force generation (Roh et al., 2012). Their flexion pattern consisting of BRAD and BI with DP activity is similar to W_1 identified in our experiments, while their flexion pattern comprised of TRILA, TRIL, and PM is similar to the W_3 (see Figure 4). Figure 6 exhibits that neuromuscular strategies remain the same in the three classes, interpreting that joystick manipulation experience does not cause variations in the pattern of muscle synergies. Previous studies on lifting or shoulder movement had similar results: Muscle synergy is consistent between experts and normal

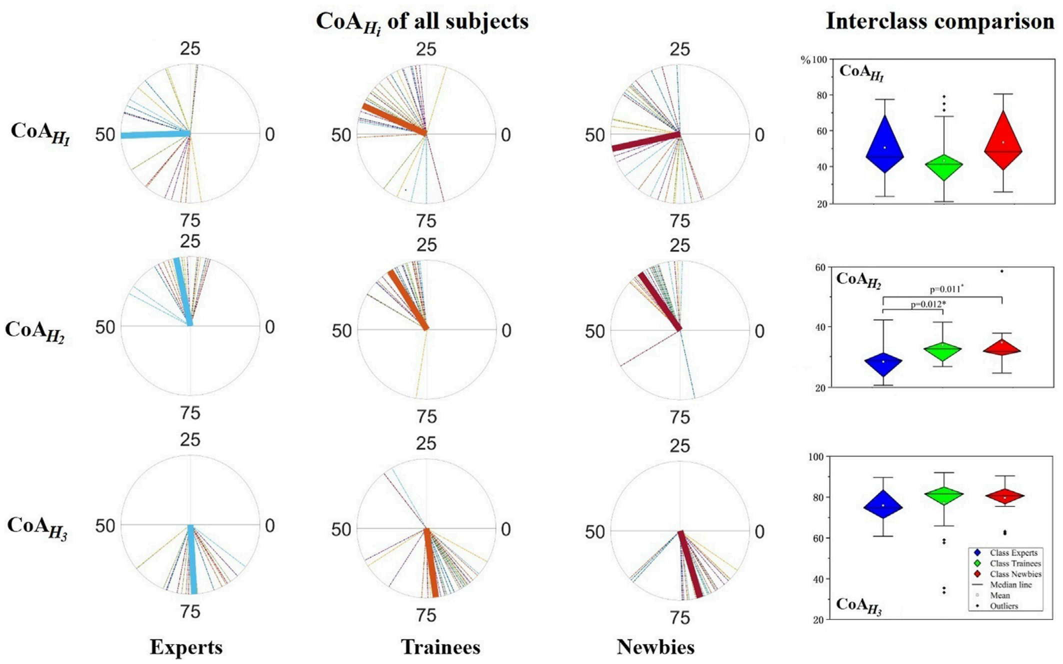

FIGURE 9
Center of activity (CoA) analysis for muscle synergy. Left: CoA$_{H_i}$ among subjects across the whole experiment, where the averaged CoA$_{H_i}$ values of subjects lie in the polar coordinate, and the polar directions denote the relative time over each trial cycle with clockwise time progression; Right: significance results of the three classes' CoA$_{H_i}$s analyzed by nonparametric test, where the vertical axes indicate CoA$_{H_i}$ values. The asterisks indicate high significance (p <0.05).

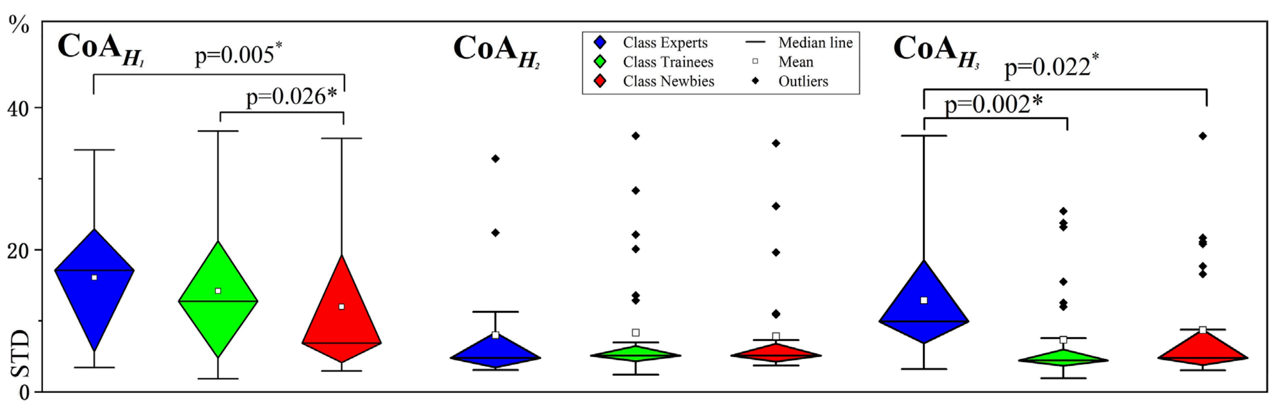

FIGURE 10
Variability analysis for muscle synergy. The vertical axes indicate standard deviation (STD) values. The asterisks indicate high significance (p < 0.05).

people during lifting (Zhao et al., 2021) or shoulder movement (Turpin et al., 2020). In general, the structure of the muscle synergy was influenced by biomechanics and task constraints (Roh et al., 2012).

5.2 Muscle synergy variability

Muscle synergy spaces vary with training. Previous studies have suggested that muscle synergies may be formed by adaptive processes related to the individual's experience. The activity of the primary motor cortex is adapted with training, associated with changes in either the amplitude of activation or the composition of the correlated synergy. As a result of maintaining balance, the body will achieve a stable pattern of muscle synergy and variable activation after training (Alnajjar et al., 2013). CNS searches for the most appropriate synergy space region, evoking various strategies by tuning W. In such a search stage, low stability of W is observed. The modulation of the muscle synergy composition will develop to a stable state during skill learning (Kargo and Nitz, 2003)

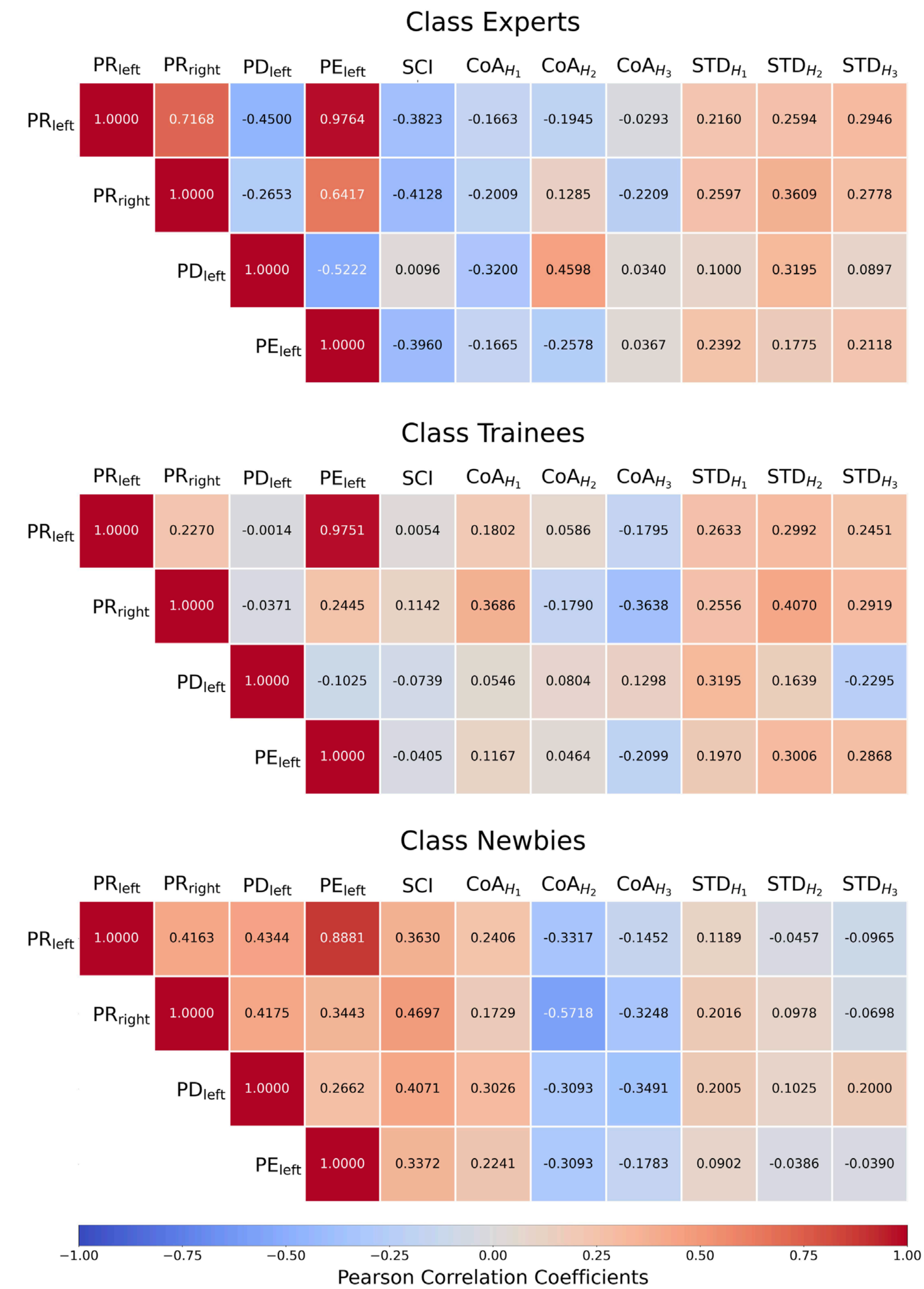

FIGURE 11
Three classes' heatmaps of the Pearson correlation coefficients between manipulation performance metrics and synergy coordination index (SCI)/the center of activity (CoA)/CoA's standard deviation (STD).

(see Figure 8). Experts showed higher SCI, representing smaller muscle synergy spaces and more excellent stability. The relatively concentrated muscle synergy spaces observed among experts should be explained by their long-term maneuvering experience, which enables their CNS to create optimal sets of efficient behaviors by optimizing the size of the synergy space in the appropriate region (Alnajjar et al., 2013).

In addition to space properties, the variability of temporal activation is also affected by training. Previous studies have shown that CoA changes with walking speed (Kibushi et al., 2018b), load (Labini et al., 2011; Sylos-Labini et al., 2014), and cerebellar ataxia (Martino et al., 2014), among others. This study reveals a significant shift in CoA_{H_2} between Experts and other subjects (see Figure 9). Literature showed that during the bench press, experts' variability of the coactivation coefficient is higher than normal subjects', while the muscle coactivation vector shows low variability (Kristiansen et al., 2015). In our study, Experts showed higher variability (STD) in CoA_{H_3}, which contributed to the pronation of the forearm and shoulder to acquire better position accuracy of the left position (see Figure 10): Moreover, Experts' variability (STD) in CoA_{H_1} is also more obvious. After learning, W becomes more stable in a particular region and smaller, and the constraint on the variability of H gradually eases (Alnajjar et al., 2013).

5.3 Significant negative correlation between manipulation performance metrics and muscle synergy variability

A smaller synergy space is often used for a better performance, which can answer why the coordinated movements respond to disturbance (Alnajjar and Shimoda, 2017). In this study, Figure 11 evinces that the stability of the muscle synergy space is positively correlated with the manipulating error in the novice stage (Newbies) and negatively correlated in the veteran stage (Experts). On Experts, the smaller the synergy space, the better the performance. In contrast, Newbies are in the search stage of W, so the larger the synergy space, the better the performance.

The CNS learning model suggests that the CNS attempts to reduce the degrees of freedom of the resulting motions by restricting the variability of the synergy coefficient matrix H) during the search stage of W and simplifies the handling of its high temporal variability (Alnajjar et al., 2013). Therefore, Newbies' correlation between CoA and manipulation performance is more significant than that of the other two classes. In the Experts and Trainees classes, no significant correlation is detected between CoA and manipulation performance. Consistent with previous studies, manipulation performance can reflect proficiency degree: Once a certain proficiency level is reached, the body's restrictions on muscle activation will be lifted, endowing a complete utilization of the body's potency (i.e., W variability decreases, H variability increases) (Alnajjar et al., 2013).

Expert's and Trainees' variability (STD) of CoA_{H_1} and CoA_{H_3} is more pronounced than Newbies' (see Figure 10). Although muscle activation variability decreased with increasing training degrees interclass-wise, a positive correlation can be found between variability and manipulation performance intraclass-wise. The intraclass analysis discloses that correlation values increase as experience improves and that the significance levels of the three classes are low. Research has ascertained that many compensatory solutions exist for different motor tasks and that various solutions can generate the same movement (Ting and Macpherson, 2005; McKay and Ting, 2008). The CNS adjusts motor impedance by activating antagonistic muscles to minimize the interference effect caused by load, thus improving movement accuracy (Burdet et al., 2001; Franklin et al., 2007).

6 Conclusion

This article analyses manipulation performance and muscle synergy in three classes of subjects with different maneuvering experiences. Different levels of experience and training lead to apparent differences in the space size of W and the variability of H. The precision of the manipulation is related to the variability of muscle synergy. Long-term training compresses muscle synergy space, which enhances muscle manipulation performance. Experts have significantly higher muscle synergy space stability and activation variability than the other two classes. Experts' and Trainees' correlation values between manipulation performance and the standard deviation of CoA are more significant than Newbies'.

This work has designed experiments, grouped 77 subjects, collected multimodal data, and conducted various experimental analyses, all of which have informed subsequent research. Our findings and validations are looked to for progressive practical applications that can provide important references for the development of software to aid pilot training, such as tips and training procedures to reduce manipulation errors as well as training result analysis and evaluation, which can improve efficiency, save costs, and potentially increase the safety of flight.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors upon request, without undue reservation, except for commercial use.

Ethics statement

The studies involving humans were approved by Ethics Committee, Fudan 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

LC: Conceptualization, Funding acquisition, Methodology, Software, Writing–original draft, Visualization. SY: Data curation, Writing–original draft, Writing–review and editing. CO: Data curation, Writing–review and editing. TZ: Investigation, Writing–review and editing. JZ: Formal Analysis, Writing–review and editing. LC: Formal Analysis, Writing–review and editing. XM: Formal Analysis, Supervision, Validation, Writing–review and editing. HL: Formal Analysis, Funding acquisition, Supervision, Writing–review and editing, Validation, Visualization, Writing–original draft.

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Conflict of interest

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

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Effects of different plyometric training frequencies on physical performance in youth male volleyball players: a randomized trial

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This study aimed to analyze the effect of plyometric training (PT) at different frequencies on jump performance, running sprint speed, and service speed in youth male volleyball players. The participants were randomly assigned to one PT session per week (Experimental Group 1, EG1, $n = 15$), two PT sessions per week (Experimental Group 2, EG2, $n = 14$), and a control group (CG, $n = 13$). The total weekly jumping ranged between 98 and 196 jumps (equalized between, EG1 and, EG2). The assessments performed were squat jump (SJ), countermovement jump (CMJ), CMJ-arms, drop jump (DJ), 5-m sprint, 10-m sprint, and service speed. The intragroup comparisons showed that, EG1 significantly ($p < 0.001$) improved SJ ($\Delta = 12.74\%$; $d = 1.30$), CMJ ($\Delta = 11.94\%$; $d = 1.71$), CMJ-arms ($\Delta = 12.02\%$; $d = 1.47$), DJ ($\Delta = 10.93\%$; $d = 1.30$), 5-m sprint ($\Delta = -4.61\%$; $d = 0.29$), 10-m sprint ($\Delta = -3.95\%$; $d = 0.40$) and service speed ($\Delta = 8.17\%$; $d = 1.53$). Similarly, EG2 significantly ($p^{<}$ 0.001) improved SJ ($\Delta = 11.52\%$; $d = 1.25$), CMJ ($\Delta = 11.29\%$; $d = 1.38$), CMJ-arms ($\Delta = 11.42\%$; $d = 1.26$), DJ ($\Delta = 13.90\%$; $d = 2.17$), 5-m sprint ($\Delta = -3.85\%$; $d = 0.25$), 10-m sprint ($\Delta = -2.73\%$; $d = 0.25$) and service speed ($\Delta = 6.77\%$; $d = 1.44$). The CG significantly ($p < 0.05$) improved SJ ($\Delta = 2.68$; $d = 0.28$), CMJ-arms ($\Delta = 2.30$; $d = 0.35$), 5-m sprint ($\Delta = -1.27$; $d = 0.10$) and service speed ($\Delta = 1.42$; $d = 0.30$). Intergroup comparisons revealed significantly greater improvements in all variables ($p < 0.001$) in, EG1 and, EG2 concerning to

CG. However, no significant differences were found between, EG1 and, EG2. A moderate weekly PT volume, distributed in one or two sessions per week, seems equally effective.

KEYWORDS

muscle power, strength, plyometric exercise, sports, young, physical fitness

1 Introduction

Volleyball is a sport of multidirectional movements that requires between 250 and 300 explosive actions, which occur repetitively during a match (Tramel et al., 2019). Among the most recurrent technical actions during the match are serving, setting, attacking, blocking (Pawlik et al., 2020), jumping, and ball spiking (Hernández Martínez, 2022). During a match, between 77% and 90% of jumps are executed, where outside attackers and middle blockers execute between 12 and 23 jumps per set (Lima et al., 2019), while ball spikes can reach >40,000 per year in elite players (Sarvestan et al., 2020). Therefore, it is important to implement training programs that enhance physical performance, focusing primarily on high-intensity actions such as jumping and serving (Oliveira et al., 2020; Ramirez-Campillo et al., 2020). Therefore, it is important to monitor the physical performance of volleyball players during competition (Sousa et al., 2023). This is achieved through the measurement and permanent monitoring of athlete's performance and physical fitness (Sousa et al., 2023).

Plyometric training (PT) effectively improves vertical jump height and ball spiking in volleyball players (Silva et al., 2019; Ramirez-Campillo et al., 2021). In a study by Idrizovic et al. (2018) in youth female volleyball players (mean aged of 16.6 years), significant improvements in the countermovement jump (CMJ) of 16.9% ($p < 0.05$; $\eta^2 = 0.29$; *large effect*) were detected in favor of intervened with PT compared to a control group that performed a traditional training program. While Mroczek et al. (2019) detected significant improvements in the squat jump (SJ) test of 2.9% ($p = 0.03$; *moderate effect*) and 4.2% in CMJ ($p = 0.00$; *large effect*) following a 6-week PT intervention concerning the control group (no PT) in male high school volleyball players. In the study by Mackala et al. (2020), a PT intervention was carried out for 4 weeks in female high school volleyball players showing significant improvements in the drop jump (DJ) test of 7% ($p = 0.00$; *small effect*) compared to the control group. Similarly, an upper limbs-specific PT intervention performed for 8 weeks in adult volleyball players showed significant improvements ($p < 0.001$) in ball spiking by 3.8% compared to the control group (Valades Cerrato et al., 2018).

While PT at different periodizations (between 4 and 12 weeks) has been shown to positively affect physical performance in volleyball players (Idrizovic et al., 2018; Valades Cerrato et al., 2018), PT at different training frequencies (≤2 vs. >2 sessions per week) has been reported to lead to a significant improvement in vertical jump height in volleyball players (Ramirez-Campillo et al., 2021). In a systematic review by Silva et al. (2019) in volleyball players, they detected improvements located between 16.9% and 27.6% in CMJ and 5.2%–7.6% in 20-m sprint using interventions between 6 and 12 weeks of PT with a frequency of 2 and 3 sessions per week. In the study by Gjinovci et al. (2017), improvements of 8% in 20-m sprint and 27% in CMJ were reported by PT in a 12-week intervention with a frequency of 2 sessions per week. While Idrizovic et al. (2018), detected significant improvements by 16.9% in CMJ through a 12-week PT intervention with a frequency of 1 session per week in youth volleyball players. In contrast, Ramirez-Campillo et al. (2018), in a randomized controlled trial, compared different PT frequencies (1 session vs. 2 sessions per week) in amateur soccer players, reporting significant improvements in CMJ by 10.5% vs. 9.8% in DJ by 13.6% vs. 12.9% and in 15-m sprint by 8.2% vs. 9.6% compared to a control group. However, no significant differences were found when comparing PT groups. In another study conducted by Bouguezzi et al. (2020) in prepubertal soccer players comparing different PT frequencies (1 session vs. 2 sessions per week) without a control group, improvements were detected in both groups SJ 25.82% vs. 27.62%, in CMJ 23.41% vs. 20.04%, in 5-m sprint by −2.13% vs. −4.77% and in 10-m sprint by −1.10% vs. −2.13%. However, no significant differences were found when comparing PT groups.

Considering that PT at different frequencies both 1 and 2 sessions lead to significant improvements in physical performance in volleyball players (Gjinovci et al., 2017; Idrizovic et al., 2018; Ramirez-Campillo et al., 2020), it is necessary to identify the optimal dosage of jumps according to age, maturity and competitive level of the athletes to reduce the risk of injury (Ramirez-Campillo et al., 2023). To the best of our knowledge, only the effect of PT at different frequencies has been analyzed in a randomized controlled trial in amateur soccer players (Ramirez-Campillo et al., 2018). Therefore, the present study aimed to analyze the effect of PT at different frequencies on jump performance (SJ, CMJ, CMJ-arms, and DJ), running sprint speed (5-m sprint and 10-m sprint), and service speed in youth male volleyball players.

2 Methods

2.1 Study design

A single-blind, randomized, controlled trial of three parallel groups was conducted to compare the effects of 8 weeks of PT during the pre-season in youth male volleyball players. The experimental groups carried out PT sessions for 30 min, experimental group 1 (EG1) carried out one session per week of PT; experimental group 2 (EG2) carried out 2 training sessions per week, and the control group (CG) carried out a traditional volleyball training consisting of displacement exercises in different positions along with passing and spiking. Physical performance assessments were performed pre- and post-intervention consisting of SJ, CMJ, CMJ-arms, DJ, 5-m sprint, 10-m sprint, and service speed with both hands. One week before the start of the study, two familiarization sessions of 30 min each were

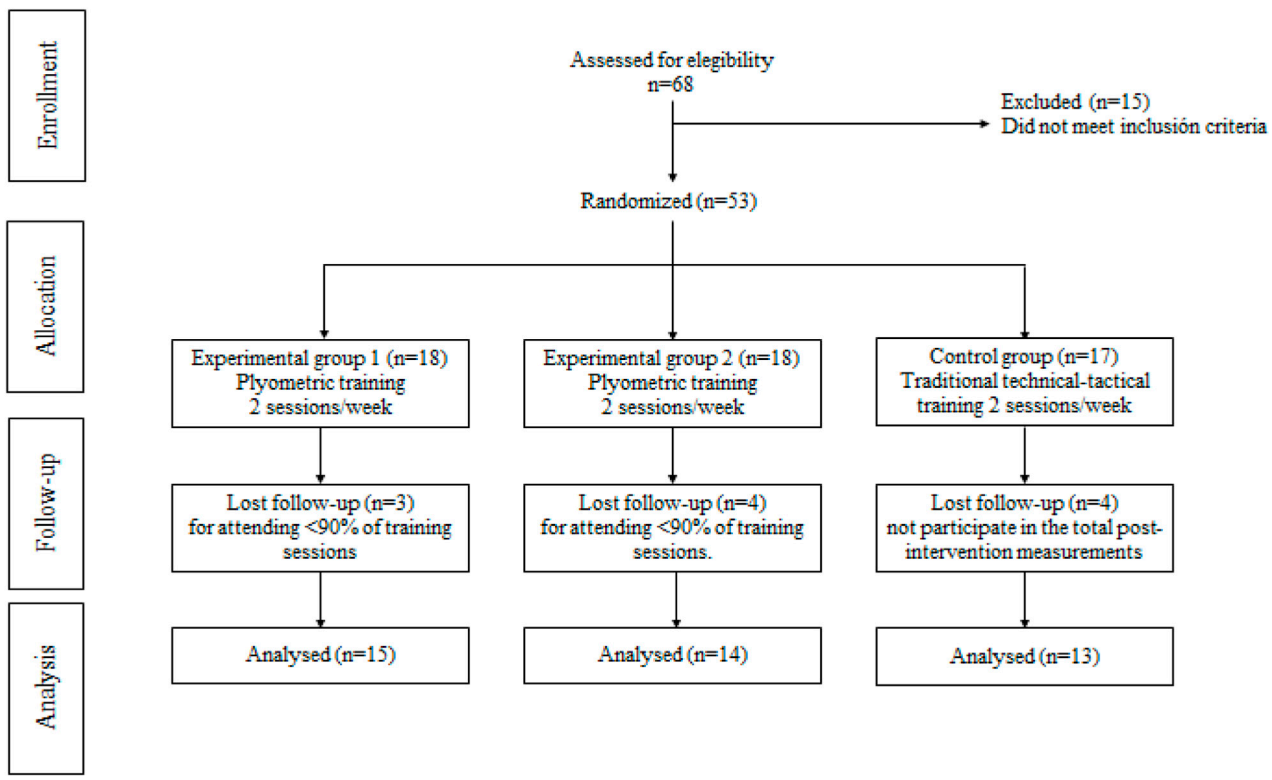


FIGURE 1
Flowchart of the recruitment process.

conducted to explain and perform the test and training procedures to all participants to reduce possible learning effects.

2.2 Participants

According to a previous study, the sample size calculation indicated that the ideal number of participants per group is 12 (Ramirez-Campillo et al., 2018). An alpha level of 0.05 was considered with a power of 80% with an effect size of d = 0.20. GPower software (version 3.1.9.6, Franz Faul, University Kiel, Germany) was used to calculate statistical power (Kang, 2021). The inclusion criteria were: *i*) have been practicing competitively for more than 6 months; *ii*) enrolled in federated clubs; *iii*) not having injuries that prevented them from performing the PT and physical performance assessments; *iv*) having the appropriate sports clothing to carry out the procedures; *v*) not being training in another club or national team attached to the existing one; *vi*) not being in competitions on the same days in which the PT were performed; *vii*) no systematic experience in PT during the last 6 months (*viii*) absence of any surgery of the lower and upper limbs in the last 2 years. Exclusion criteria were considered: *i*) those who presented cardiovascular or musculoskeletal pathologies that prevented them from performing the PT sessions; *ii*) not participating in all PT sessions. Sixty-eight youth male volleyball players from the Osorno, Chile, school league were recruited. Fifteen participants were excluded because they did not meet the inclusion criteria. Subsequently, 53 participants (aged = 14.7 ± 0.26 years, body mass = 58.1 ± 1.47 kg, bipedal height = 1.66 ± 3.66 m, body mass index [BMI] = 20.6 ± 1.15 kg/m^2) were randomly assigned to: EG1 (n = 18), EG2 (n = 18), CG (n = 17). Eleven participants were excluded because: 4 did not participate in the total post-intervention measurements, and 7 did not complete ≥90% of the interventions. Therefore, the final sample included 15 participants in, EG1, 14 in, EG2, and 13 CG, who were considered for the subsequent analyses. No injuries were reported during the performance of the PT sessions and physical performance assessments. The sample selection process is presented in Figure 1 and the general characteristics of the sample in Table 1.

All participants and their legal guardians accepted the criteria for using and handling the data by providing assent and signed informed consent, authorizing the use of the information for scientific purposes. The research protocol was reviewed and approved by the Scientific Ethics Committee of the Universidad Autónoma de Chile (approval number: N° 126-18) and developed following the guidelines of the Helsinki Declaration statement for studies with human beings.

2.3 Anthropometric measurements

Bipedal height was measured using the Frankfort plane in a horizontal position, with a tape measure (Bodymeter 206, SECA, Germany; accuracy 0.1 cm) attached to the wall. Body mass was measured with an electronic scale (Omron HBF 514: accuracy 0.1 kg), while BMI was calculated by dividing body mass by

TABLE 1 Baseline characteristics of the sample.

	EG1 (*n* = 15)	EG2 (*n* = 14)	CG (*n* = 13)
Age (years)	14.6 ± 0.89	14.5 ± 0.57	15.0 ± 0.85
Body mass (kg)	57.4 ± 12.0	57.1 ± 6.87	59.8 ± 14.8
Height m)	1.69 ± 0.11	1.68 ± 0.07	1.62 ± 0.08
BMI (kg/m^2)	19.7 ± 1.82	20.2 ± 1.82	21.9 ± 5.69
Experience (years)	4.65 ± 2.34	4.34 ± 2.12	4.78 ± 3.42
Training per week (days)	3	3	3
Training per week (min)	90	90	90
Competitive level	youth team	youth team	youth team

Data were presented as mean and (±) standard deviation; CG: control group; E. G1: Experimental Group 1; EG2: Experimental Group 2; kg: kilograms; m: meters; BMI: body mass index.

bipedal height squared (kg/m^2). All measurements were performed according to the recommendations of the International Society for the Advances in Kinanthropometry (ISAK) (Marfell-Jones et al., 2012).

2.4 Jump performance

All jumping tests were performed according to previous recommendations (Bosco et al., 1983). For the CMJ, volleyball players executed maximal effort jumps on an Ergojump® Globus mobile contact platform (ErgoTest, Codogne, Italy) with arms over the iliac crests. Take-off and landing were standardized at the exact location, and players executed full knee and ankle extensions during the flight phase. The CMJ arms were performed similarly to the CMJ, except the upper limbs had freedom of action. For the SJ, the players stepped on the contact platform with arms over the iliac crest and a semi-flexed knee position at a 90° angle and the "stop" signal; the player maintained this posterior position, performing the maximum jump. The take-off and landing were standardized at the exact location, and the players executed full knee and ankle extensions during the flight phase. In the DJ test, participants were instructed to minimize ground contact time (<250 ms) after descending from a 20-cm box (Ramirez-Campillo et al., 2021). The best of three jumps (with a 1-min rest between each attempt) was recorded in CMJ, CMJ-arms, SJ, and DJ.

2.5 Running sprint speed

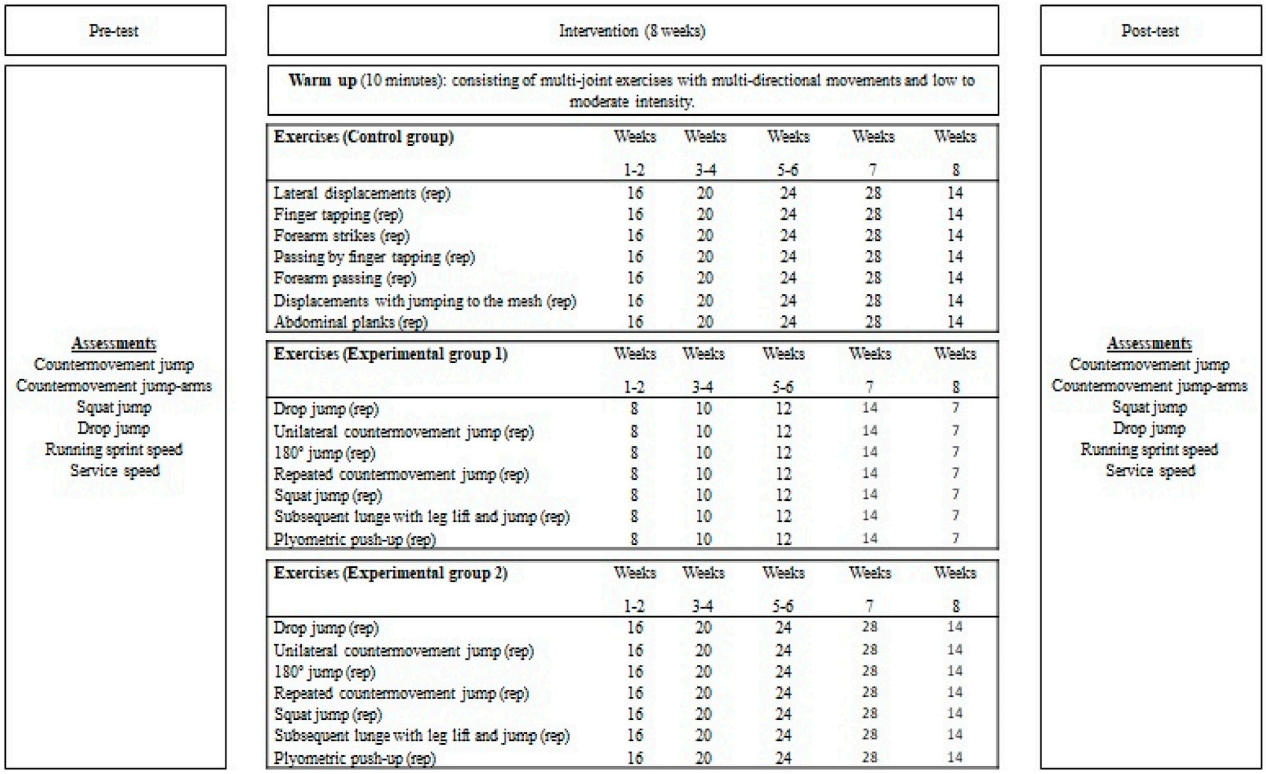
Sprint time was assessed to an accuracy of 0.01 s using Brower® Timing System single-beam timing gates (Salt Lake City, Utah, United States). Participants started by positioning themselves behind the starting line. The sprint began when the participants started the event, automatically triggering the timing. Timing gates were placed at the start (0.3 m in front of the participant) at 5-m sprint and 10-m sprint. They were placed ~0.7 m above the ground (approximately hip height). This system allows trunk movement to be captured trunk movement rather than the false triggering of a limb. Three sprints were performed, recording the best of the three sprints with 1 minute rest between each attempt (Sebastia-Amat et al., 2020).

2.6 Service speed

The youth volleyball players performed a service-like action to measure the ball's maximum speed (km/h). The players used the tennis serve technique and were placed 2 m behind the end line of the court for the execution; the evaluator was located behind the end line of the opposing field, 20 m from the athlete, and pointed the radar gun for measurement to the participant. It was requested to serve with the maximum possible force to reach the opposite court's interior. The serve was executed without jumps, given its influence on speed, and the ball could not touch the net. The players were instructed to serve inside the volleyball court, with the measurements of 9 m wide by 18 m long and a net height in the center of the field at 2.43 m. According to the International Volleyball Federation (FIV) regulations, a volleyball ball between 65 and 67 cm (Mikasa V200W) with an inflation pressure of 0.3–0.325 km/cm^2 was used. Maximum speed was measured with a radar gun (Speed Gun SR3600; Sports Radar®, Homosassa, Florida, United States) with a pressure of 3%/1 Mile per hour (MPH) or 1 Kilometer per hour (Km/h) (Telles et al., 2021). Three attempts were carried out, recording the best of the three, with a minimum rest of 1 minute between each (Valades et al., 2016).

2.7 Training program

A traditional volleyball training session consists of three parts: *i*) analytical: technical work, individual, doubles, finger, and forearm shots; *ii*) synthetic: physical-technical work, passing, attacking, and blocking; and *iii*) global: controlled games. The training program was performed during the pre-season. The exercises, sets, repetitions, and progressions per week are detailed in Figure 2. The CG continued their traditional volleyball training (i.e., mainly technical-tactical exercises, displacements in different directions, passes by finger and forearm strikes, ball spikes, and exercises to prevent injuries). The design of the PT intervention was based on the records in a previous modified study (Ramirez-Campillo et al., 2018). Unilateral, bilateral, cyclic (i.e., repeated), acyclic (i.e., non-repetitive), vertical, horizontal, and twisting jumping exercises were included, in addition to fast (<250 ms foot-to-ground contact time) and slow (≥250 ms ground contact time) muscle contractions of the stretch-shortening cycle, with a strong


Pre-test

Assessments
Countermovement jump
Countermovement jump-arms
Squat jump
Drop jump
Running sprint speed
Service speed

Intervention (8 weeks)

Warm up (10 minutes): consisting of multi-joint exercises with multi-directional movements and low to moderate intensity.

Exercises (Control group)	Weeks 1-2	Weeks 3-4	Weeks 5-6	Weeks 7	Weeks 8
Lateral displacements (rep)	16	20	24	28	14
Finger tapping (rep)	16	20	24	28	14
Forearm strikes (rep)	16	20	24	28	14
Passing by finger tapping (rep)	16	20	24	28	14
Forearm passing (rep)	16	20	24	28	14
Displacements with jumping to the mesh (rep)	16	20	24	28	14
Abdominal planks (rep)	16	20	24	28	14

Exercises (Experimental group 1)	Weeks 1-2	Weeks 3-4	Weeks 5-6	Weeks 7	Weeks 8
Drop jump (rep)	8	10	12	14	7
Unilateral countermovement jump (rep)	8	10	12	14	7
180° jump (rep)	8	10	12	14	7
Repeated countermovement jump (rep)	8	10	12	14	7
Squat jump (rep)	8	10	12	14	7
Subsequent lunge with leg lift and jump (rep)	8	10	12	14	7
Plyometric push-up (rep)	8	10	12	14	7

Exercises (Experimental group 2)	Weeks 1-2	Weeks 3-4	Weeks 5-6	Weeks 7	Weeks 8
Drop jump (rep)	16	20	24	28	14
Unilateral countermovement jump (rep)	16	20	24	28	14
180° jump (rep)	16	20	24	28	14
Repeated countermovement jump (rep)	16	20	24	28	14
Squat jump (rep)	16	20	24	28	14
Subsequent lunge with leg lift and jump (rep)	16	20	24	28	14
Plyometric push-up (rep)	16	20	24	28	14

Post-test

Assessments
Countermovement jump
Countermovement jump-arms
Squat jump
Drop jump
Running sprint speed
Service speed

FIGURE 2
Assessments and training program.

emphasis on PT landing and cushioning technique, using a medium hardness surface with PVC flooring (polyurethane) for the indoor gymnasiums. The PT was not added to traditional volleyball training but was performed immediately after the warm-up in replacement of some low to moderate-intensity volleyball technical-tactical exercises measured with the ten-point rating of perceived exertion (RPE) (Borg, 1982). Therefore, PT was conducted within the regular 90-min training period in which, EG1 conducted one PT session per week, and, EG2 conducted two PT sessions per week during the 8-week intervention period. The volume of total weekly jumping was equalized between, EG1 and, EG2, starting with 112 jumps between weeks 1–2, 140 jumps between weeks 3–4, 168 jumps between weeks 5–6, 196 jumps in week 7 and, 98 jumps for week 8. Each PT session included a set of 7 different jumping exercises, with 7–14 repetitions per set for, EG1 and 14 to 28 repetitions per set for, EG2. The jumping exercises were: *i*) DJ; *ii*) unilateral CMJ; *iii*) 180° jumps; *iv*) repeated CMJ; *v*) SJ; *vi*) reverse lunge to single leg skip jump; *vii*) plyometric push-up. During the DJ exercise, players were instructed to maximize the relationship between vertical height and ground contact time. It should be noted that players used individualized box heights; this was individualized by calculating the optimum reactive force index (i.e., from 5 to 35 cm) (Ramirez-Campillo et al., 2018).

The exercises were ordered and randomized each week, varying the training and avoiding possible monotony. The training volume was progressively increased from the first week to the seventh training week. During the eighth week, an adjustment strategy in terms of training volume was applied. During all training sessions, a researcher-participant ratio of 1:7 was applied, and special attention was paid to the technical execution of jumps. All PT sessions lasted between 12 and 25 min. The training sessions for, EG2 were twice as long as those for, EG1 due to the higher training volume per session. However, the total number of jumps performed during the entire training intervention (i.e., 8 weeks) was similar for both groups because the number of jumps performed during one session was equally distributed over two sessions. Both PT groups trained simultaneously (from 18:30 to 20:00 h), with the same rest intervals between exercise sets (i.e., 30–60 s). The intensities for both groups in the intervention sessions during the 8 weeks ranged from 3 to 6 RPE.

2.8 Statistical analysis

Data were presented as the mean and standard deviation, and statistical analyses were performed using the GraphPad Prism 8 (GraphPad Software, Inc, La Jolla, CA). The intraclass correlation coefficient (ICC) was calculated to determine the test-retest reliability of the physical performance assessments through a two-way mixed model consistency type. The Shapiro-Wilk normality test was used to determine the data distribution. The 3 × 2 mixed ANOVA model with repeated measures was performed to measure the group×time effect of all variables. When the group×time interaction was significant, Bonferroni *post hoc* test was performed to establish intragroup differences (pre vs. post) and intergroup differences (CG vs. EG1 vs. EG2). The partial eta squared (η_p^2) was calculated to determine the effect size of the group×time

TABLE 2 Intragroup multiple comparisons on physical performance in youth male volleyball players.

Assessments	Groups	PRE		Post		*p*-Value[#]	Change (%)	ES
		Mean	SD	Mean	SD			
Squat jump (cm)	CG (*n* = 12)	30.92	3.09	31.75	2.93	**0.040***	2.68	0.28
	EG1 (*n* = 15)	31.40	2.72	35.40	3.40	**<0.001*****	12.74	1.30
	EG2 (*n* = 14)	31.00	2.63	34.57	3.06	**<0.001*****	11.52	1.25
CMJ (cm)	CG (*n* = 12)	31.75	2.22	32.00	2.17	0.999	0.79	0.11
	EG1 (*n* = 15)	32.40	2.41	36.27	2.12	**<0.001*****	11.94	1.71
	EG2 (*n* = 14)	31.00	2.63	34.50	2.44	**<0.001*****	11.29	1.38
CMJ-arms (cm)	CG (*n* = 12)	32.67	2.35	33.42	1.98	**0.031***	2.30	0.35
	EG1 (*n* = 15)	33.27	2.60	37.27	2.84	**<0.001*****	12.02	1.47
	EG2 (*n* = 14)	31.86	2.91	35.50	2.85	**<0.001*****	11.42	1.26
Drop jump (cm)	CG (*n* = 12)	28.75	2.67	29.83	2.33	**0.098**	3.76	0.43
	EG1 (*n* = 15)	30.47	2.39	33.80	2.73	**<0.001*****	10.93	1.30
	EG2 (*n* = 14)	30.79	2.05	35.07	1.90	**<0.001*****	13.90	2.17
5-m sprint s)	CG (*n* = 12)	1.57	0.21	1.55	0.20	**0.015***	−1.27	0.10
	EG1 (*n* = 15)	1.52	0.22	1.45	0.26	**<0.001*****	−4.61	0.29
	EG2 (*n* = 14)	1.56	0.20	1.50	0.28	**<0.001*****	−3.85	0.25
10-m sprint s)	CG (*n* = 12)	2.58	0.27	2.56	0.26	**0.620**	−0.78	0.08
	EG1 (*n* = 15)	2.53	0.27	2.43	0.23	**<0.001*****	−3.95	0.40
	EG2 (*n* = 14)	2.56	0.28	2.49	0.28	**<0.001*****	−2.73	0.25
Service speed (km/h)	CG (*n* = 12)	59.08	2.81	59.92	2.81	**0.024***	1.42	0.30
	EG1 (*n* = 15)	57.87	3.07	62.60	3.11	**<0.001*****	8.17	1.53
	EG2 (*n* = 14)	57.00	2.94	60.86	2.41	**<0.001*****	6.77	1.44

Data were presented as mean and (±) standard deviation; *SD: standard deviation. CMJ: countermovement jump. ES: effect size.*
p< 0.05.
p< 0.01.
p< 0.001.
Bonferroni post hoc test.
Values marked in bold show that there are statistically significant differences. $p < 0.05^*$, $p < 0.01^{**}$, $p < 0.001^{***}$.

interaction, which was interpreted considering the ηp^2 values of 0.01, 0.06, and 0.14, which correspond to an effect size small, medium, and large, respectively (Pallant, 2011). For multiple comparisons, the effect size was calculated using Cohen's *d* (Cohen, 1992); considering a small (0.20–0.49), moderate (0.50–0.79), or large (≥0.80) effect, the formula used was d= (M1-M2)/SD (Rendón-Macías et al., 2021). Besides, the relative delta *Δ* also was calculated. A significance level of $p < 0.05$ was established.

3 Results

The reliability analysis of the physical performance assessments demonstrated large reliability values. The vertical jump height, as measured using the CMJ, showed a high reliability of 0.98. Similarly, CMJ-arms exhibited a reliability score of 0.92, while SJ and DJ boasted reliabilities of 0.95 and 0.91, respectively, reflecting a high level of consistency. Additionally, the data obtained for maximum velocity during 5-m and 10-m sprints exhibited high reliability, with an ICC of 0.95. Furthermore, the data collected for service speed demonstrated a high reliability of 0.93.

The group×time repeated measures ANOVA revealed a significant interaction for SJ ($F_{(2,38)} = 30.53$; $p < 0.001$; $\eta_p^2 = 0.616$; *large effect*), CMJ ($F_{(2,38)} = 32.39$; $p < 0.001$; $\eta_p^2 = 0.630$; *large effect*), CMJ-arms ($F_{(2,38)} = 43.57$; $p < 0.001$; $\eta_p^2 = 0.696$; *large effect*), DJ ($F_{(2,38)} = 12.00$; $p < 0.001$; $\eta_p^2 = 0.387$; *large effect*), 5-m sprint ($F_{(2,38)} = 15.82$; $p < 0.001$; $\eta_p^2 = 0.454$; *large effect*), 10-m sprint ($F_{(2,38)} = 6.79$; $p < 0.003$; $\eta_p^2 = 0.263$; *large effect*), and service speed ($F_{(2,38)} = 50.98$; $p < 0.001$; $\eta_p^2 = 0.728$; *large effect*).

Intragroup multiple comparisons showed that, EG1 improved performance in SJ ($p < 0.001$; $d = 1.30$; *large effect*), CMJ ($p < 0.001$; $d = 1.71$; *large effect*), CMJ-arms ($p < 0.001$; $d = 1.47$; *large effect*), DJ ($p < 0.001$; $d = 1.30$; *large effect*), 5-m sprint ($p < 0.001$; $d = 0.29$; *small effect*), 10-m sprint ($p < 0.001$; $d = 0.40$; *small effect*), and service speed ($p < 0.001$; $d = 1.53$; *large effect*). In the same way, EG2 showed significant improvement in SJ ($p < 0.001$; $d = 1.25$; *large*

TABLE 3 Intergroup multiple comparisons on the effects of different plyometric training frequencies on physical performance in youth male volleyball players.

Assessments	CG vs. EG1	CG vs. EG2	EG1 vs. EG2
Squat Jump (cm)	**p< 0.001*****	**p= 0.001****	p = 0.999
	ES = 1.15	ES = 0.94	ES = 0.25
CMJ (cm)	**p= 0.001****	**p< 0.001*****	p = 0.999
	ES = 1.99	ES = 1.08	ES = 0.47
CMJ-arms (cm)	**p< 0.001*****	**p< 0.001*****	p = 0.999
	ES = 1.57	ES = 0.84	ES = 0.62
Drop Jump (cm)	**p= 0.001****	**p< 0.001*****	p = 0.999
	ES = 1.56	ES = 2.42	ES = 0.53
5-m sprint s)	**p< 0.001*****	**p< 0.001*****	p = 0.999
	ES = 0.43	ES = 0.20	ES = 0.18
10-m sprint s)	**p< 0.001*****	**p= 0.001****	p = 0.999
	ES = 0.53	ES = 0.25	ES = 0.23
Service speed (km/h)	**p< 0.001*****	**p< 0.001*****	p = 0.999
	ES = 0.90	ES = 0.62	ES = 0.35

Bonferroni *post hoc* test.
p< 0.05.
p< 0.01.
p< 0.001. p: p-value. ES: effect size. CG: control group. E.G.,1: experimental group 1. E.G.,2: experimental group 2. CMJ: countermovement jump.
Values marked in bold show that there are statistically significant differences. p < 0.05*, p < 0.01**, p < 0.001***.

effect), CMJ ($p < 0.001$; $d = 1.38$; *large effect*), CMJ-arms ($p < 0.001$; $d = 1.26$; *large effect*), DJ ($p < 0.001$; $d = 2.17$; *large effect*), 5-m sprint ($p < 0.001$; $d = 0.25$; *small effect*), 10-m sprint ($p < 0.001$; $d = 0.25$; *small effect*), and service speed ($p < 0.001$; $d = 1.44$; *large effect*). In this intervention, the greatest changes in, EG2 were observed in SJ and DJ tests with a percentage change of $\Delta = 11.5\%$ and $\Delta = 13.9\%$, respectively. On the other hand, in CG, significant improvements were observed in SJ ($p = 0.040$; $d = 0.28$; *small effect*), CMJ-arms ($p = 0.031$; $d = 0.35$; *small effect*), 5-m sprint ($p = 0.015$; $d = 0.10$; *small effect*), and service speed ($p = 0.024$; $d = 0.30$; *small effect*). The highest change percentages in CG were shown in SJ and DJ, with $\Delta = 2.7\%$ and $\Delta = 3.8\%$, respectively. Table 2 presents intragroup multiple physical performance comparisons in youth male volleyball players.

Intergroup multiple comparisons revealed significant differences in all the variables assessed in favor of, EG1 and, EG2 concerning CG ($p < 0.001$), with no differences between, EG1 and, EG2. Table 3 presents multiple intergroup comparisons on the effects of different PT frequencies on physical performance in youth male volleyball players.

4 Discussion

The present study aimed to analyze the effect of PT at different frequencies on jump performance (SJ, CMJ, CMJ-arms, DJ), running sprint speed (5-m sprint, 10-m sprint), and service speed in youth male volleyball players. Our main outcomes showed that both interventions with PT in one (EG1) and two sessions (EG2) weekly were equally effective in improving the components of physical performance in youth volleyball players under controlled training volume, these being statistically significant improvements in jump performance, running sprint speed, and service speed. Therefore, one weekly PT session has a similar effect to two weekly sessions during the pre-season (8 weeks) on physical performance in youth volleyball players.

In the present study, significant improvements in SJ and CMJ-arms in CG and, after PT intervention were detected in both, EG1and, EG2 in SJ, CMJ, CMJ-arms and DJ in youth male volleyball players. These findings confirm the results of previous systematic reviews indicating significantly greater responses in volleyball players who intervened with PT in SJ ($p < 0.05$; $d = 0.56$; *moderate effect*), CMJ ($p < 0.05$; $d = 0.80$; *large effect*), and DJ ($p < 0.05$; $d = 0.81$; *large effect*) relative to active control groups (Ramirez-Campillo et al., 2021). A study conducted by Ramirez-Campillo et al. (2018) compared 1 and 2 weekly sessions of a PT intervention and found that it significantly improved SJ, CMJ, and DJ compared to the active control group in youth amateur soccer players. These improvements reported in the present study in jump performance are important because, in volleyball, actions such as blocking and spiking during a match are executed by jumping, and 80% of the points in a match are obtained by performing these actions (Carvalho et al., 2020). Therefore, a higher vertical jump height is decisive for match performance (Carvalho et al., 2020). In the systematic review with meta-analysis performed by Ramirez-Campillo et al. (2020), it was observed that both a number of PT sessions ≤16 sessions vs. >16 sessions led to significant improvements ($p < 0.05$) in vertical jump height in volleyball players with a moderate effect size (ES = 0.730–0.916) with no significant differences between groups ($p = 0.558$). As well as the number of jumps per session, ~42 jumps vs. ~160 jumps per session both lead to a significant improvement ($p < 0.05$) in vertical jump height performance in volleyball players with a moderate effect size (ES = 0.761–0.785) with no significant differences between groups ($p = 0.811$). These improvements could be due to various neuromuscular adaptations, such as improvements in intermuscular coordination, increased activation rate of alpha motor neurons, improved mechanical characteristics of the muscle-tendon complex, improved muscle size, architecture, and/or single fiber mechanics (Ramirez-Campillo et al., 2021). However, it should be considered that a very high frequency of PT can lead to a higher risk of injury due to muscle fatigue in young volleyball players (Migliorini et al., 2019; Tsarbou et al., 2021; Pawlik and Mroczek, 2022). Therefore, one session a week can generate adaptations and improvements in vertical jump height in youth volleyball players.

Another reported improvement was in running sprint speed in CG, decreasing the time in 5-m sprint and, after PT intervention with both, EG1 and, EG2 in 5-m sprint and 10-m sprint. These results confirm what was reported in the meta-analysis by Ramirez-Campillo et al. (2021) in a 10-m sprint (ES = 0.70; 95%CI = 0.31 to 1.09; $p < 0.001$; $I^2 = 46.1\%$) in youth volleyball players. In amateur soccer players, significant improvements ($p < 0.01$) in the 15-m sprint through one and two PT sessions over 8 weeks compared to an active control group were reported (ES = 2.25 and ES = 2.67) with a magnitude of change of −8.3% and −9.5%. However, no significant differences were reported when comparing both PT groups. Volleyball is a team sport characterized by intermittent efforts with periods of short duration (i.e., 3–9 s), and high-intensity activities interspersed with relatively long (i.e., 10 s–20 s) recovery periods (Ramirez-Campillo et al., 2021). Short-distance sprints (5-m sprint and 10-m sprint) form a relatively larger portion (i.e., ~30%) of the total movement distance in volleyball, particularly in linear sprints (Ramirez-Campillo et al., 2021). Likewise, a fast-running approach prior to jumping is also related to a better jump height (Ramirez-Campillo et al., 2021). Sprint performance requires explosive concentric force production and stretch-shortening cycle in the lower limb muscles and can benefit significantly from the ability of players to utilize and optimize the elastic and neural properties of the stretch-shortening cycle after PT (Silva et al., 2019). In a systematic review with meta-analysis Ramirez-Campillo et al. (2021) it has been shown that PT leads to significant improvements ($p < 0.05$) in linear sprinting of ≤10 m and >10 m in basketball players (≥16.3 years and <16.3 years) with training frequencies ≤2 sessions/week vs. >2 sessions/week. While in volleyball players (≥16 years and <16 years), the PT with frequencies of <8 weeks with <16 sessions/week vs. ≥ 8 weeks with ≥16 sessions/week led to significant improvements ($p < 0.05$) in a linear sprint with no significant differences between groups. Higher PT volume has been associated with increased injury risk (Brumitt et al., 2016; Brumitt et al., 2018). In this context, a previous study conducted among physically active participants revealed that varying jump volumes, including low (420 jumps), moderate (840 jumps), and high (1,680 jumps), resulted in comparable enhancements in linear sprint performance (Alfaro-Jiménez et al., 2018).

Also, in the present study, significant improvements in service speed in CG were reported in both, EG1 and, EG2. Similar to that reported by Valades Cerrato et al. (2018), showing significant improvements after PT in serving speed (Δ 3.8%) compared to the active control group in youth volleyball players. The explosive actions of the upper limbs, such as the power with which the ball is impacted in the service, determine success in the match (Valades Cerrato et al., 2018). The service is the first action through which a point can be scored, preceding all other scoring actions, such as the spike or the block (Quiroga et al., 2010). In a study conducted by Valades Cerrato et al. (2018), the actions that awarded the most points in the Sydney 2000 and Athens 2004 Olympic Games were the serve was between 4.4% and 8.1%, the spike of 76.8%–80%, and the block 14.5%–15.6%. The PT increases strength, speed, and muscle power in volleyball players' lower and upper limbs (Hammami et al., 2020). These improvements could be due to various neuromuscular adaptions, such as improvements in intermuscular coordination, and transfers obtained through PT leading to higher service speed in volleyball players (Valades et al., 2016).

While PT can induce a wide range of adaptions, several specific features of PT must be considered to maximize its benefits (Ramirez-Campillo et al., 2018). In this study, the PT intervention included unilateral, bilateral, cyclic, acyclic, vertical, fast, and slow muscle contraction exercises of the stretch-shortening cycle, with movements similar to sports gestures, emphasizing landing technique and shock absorption, using soft and medium hardness training surfaces. Also, PT was performed immediately after warm-up, and participants used individualized box heights (i.e., 5–35 cm) during DJs, progressively increasing the training volume, and using adequate rest between sets and repetitions (Ramirez-Campillo et al., 2018). It should be noted that all the PT sessions were carried out on surfaces that the players usually use in training and competitions. Also, taking into account previous studies (Gjinovci et al., 2017; Idrizovic et al., 2018; Ramirez-Campillo et al., 2018; Ramirez-Campillo et al., 2021) in volleyball players. This is the first study to analyze the effect of a highly specialized PT program to maximize adaptations on lower and upper limbs performance variables in youth male volleyball players. However, considering that the effects of PT may vary according to sex, sport level, age, and years of experience (Ramirez-Campillo et al., 2021). In PT programs the distribution and quantity of jumps is important to achieve the best benefits, thus the scientific literature has proposed in male and female professional and elite volleyball players (aged between 14 and 21 years) to perform a duration ≤8 weeks, with a frequency ≤2 sessions/week with a total number ≤16 sessions performing a volume of jumps <2,000 (Ramirez-Campillo et al., 2020). This better stimulates fast twitch fibers, which would help improve performance, however, there is still no consensus on the number of weekly sessions for amateur or school league players, where maturity such as competition level may influence the duration and frequency of PT (Ramirez-Campillo et al., 2023).

Because of this, the limitations of the study are: *i*) not including measurements of neurophysiological mechanisms to determine muscle activation in response to the adaptations generated by PT; *ii*) not assessing the level of physical maturation of the participants; *iii*) the absence of female in the sample; *iv*) not assessment professional or elite athletes to determine whether the same responses are generated in response to PT. Among the main strengths of the study, we can mention: *i*) the randomization of the sample; *ii*) the execution of the same protocol in both PT groups; *iii*) the equal load between, EG1 and, EG2; *iv*) the surface on which the PT intervention was carried out.

Based on the results found, one PT session week in combination with traditional volleyball training seems to be sufficient to induce improvements in jump performance (SJ, CMJ, CMJ-arms, DJ), running sprint speed (5-m sprint, 10-m sprint) and a service speed of both lower and upper limbs in youth male volleyball players, with a moderate overall training volume, a different distribution (1 or 2 sessions) of a given weekly training volume does not produce statistically significant differences in training adaptations.

5 Conclusion

A single PT session per week for 8 weeks is adequate for achieving significant improvements in jump performance, running sprint speed, and service speed. These results are comparable to those obtained from two weekly PT sessions. Therefore, the distribution of one or two sessions per week does not yield statistically significant differences in physical performance among youth male volleyball players.

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 The Scientific Ethics Committee of the Universidad Autónoma de Chile (approval number: N° 126-18). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

JH-M : Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. EG-M: Formal Analysis, Methodology, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. RR-C: Validation, Visualization, Writing–review and editing. TH-V: Validation, Visualization, Writing–review and editing. BM: Validation, Visualization, Writing–review and editing. SA-V: Investigation, Validation, Writing–review and editing. JL-B: Investigation, Validation, Visualization, Writing–review and editing. PA-S: Investigation, Validation, Visualization, Writing–review and editing. JM-C: Validation, Visualization, Writing–review and editing. PV-B: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

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

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Effects of loading positions on the activation of trunk and hip muscles during flywheel and dumbbell single-leg Romanian deadlift exercises

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Objective: The study compared the activities of the surface electromyography (sEMG) of trunk and hip muscles during single-leg Romanian deadlift (SLRDL) exercises using a flywheel and dumbbell with different loading positions (ipsilateral and contralateral).

Method: Twelve active male subjects with at least 2 years of strength training experience (age: 26.7 ± 3.3 years; weight: 73.9 ± 6.2 kg) participated in this study. sEMG in the percentage of maximum voluntary isometric contraction of four SLRDL exercises (ipsilateral and contralateral loading position for dumbbell and flywheel) in a randomized order for superior gluteus maximus (SGM), inferior gluteus maximus (IGM), gluteus medius (GM), biceps femoris (BF), erector spinae (ES), external oblique (EO), and adductor longus (AL) were measured. One-way repeated measure ANOVA with Bonferroni adjustment (statistical significance at 0.05) and the non-clinical magnitude-based decision with a standardized difference were performed for statistical analysis.

Results: The overall results demonstrated a very high level of SGM (105.4%–168.6%) and BF (69.6%–122.4%) muscle activities. A significant moderate increase of sEMG signals in GM, IGM, and ES (dominant side) and a large increase in SGM activity during concentric action when the loading position of flywheel SLRDL was changed from ipsilateral to the contralateral side. No significant difference was observed between flywheel and dumbbell SLRDL exercises.

Conclusion: Strength coaches may adopt dumbbell or flywheel SLRDL exercises using the contralateral loading position to simultaneously strengthen the hip extensors and trunk stabilizers effectively.

KEYWORDS

eccentric training, EMG, strength training, gluteus medius, hamstring, gluteus maximus

1 Introduction

Romanian deadlift (RDL) is a multi-joint closed-kinetic chain exercise for strengthening the lower limb muscles including hamstring and gluteus maximus (Koderi et al., 2020), back extensors, and also the lumbar region (Mayer et al., 2008). It is well known for its potential benefits in reducing the risk of hamstring injuries (Brughelli and Cronin, 2008). Due to the similar biomechanics with certain phases of weightlifting techniques such as clean and snatch, it can be regarded as a fundamental strengthening variant to improve hip strength, power output, and lifting posture (Weaver and Kerksick, 2017).

Single-leg RDL (SLRDL) is the progression of the RDL taking the benefits from unilateral training. In this regard, Kuki et al. (2018) highlighted its potential effects on boosting neuromuscular activation, especially for the hamstrings and gluteus medius. Apart from the posterior chain musculature, SLRDL also emphasizes the lumbopelvic muscles (Weaver and Kerksick, 2017). Since the unilateral stance limits the base of support increasing instability and the challenge of controlling the center of gravity, greater recruitment of trunk and pelvic stabilizers are required for overcoming the destabilizing torque of the movement (Saeterbakken and Fimland, 2012; Marchetti et al., 2018). Moreover, during SLRDL, the biceps femoris has dual roles including the agonist producing hip extension movement similar to bilateral RDL, and also a knee joint stabilizer in closed kinetic chain exercise (Marchetti et al., 2016). When compared with bilateral exercise, unilateral training was shown to provide a greater total volume of lifting load lifted (Costa et al., 2015) and a cross-education effect in musculoskeletal and neurological rehabilitation (Farthing and Zehr, 2014). Therefore, it is not surprising that previous studies have shown its potential superiority in enhancing strength and sports performance (Kuruganti and Murphy, 2008; Rejc et al., 2010).

In addition to the high hamstring involvement in performing RDL exercises (McAllister et al., 2014), it shares similar biomechanics with the Nordic hamstring curl that both exercises promote an increasing load when the hamstring is fully lengthened (Ribeiro-Alvares et al., 2018). Therefore, it is believed that RDL is also an effective drill to maximize eccentric hamstring strength and reduce the risk of hamstring strain during acceleration and sprinting (Mjølsnes et al., 2004). Recently, a novel training method, accentuated eccentric loading, using a flywheel device was highly promoted and widely studied for its potential superiority in eccentric strength enhancement (Wagle et al., 2017).

Accentuated eccentric loading (AEL) was proposed to overload the eccentric phase to even beyond the maximum magnitude of the concentric load with minimal disturbance to natural mechanics (Wagle et al., 2017). Flywheel, also known as isoinertial training, is one of the AEL training examples applying a linear resistance from a rotating disc with a decent mass attached to the tether keeping a distance from the axis of rotation (Chiu and Salem, 2006). The flywheel torque is based on the radius of gyration, angular acceleration, and mass meanwhile it allows for maximum concentric contraction throughout the full range of motion, an increase of eccentric load, and maximum exertion during the first concentric phase (Tesch et al., 2004; Norrbrand, 2008). Thus, flywheel training was shown to be effective to enhance maximal strength, power, muscular hypertrophy, and functional abilities in vertical and horizontal planes (Petré et al., 2018). Furthermore, some recent studies showed that isoinertial training may evoke higher electromyography (EMG) activities than gravity-dependent weight training (Norrbrand et al., 2011; Núñez et al., 2017). Despite the proposed potential benefits of AEL using flywheel over the traditional free weight training, there is no study comparing the muscle activities between the flywheel and free weight SLRDL exercises.

Although gravity contributes part of the equation in calculating the total resistance during flywheel RDL exercises, the speed and loading of the eccentric phase mostly result from the concentric effort leading to the change of direction of the wheel. Conversely, free weight is based on gravity to induce a stimulus on the musculoskeletal system (Chiu and Salem, 2006). From the biomechanics perspective, when performing the initial downward phase of SLRDL, there will be a relatively lower resistance and hence the demand on muscle activation of both agonists and stabilizers. On the other hand, Tesch et al. (2004) have shown the peak eccentric torque occurred right after the mid-point of the eccentric phase during flywheel knee extension exercise (YoYo™). In this regard, it is believed that the torque and actual resistance applied on the hip and knee joint during free weight and flywheel SLRDL are different.

Besides the sagittal loading applied to the hamstrings for strength enhancement, it is worth noting that aberrant pelvic motion is one of the key factors contributing to hamstring tear (Chumanov et al., 2007). Numerous studies showed that sufficient abdominal oblique activation and lumbopelvic stability are also critical in reducing the risk of hamstring injuries (McCall et al., 2014; Donaldson et al., 2015). Therefore, unilateral training using SLRDL with asymmetric load is believed to be favorable for addressing hamstrings strength and lumbopelvic stability simultaneously (Willardson, 2007). As changing the loading position, especially in the frontal plane can alter the center of gravity (Stastny et al., 2015), it is speculated that changing the loading position (i.e., contralateral vs ipsilateral) in SLRDL will potentially induce different demands and challenges on lumbopelvic stability and relevant stabilizers. In this regard, our gluteus medius is one of the most important pelvic and knee stabilizers to perform both hip abduction and lateral pelvic tilt. Strong evidence on knee injury prevention and rehabilitation (e.g., anterior cruciate ligament injury and anterior knee pain) emphasizing the high-intensity training on this muscle was well established (Powers, 2010; Stastny et al., 2016). Moreover, the superior fibers of the gluteus maximus have a similar location (more lateral on the pelvis) and orientation (diagonal towards the greater trochanter) with the gluteus medius and therefore, these gluteal muscle portions are highly responsible for the pelvic, hip, and knee stability in both the frontal and transverse plane (Powers, 2010; Ho et al., 2020). Since bodyweight SLRDL was shown to be an effective exercise in activating gluteus medius (56%–58% in terms of maximum voluntary isometric contraction) (Stastny et al., 2016), based on the anatomical and biomechanical characteristics of this muscle, it is hypothesized that the change of loading positions potentially increase the muscle activity on the standing leg when the frontal and transverse stability becomes more challenging in performing the unilaterally loaded SLRDL. With limited research in this regard, it is interesting to compare the muscle activities of the trunk and pelvic muscles with different SLRDL loading positions.

To the best knowledge of the authors, the effect of the loading position on muscle activation during SLRDL using a flywheel and dumbbell has not yet been investigated. Therefore, the purpose of this study is to determine the effect of loading position (contralateral vs ipsilateral) and methods (dumbbell vs flywheel) on the surface electromyography (sEMG) of superior gluteus maximus (SGM), inferior gluteus maximus (IGM), gluteus medius (GM), biceps femoris (BF), erector spinae (ES), external oblique (EO), and adductor longus (AL) on SLRDL.

2 Materials and methods

2.1 Experimental approach to the problem

Subjects were required to attend one familiarization and another data collection session at least 4 days apart. To generalize the result to trained populations, subjects with at least 2 years of strength training experience were recruited. This within-subject repeated measure study investigated the sEMG activities for the four selected SLRDL variants including flywheel with ipsilateral (FLY-Ipsi) and contralateral (FLY-Con) loading positions, and dumbbell with ipsilateral (DB-Ipsi) and contralateral (DB-Con) loading positions in randomized order. Nine lower limb and trunk muscles were selected for measuring muscle activity including the EO of dominant (EO-D) and non-dominant side (EO-ND), ES of dominant (ES-D), and non-dominant side (ES-ND), AL, GM, SGM, IGM, and BF.

2.2 Subjects

Twelve young male subjects with at least 2 years of resistance training experience (age: 26.7 ± 3.3 years; weight: 73.9 ± 6.2 kg; height: 172.6 ± 11.1) volunteered to participate in the present study. All subjects completed the Physical Readiness Questionnaire (PAR-Q) and informed consent form meanwhile the study was approved by the Human Research Committee. Subject exclusion criteria include 1) a history of injury and/or surgery on the spinal region or lower extremity or lower back pain in the past 12 months (Ho et al., 2020); 2) uncertain or potential cardiovascular or respiratory diseases indicated in PAR-Q or past medical history; 3) ≥16.6% body fat measured by body composition analyzer (InBody 720, Biospace South Korea); and 4) unable to perform the four variations of the single-leg RDL correctly or occurrence of pain during the familiarization session. Besides, subjects refrained from vigorous activities or resistance training at least 48 h before the data collection session.

2.3 Procedures

During the familiarization session, subjects were instructed on the proper technique of all SLRDL exercises. After that, subjects performed a maximal speed of SLRDL using a flywheel with ipsilateral and contralateral loading positions for six repetitions to determine the movement velocity and dumbbell loading intensity. According to Sabido et al. (Sabido et al., 2017), using a light inertial load of 0.025 kg m^2 on flywheel devices enables the subjects to generate higher power in both concentric and eccentric actions, and therefore, an inertial setting of 0.025 kg m^2 was used in this study for intensity estimation. A velocity-based training (VBT) sensor (Push Pro Band 2.0) was adopted to the handle of the flywheel device for testing the movement velocity. The data of the first two repetitions for flywheel acceleration and movement amplitude stabilization were discarded (Sabido et al., 2017; Darjan et al., 2020), while the mean velocity of the last four repetitions during the concentric phase was used. Subsequently, the actual dumbbell loading for testing purposes was determined when the subjects successfully performed six repetitions of SLRDL in DB-Con and DB-Ipsi positions using the highest weight with good balance and technique, and the equivalent concentric velocity (±0.1 m/s) as the FLY-Con and FLY-Ipsi accordingly. The pace of the DB-Con and DB-Ipsi was controlled by a digital metronome. A minimum of 4 minutes of rest was given between trials. The weights of dumbbells used for testing purposes as well as the tempos are shown in Table 1.

For the data collection session, muscle activities of EO and ES (at L3 level), and the dominant side of GM, SGM, IGM, BF, and AL were measured using the sEMG system (MyoMuscle, Noraxon, United States, Inc., Scottsdale, AZ) at a sample rate of 1,000 Hz with the TeleMyo DTS Desk Receiver. The sites for electrode placement were rubbed and cleaned with alcohol pads until the skin showed slight redness meanwhile the hair was shaved to avoid skin impedance and maximize the quality of the sEMG signals (Ho et al., 2020). Disposal sEMG electrodes containing silver-silver chloride (Ag/AgCl) and conductive wet gel (Blue Sensor T-00-S, Ambu Inc., Malaysia), with a center-to-center inter-electrode distance of 35 mm were used (Ho et al., 2020). Several 3M™ tapes were applied to secure the electrodes. Raw data were processed with MyoResearch 3.8 software (Noraxon United States, Inc., Scottsdale, AZ) with full-wave rectified, band-pass filtered from 50 to 500 Hz and smoothed via the root-mean-square (RMS) algorithm and 100-millisecond moving window.

Based on the recommendation from previous studies, electrodes for the following muscles were placed: EO) a diagonal line with 45° and upper-level of the anterior superior iliac spine which closed by the level of the umbilicus; ES) 3 cm lateral to the spinous process and nearly level with the iliac crest between L3 and L4 vertebrae (Escamilla et al., 2010); SGM) upper and laterally to the middle of the line connecting from the posterior superior iliac spine (PSIS) and the posterior greater trochanter; IGM) inferiorly and medially to the middle of the line connecting from the PSIS and the posterior greater trochanter, and approximately 2.5–5 cm above the gluteal fold (Selkowitz et al., 2016); GM) a half of the distance between the iliac crest and the greater trochanter anteriorly and upper from the gluteus maximus; AL) medially to the thigh and same to the proximal one-third of the distance from the pubic tubercle to the linea aspera on the femur (Serner et al., 2014); BF) a half of the line between ischial tuberosity and lateral epicondyle (Ho et al., 2020). The dominant side of the body was determined by the usual kicking leg. All electrodes were placed parallel to the muscle fibers for better sensitivity.

2.4 Data collection and normalization

Subjects initially performed a 5-min self-paced slow jogging on the treadmill as the standardized warm-up before performing

TABLE 1 The weight and tempo of the dumbbell Romanian deadlift used.

Subject ID	Dumbbell on ipsilateral in kg (tempo in m/s)	Dumbbell on contralateral in kg (tempo in m/s)
1	28.0 (0.96)	28.0 (1.01)
2	22.5 (0.98)	20.0 (0.60)
3	28.0 (1.27)	25.0 (0.97)
4	30.0 (0.65)	30.0 (0.54)
5	22.5 (0.97)	22.5 (0.96)
6	28.0 (0.70)	22.5 (0.66)
7	30.0 (0.83)	30.0 (0.78)
8	30.0 (0.88)	32.0 (0.78)
9	30.0 (0.68)	30.0 (0.64)
10	28.0 (0.72)	30.0 (0.70)
11	30.0 (0.74)	28.0 (0.60)
12	22.5 (0.97)	28.0 (0.80)
Average	27.5 (0.86)	27.2 (0.75)

SLRDLs. After that, subjects performed the MVIC tests for EMG normalization. The MVIC testing protocols of selected muscles were referenced from the positions described in Kendall et al. (2005), Escamilla et al. (2010), Selkowitz et al. (2016), and Delmore et al. (2014). The peak EMG amplitude of each muscle was obtained through three maximal isometric contractions of 5 seconds using manual resistance with 1-min rest between trials (Burden, 2010; Chuang and Acker, 2019). Verbal encouragement was consistently provided during the MVIC test. After that, subjects performed four SLRDL variants in a randomized order for one set of six repetitions with a 4 minutes rest between exercises (Pearson et al., 2000). Both concentric and eccentric actions in all SLRDL exercises were performed with maximal speed. Before data collection, the foot placement and the grip position of SLRDL exercises were standardized. Throughout the trials, subjects maintained the knee flexion angle at approximately 15°, and at the bottom position upon the end of the eccentric phase, the trunk position was about parallel to the ground. If subjects failed to complete the six repetitions continuously, they were required to redo after a 4-min rest until a successful trial was made. The last 4 repetitions of each SLRDL variation were used for further analysis. For the FLY-Con and FLY-Ipsi conditions, subjects started with a unilateral stance with the dominant leg right behind the handle of the flywheel device such that the shoulder was in line with the handle. Meanwhile, the instructor slowly rotated the wheel of the flywheel device to lower the grip and prepare for the initiation. Once the trunk paralleled the ground, the subjects were instructed to fully extend the hip to initiate the SLRDL exercise. Subjects were encouraged to give maximal speed and effort throughout the flywheel SLRDL exercises. For the FLY-Con, the handle was gripped by the non-dominant side and in line with the contralateral shoulder. Subjects performed the DB-Con and DB-Ipsi conditions with identical body postures as the FLY-Con and FLY-Ipsi respectively.

2.5 Statistical analysis

sEMG data were normalized as the percentage of MVIC (% MVIC) and expressed as mean and ±SD. The activation was deemed low, moderate, high, and very high for 0%–20%, 21%–40%, 41%–60%, and over 60% respectively (Escamilla et al., 2009). The data of the dominant side was defined as the usual limb for kicking a ball (Selkowitz et al., 2016). A two-way mixed model intraclass correlation coefficient (ICC) was used for analyzing the relative test-retest reliability throughout the final four repetitions. One-way repeated measure ANOVA was used for analyzing the difference in muscle activity between SLRDL variations. A *post hoc* pairwise comparison with Bonferroni adjustment was applied while 0.05 was set for statistical significance.

In addition to the traditional statistical analyses, the non-clinical magnitude-based decision and precision of estimation were used with differences between conditions assessed via corresponding 90% confidence intervals, and their standardized effect (mean difference divided by the standardized unit) of each pairwise comparison was calculated. The smallest worthwhile difference was set at 0.2 while thresholds for the magnitudes of effects were: 0.2, small; 0.6, moderate; 1.2, large; 2.0, very large; and 4.0, extremely large (Hopkins et al., 2009). The effects were unclear if the respective 90% confidence intervals crossed the thresholds of the effect being substantially positive and negative by >5%. Otherwise, the clear effect with the percentage likelihood of effects being substantially positive, trivial, and substantially negative was observed, and the corresponding qualitative inference was produced. The probabilistic terms for classifying likelihood values were as follows: <0.5%, almost certainly not; 0.5%–5% very unlikely; 5%–25% unlikely; 25%–75% possibly; 75%–95% likely; 95%–99.5% very likely; >99.5% almost certainly (Hopkins et al., 2009). All data analyses were performed using RStudio software (version 1.2.5001).

TABLE 2 sEMG values of the trunk and lower limb muscles of the 4 variations of single-leg Romanian deadlift (mean ± SD).

	EO-D	EO-ND	AL	GM	ES-D	ES-ND	SGM	IGM	BF
Concentric phase									
FLY-Con	27.49 ± 17.15	26.10 ± 12.72	22.00 ± 12.05	88.67 ± 37.46	104.63 ± 39.05	87.26 ± 37.45	168.62 ± 67.93	112.8 ± 53.11	122.40 ± 47.08
FLY-Ipsi	30.49 ± 30.29	41.94 ± 18.60	43.91 ± 26.51	54.61 ± 26.73	78.06 ± 30.67	114.25 ± 39.81	91.68 ± 34.30	79.94 ± 35.42	111.92 ± 50.54
DB-Con	25.47 ± 14.11	21.30 ± 9.11	21.35 ± 11.10	79.80 ± 35.06	93.79 ± 39.77	94.27 ± 44.35	167.32 ± 71.18	97.21 ± 38.13	112.96 ± 53.86
DB-Ipsi	21.86 ± 14.36	28.56 ± 11.80	34.90 ± 15.05	62.85 ± 29.71	75.05 ± 40.37	103.47 ± 51.03	114.36 ± 47.81	78.28 ± 27.70	115.22 ± 48.61
Eccentric phase									
FLY-Con	29.37 ± 20.53	28.47 ± 17.04	16.07 ± 6.70	59.03 ± 20.81	61.20 ± 15.00	52.81 ± 19.77	105.35 ± 54.59	59.81 ± 42.89	70.61 ± 31.17
FLY-Ipsi	24.03 ± 15.05	30.95 ± 14.61	27.53 ± 15.94	41.22 ± 19.24	56.98 ± 19.25	63.77 ± 16.63	75.26 ± 47.93	48.47 ± 30.13	69.63 ± 45.79
DB-Con	24.63 ± 14.10	20.02 ± 9.46	14.10 ± 8.02	57.49 ± 23.00	64.61 ± 21.96	59.91 ± 30.13	106.80 ± 51.29	56.58 ± 30.78	70.39 ± 43.17
DB-Ipsi	19.52 ± 15.32	24.03 ± 14.24	19.75 ± 9.10	40.59 ± 17.78	51.31 ± 17.82	68.45 ± 24.36	73.11 ± 29.25	42.45 ± 16.78	70.62 ± 43.39

EO-D: the dominant side of external oblique; EO-ND: the non-dominant side of external oblique; AL: adductor longus; GM: gluteus medius; ES-D: the dominant side of erector spinae; ES-ND: the non-dominant side of erector spinae; SGM: superior gluteus maximus; IGM: inferior gluteus maximus; BF: biceps femoris; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading.

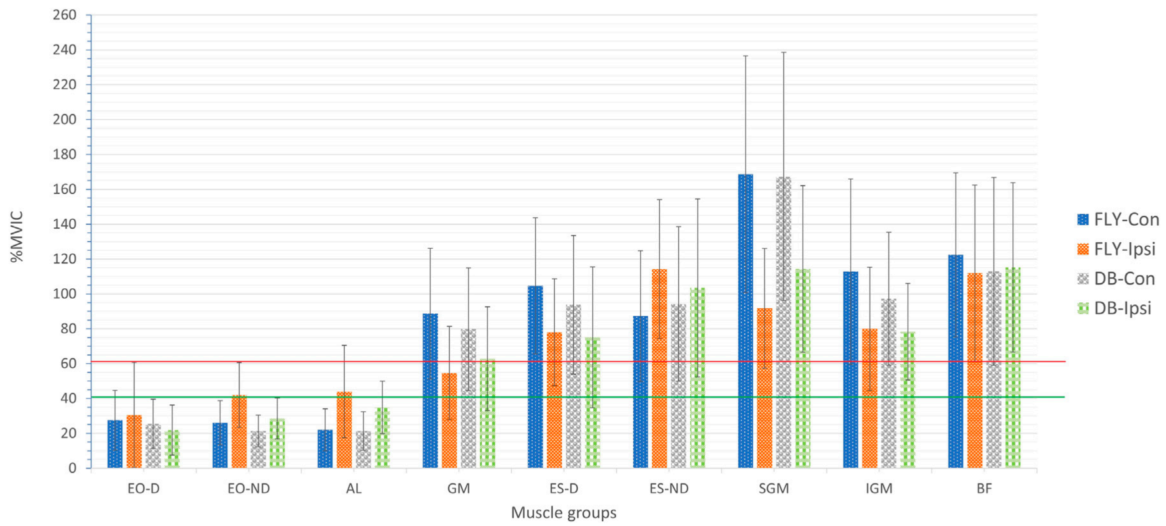

FIGURE 1
The results of magnitude-based decision for biceps femoris and adductor longus during the concentric phase AL: adductor longus; BF: biceps femoris; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading.

3 Results

The muscle activities in terms of %MVIC of all conditions were presented in Table 2 and graphically in Figure 1. All data were normally distributed based on the Shapiro-Wilk test ($p > 0.05$) or visual inspection, and most sEMG results demonstrated good to excellent relative test-retest reliability (ICCs: 0.75–0.99) except the EO-D in FLY-Con during the concentric phase (ICC = 0.49) and ES-D in FLY-Ipsi condition during the eccentric phase (ICC = 0.43) providing poor reliability. Regarding the magnitude of the sEMG signals, the concentric (FYL-Con: 168.6% ± 67.9%; DB-Con: 167.2% ± 71.2%) and eccentric (FYL-Con: 105.4% ± 54.6%; DB-Con: 106.8% ± 51.3%) contraction of SGMax demonstrated a very high level of activation (>60%) (Figures 1, 2). BF muscle also produced very high muscle activities in all conditions (69.6%–122.4%) (Table 2). Conversely, both concentric and eccentric phases of EO-D only yielded low to moderate levels of activation in all conditions.

The sEMG values of most muscles observed in different conditions showed significant differences using one-way repeated measure ANOVAs ($p < 0.05$) except the EO-D and BF muscles in both concentric and eccentric phases, and the ES-D during the eccentric phase showing no significant difference among four training conditions.

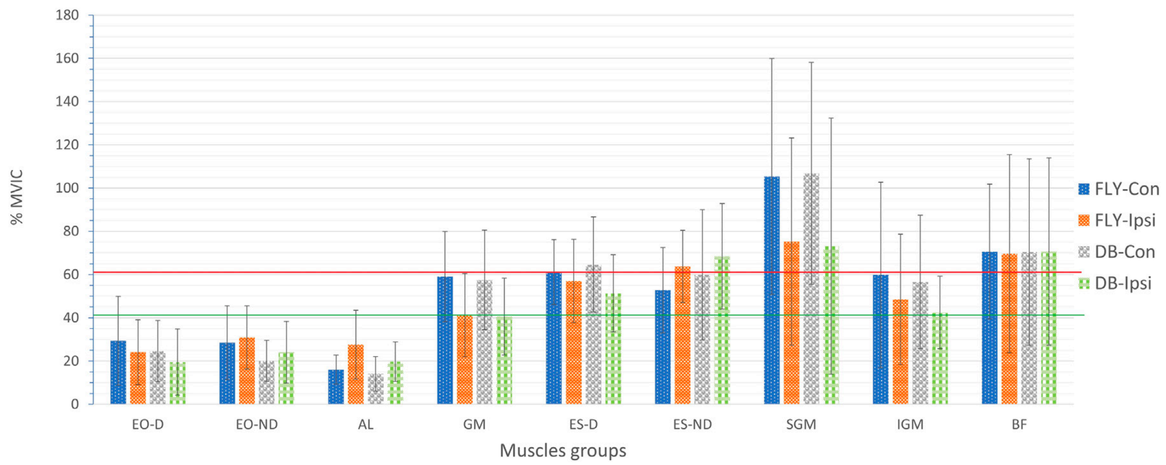

FIGURE 2
The results of magnitude-based decision for erector spinae muscle during the eccentric phase ES-D: the dominant side of erector spinae; ES-ND: the non-dominant side of erector spinae; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading.

When comparing the loading position, *post hoc* and MBD pairwise comparisons showed a significant moderate increase of sEMG activities in GM, IGM, and ES-D and a large increase in SGM activity during concentric action when changing the loading position from FLY-Ipsi to FLY-Con. Similarly, DB-Con showed a significant moderate increase in SGM in concentric action, both GM, ES-D, and SGM during eccentric action over the DB-Ipsi condition (Table 3).

When comparing the training methods in the same loading position, no significant difference was observed between FLY and DB conditions while MBD showed a small increase in ES-D, GM, and IGM during concentric action and a small increase in EO-D, EO-ND, and AL in eccentric action when changing from DB-Con to FLY-Con. Similarly, a small increase in EO-D, AL, and ES-ND while a moderate increase in EO-ND during concentric action, and a small increase in EO-D, EO-ND, AL, ES-D, and IGM during the eccentric phase when changing from DB-Ipsi to FLY-Ipsi were observed (Table 4). All MBD results were shown in Figures 3–10.

4 Discussion

The current study aims to compare the muscle activities of EO-D, EO-ND, AL, GM, ES-D, ES-ND, SGM, IGM, and BF between the four variations of SLRDL (FLY-Con, DB-Con, FLY-Ipsi & DB-Ipsi). According to Macadam et al. (2015), approximately 40%–60% of MVIC is required to produce sufficient stimulus for improving muscle strength and therefore, SLRDL exercises yielded >60% (very high activation) were deemed adequate for strength enhancement in this study.

Regarding the activation of all our selected muscles, SLRDL variations were effective in strengthening the BF, IGM, SGM, ES-D, and ES-ND while FLY variations were also useful for strengthening GM during the concentric phase (Figure 1). For the eccentric action, only BF and SGM were highly activated in all SLRDL conditions to provide sufficient strengthening effect while the DB conditions could also produce good strengthening stimuli to ES-ND (Figure 2). Since the BF and SGM are the major hip extensors, it is not surprised for such high muscle activities in both concentric and eccentric SLRDL actions especially when movements were performed with maximum movement speed potentially favoring the additional recruitment of fast-twitch fibers and higher sEMG signal (Sakamoto and Sinclair, 2011). Recent literature has stated that there were approximately 30%–40% and 15%–20% of MVIC in BF during concentric and eccentric actions respectively using 12 repetition maximum of unilateral barbell RDL exercises, and it was regarded as the second-lowest muscle activity among selected hamstring exercises (e.g., good morning and straight leg bridge) (Hegyi et al., 2018). Conversely, our study produced 112%–123% and 70%–71% of MVIC during the concentric and eccentric phase of DB and FLY SLRDL variations respectively when six repetitions with maximum speed were performed. Similarly, Koderi et al. (Koderi et al., 2020) have reported moderately high activity (47.3% of MVIC) in the gluteus maximus during barbell RDL using seven repetitions and constant tempo while all our SLRDL conditions yielded substantially higher muscle activities in both SGM and IGM. Apart from the additional motor unit recruitment when performing high-speed actions, it is speculated that the use of unilateral load may have imposed extra demands on the gluteal contraction. In this regard, it is worth noting that all SLRDL conditions in our study have shown a higher activation in SGM than IGM. Ho et al. (2020) have addressed the unique fiber orientation of SGM for producing additional hip abduction (in the frontal plane) and external rotation (in the transverse plane) movements when compared with the function of IGM. Given the nature of single-leg standing and using unilateral resistance in SLRDL, it is believed that higher demand for stabilization tasks in the frontal and transverse plane is imposed on SGM.

Although ES-D and ES-ND were not the primary agonists for hip extension in SLRDLs, these muscles were highly active in our

TABLE 3 Comparison of sEMG activities between loading positions during the single leg Romanian deadlift exercises.

	FLY-Con - FLY-Ipsi		DB-Con - DB-Ipsi	
	Difference in mean %MVIC±SD (95% CI)	Standardized difference (90% CI)	Difference in mean %MVIC±SD (95% CI)	Standardized difference (90% CI)
Concentric phase				
EO-D	−2.99 ± 17.59 (−19.08, 13.10)	−0.11 (−0.45, 0.23)	3.62 ± 9.28 (−4.89, 12.12)	0.24 (−0.07, 0.54)
EO-ND	−15.84 ± 17.41 (−31.93, 0.24)	−0.92 (−1.44, −0.4)	−7.53 ± 11.95 (−18.39, 3.87)	−0.64 (−1.18, −0.09)
AL	−21.90 ± 20.66 (−41.09, −2.71)[a]	−0.98 (−1.47, −0.5)	−13.55 ± 10.27 (−23.05, −4.06)**	−0.95 (−1.32, −0.58)
GM	34.06 ± 18.12 (17.24, 50.88)**	0.97 (0.70, 1.24)	16.95 ± 17.29 (0.99, 32.01)[a]	0.48 (0.23, 0.74)
ES-D	26.57 ± 12.93 (14.90, 38.25)**	0.70 (0.53, 0.87)	18.75 ± 14.88 (4.93, 32.57)**	0.43 (0.25, 0.61)
ES-ND	−26.993 ± 19.14 (−44.78, −9.21)**	−0.65 (−0.88, −.041)	−9.20 ± 23.01 (−30.70, 12.29)	−0.18 (−0.41, 0.05)
SGM	76.943 ± 45.26 (34.92, 118.97)**	1.32 (0.92, 1.73)	52.97 ± 49.5 (7.22, 98.71)[a]	0.81 (0.42, 1.2)
IGM	32.865 ± 23.31 (11.39, 54.34)**	0.67 (0.43, 0.92)	18.93 ± 19.52 (0.83, 37.04)[a]	0.53 (0.24, 0.81)
BF	10.480 ± 25.56 (−13.05, 34.01)	0.2 (−0.05, 0.45)	−2.27 ± 20.59 (−22.24, 17.71)	−0.04 (−0.24, 0.16)
Eccentric phase				
EO-D	5.39 ± 17.22 (−10.42, 21.10)	0.27 (−0.18, 0.73)	5.12 ± 10.88 (−5.05, 15.28)	0.32 (−0.04, 0.68)
EO-ND	−2.48 ± 6.71 (−8.75, 3.79)	−0.14 (−0.35, 0.06)	−4.01 ± 11.47 (−14.52, 6.49)	−0.31 (−0.76, 0.14)
AL	−11.46 ± 13.17 (−23.61, 0.6)	−0.87 (−1.38, −0.35)	−5.65 ± 4.95 (−10.24, −1.06)[a]	−0.61 (−0.89, −0.33)
GM	17.81 ± 13.49 (5.28, 30.34)**	0.82 (0.50, 1.15)	16.90 ± 12.24 (5.57, 28.23)**	0.76 (0.47, 1.05)
ES-D	4.22 ± 18.34 (−13.02, 21.46)	0.23 (−0.29, 0.74)	13.30 ± 8.42 (5.52, 21.08)**	0.62 (0.41, 0.82)
ES-ND	−10.96 ± 10.54 (−20.69, −1.23)[a]	−0.55 (−0.83, −0.28)	−8.54 ± 13.56 (−21.01, 3.92)	−0.29 (−0.52, −0.05)
SGM	30.08 ± 25.07 (6.94, 53.23)**	0.54 (0.31, 0.77)	33.69 ± 28.55 (7.22, 60.16)[a]	0.75 (0.42, 1.07)
IGM	11.33 ± 18.89 (−6.13, 28.79)	0.28 (0.04, 0.53)	14.12 ± 16.23 (−0.90, 29.15)	0.53 (0.21, 0.84)
BF	0.98 ± 32.77 (−32.23, 34.19)	0.02 (−0.42, 0.46)	−0.22 ± 22.3 (−12.68, 12.24)	−0.01 (−0.18, 0.17)

EO-D: the dominant side of external oblique; EO-ND: the non-dominant side of external oblique; AL: adductor longus; GM: gluteus medius; ES-D: the dominant side of erector spinae; ES-ND: the non-dominant side of erector spinae; SGM: superior gluteus maximus; IGM: inferior gluteus maximus; BF: biceps femoris; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading; CI: confidence interval.
[a]Significant difference with $p < 0.05$; **: significant difference with $p < 0.01$.

study to contract isometrically for spinal stabilization. In addition, most SLRDL variations in the current study yielded a moderate activation in EO-D and EO-ND while such a level of activation was believed to be sufficient to provide postural endurance and pelvic stabilization tasks (Hortobagyi et al., 2001), including antero-posterior tilt, lateral tilt, and transverse rotation. Besides, a high to very high activation in GM (40.6%–88.7%) was observed in our studies and these were comparable to the results demonstrated by Lane et al. (2019) and Stastny et al. (2016) using double-leg barbell and SL bodyweight RDL respectively. Since GM is an important stabilizer to control lateral pelvic tilt in the frontal plane, it is believed that the additional asymmetric load on SLRDL produced destabilizing torque on the pelvis in the frontal plane and led to a higher GM recruitment for pelvic stabilization. Based on these observations, unilaterally loaded SLRDL potentially provided dual training effects simultaneously including the strength enhancement of hip extensors and pelvic stabilization.

Interestingly, our results have shown no significant difference when comparing the FLY and DB SLRDL conditions. Only the non-clinical MBD showed a moderate increase of EO-ND when changing from DB-Ipsi to FLY-Ipsi conditions during concentric and also close to a moderate increase of EO-ND when changing the condition from DB-Con to FLY-Con during eccentric phases. Regarding the movement patterns of these two different SLRDL methods, both exercises required hip extension and posterior pelvic rotation in performing the concentric phase whereas hip flexion and anterior pelvic rotation of the supporting side were demanded during eccentric phase. Since the gripping position of dumbbell and the flywheel were standardized, the demand on maintaining spinal stability in both sagittal, frontal and transverse plane as well as the knee flexion angle of the supporting leg were comparable. Therefore, the identical movement patterns in the anatomical perspectives can justify for the high similarities of muscle activities between these two conditions. Nevertheless, it is noteworthy that the acceleration (during

TABLE 4 Comparison of sEMG activities between loading methods (dumbbell vs flywheel) during the single leg Romanian deadlift exercises.

	FLY-Con - DB-Con		FLY-Ipsi - DB-Ipsi	
	Difference in mean %MVIC±SD (95% CI)	Standardized difference (90% CI)	Difference in mean %MVIC±SD (95% CI)	Standardized difference (90% CI)
Concentric phase				
EO-D	2.02 ± 10.11 (−7.29, 11.33)	0.12 (−0.19, 0.43)	8.27 ± 17.98 (−8.19, 25.45)	0.34 (−0.03, 0.70)
EO-ND	4.80 ± 12.62 (−6.94, 16.36)	0.4 (−0.15, 0.95)	13.38 ± 16.52 (−1.89, 28.66)	0.79, (0.29, 1.30)
AL	0.65 ± 5.02 (−3.83, 5.13)	0.05 (−0.15, 0.25)	9.00 ± 19.16 (−8.70, 26.70)	0.39 (−0.04, 0.81)
GM	8.87 ± 26.87 (−15.83, 33.56)	0.23 (−0.13, 0.58)	−8.25 ± 4.34 (−22.77, 6.27)	−0.27 (−0.54, 0.00)
ES-D	10.84 ± 28.53 (−15.47, 37.15)	0.25 (−0.09, 0.60)	3.02 ± 20.11 (−15.65, 21.69)	0.08 (−0.19, 0.35)
ES-ND	−7.01 ± 21.24 (−26.43, 12.42)	−0.16 (−0.40, 0.09)	10.78 ± 26.96 (−14.18, 35.75)	0.22 (−0.06, 0.50)
SGM	1.30 ± 64.85 (−51.04, 53.63)	0.02 (−0.37, 0.41)	−22.68 ± 28.71 (−49.16, 3.80)	−0.50 (−0.83, −0.17)
IGM	15.59 ± 22.93 (−5.57, 36.75)	0.31 (0.07, 0.55)	1.66 ± 18.43 (−15.47, 18.79)	0.05 (−0.23, 0.33)
BF	9.45 ± 23.61 (−12.69, 31.59)	0.17 (−0.05, 0.4)	−3.30 ± 27.49 (−29.73, 23.13)	0.17, (−0.95, 0.40)
Eccentric phase				
EO-D	4.74 ± 13.95 (−8.29, 17.77)	0.25 (−0.13, 0.63)	4.52 ± 5.51 (−0.60, 9.63)	0.28 (0.10, 0.45)
EO-ND	8.45 ± 12.81 (−3.49, 20.39)	0.57 (0.12, 1.02)	6.92 ± 9.10 (−0.54, 15.37)	0.44 (0.14, 0.75)
AL	1.96 ± 3.78 (−1.51, 5.44)	0.25 (0.00, 0.49)	7.78 ± 12.34 (−3.66, 19.21)	0.55 (0.10, 1.01)
GM	1.54 ± 17.10 (−15.15, 18.23)	0.06 (−0.33, 0.46)	0.63 ± 9.00 (−7.96, 9.22)	0.03 (−0.21, 0.27)
ES-D	−3.42 ± 14.86 (−17.26, 10.42)	−0.17 (−0.55, 0.21)	5.67 ± 21.79 (−16.67, 26.00)	0.28 (−0.29, 0.85)
ES-ND	−7.10 ± 16.90 (−22.91, 8.72)	−0.26 (−0.58, 0.06)	−4.68 ± 14.18 (−17.62, 8.26)	−0.21 (−0.53, 0.11)
SGM	−1.45 ± 36.25 (−32.99, 30.09)	−0.03 (−0.33, 0.28)	2.16 ± 35.95 (−28.97, 33.29)	0.05 (−0.36, 0.46)
IGM	3.23 ± 17.00 (−12.75, 19.21)	0.08 (−0.14, 0.30)	6.02 ± 17.70 (−10.28, 22.32)	0.23 (−0.12, 0.57)
BF	0.22 ± 10.85 (−28.76, 29.13)	0.01 (−0.39, 0.40)	−0.99 ± 49.45 (−38.70, 36.72)	−0.02 (−0.46, 0.42)

EO-D: the dominant side of external oblique; EO-ND: the non-dominant side of external oblique; AL: adductor longus; GM: gluteus medius; ES-D: the dominant side of erector spinae; ES-ND: the non-dominant side of erector spinae; SGM: superior gluteus maximus; IGM: inferior gluteus maximus; BF: biceps femoris; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading; CI: confidence interval.

[a]Significant difference with $p < 0.05$; **: significant difference with $p < 0.01$.

concentric) and deceleration (during eccentric) in DB SLRDL might induce certain inertia and probably slightly change the actual perceived loading whereas the FLY provided an isoinertial condition. In contrast, participants might not be able to anticipate the sudden change of loading between the concentric and eccentric phases in FLY conditions. All these factors might contribute to any observable activation differences between FLY and DB SLRDL exercises. Further studies focusing on the onset of muscle activations during different moments of FLY and DB SLRDL are warranted. Although the exact resistance torque applied on the body was supposed to be different between FLY and DB conditions, when the selected load of DB SLRDL was adjusted to accommodate for equivalent movement speed as the FLY SLRDL drills, both exercises produced comparable hip and trunk muscle activities. Theoretically, the flywheel could overload and hence produce higher muscle activities during eccentric action (Norrbrand, 2008). In fact, it seemed that balance might also negatively affect the activation of prime movers (Marchetti et al., 2016). In this regard, it is speculated that the decrease of the base of support in our SLRDL during FLY conditions as well as the sudden change of pulling direction when starting the eccentric phase might increase the instability and hence hinder the proposed benefits of additional activation of the agonists.

When comparing the muscle activities between loading positions in FLY and DB conditions, contralaterally loaded conditions of FLY-Con and DB-Con have shown significantly higher GM and SGM activities than those ipsilaterally loaded conditions of FLY-Ipsi and DB-Ipsi respectively. Given the unique but similar fiber orientations of these two gluteal parts for providing lateral pelvic stability in the frontal plane, both FLY-Con and DB-Con placed the load further away from the supporting leg as the axis of rotation and hence higher demands on lateral stability in both the trunk and pelvic region. Likewise, a similar observation was made in the ES-D muscle while the ES-ND has shown an opposite result (FLY-Con < FLY-Ipsi; DB-Con < DB-Ipsi). On the other hand, although the external oblique

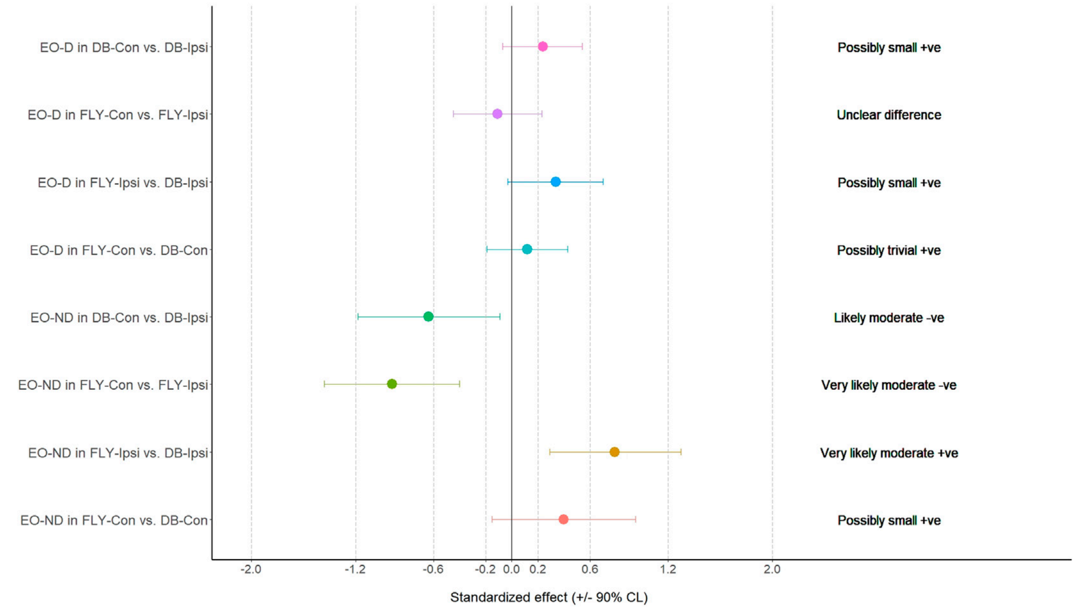

FIGURE 3
The results of magnitude-based decision for external oblique muscle during the eccentric phase EO-D: the dominant side of external oblique; EO-ND: the non-dominant side of external oblique; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading.

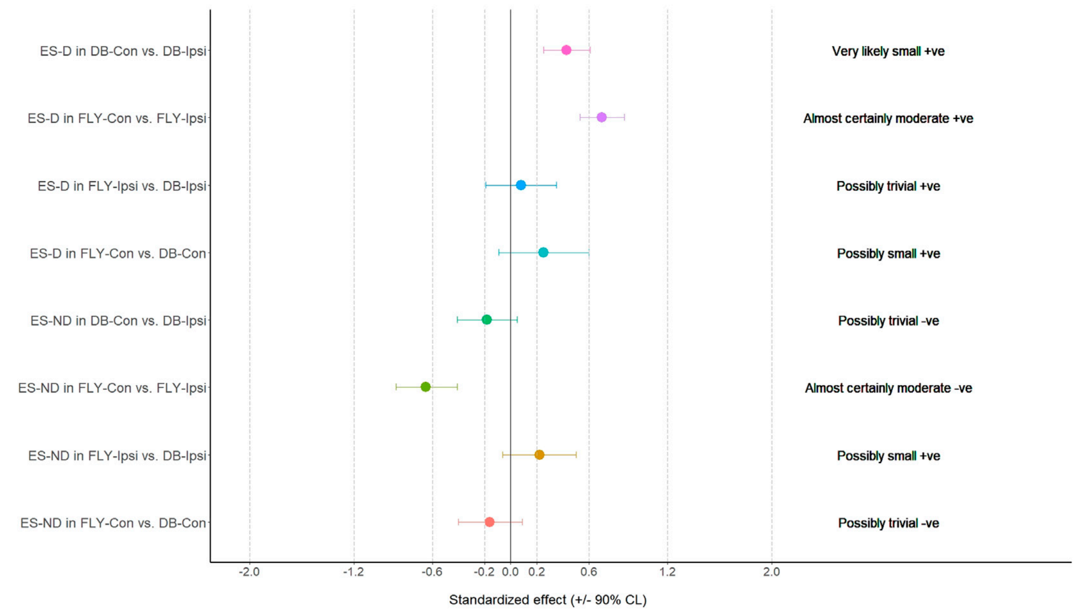

FIGURE 4
The results of magnitude-based decision for gluteal muscles during the eccentric phase GM: gluteus medius; SGM: superior gluteus maximus; IGM: inferior gluteus maximus; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading.

muscle was responsible for both rotational and lateral stability in trunk and pelvic regions, the SLRDL exercises provided the anti-flexion challenge to the spine rather than anti-extension, therefore EO-D and EO-ND were not as active as ES-D and ES-ND. Our results showed no significant difference between contralateral and ipsilateral conditions for EO-D and EO-ND parts whereas moderate effects existed when comparing the FLY-Ipsi or DB-Ipsi with FLY-Con and DB-Con. Such potential clear differences could be attributable to the additional anti-rotation works produced by EO for postural control and balance during SLRDL with different loading positions.

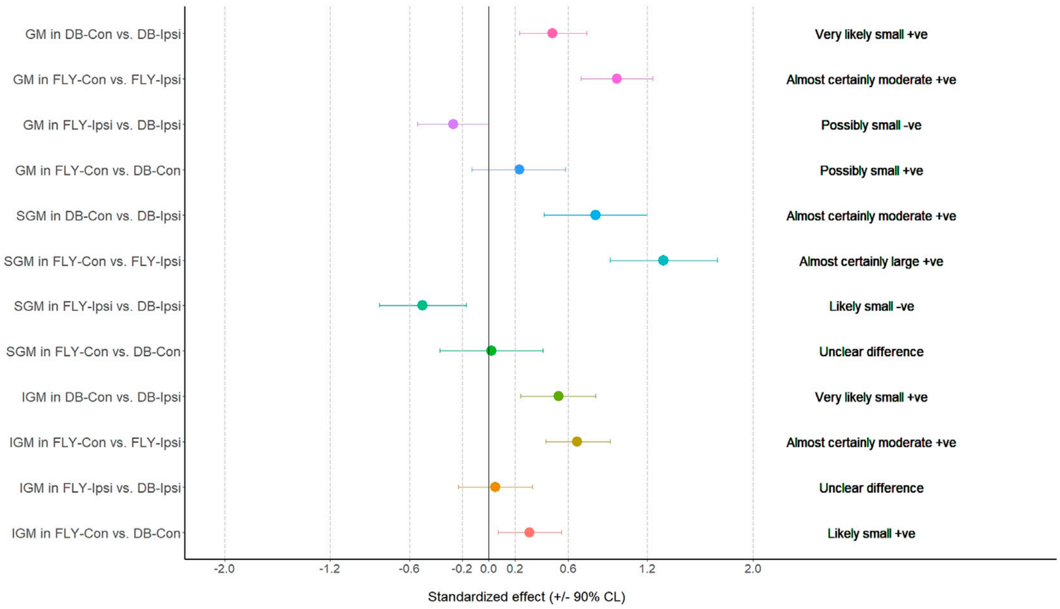

FIGURE 5
The results of magnitude-based decision for biceps femoris and adductor longus during the eccentric phase AL: adductor longus; BF: biceps femoris; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading.

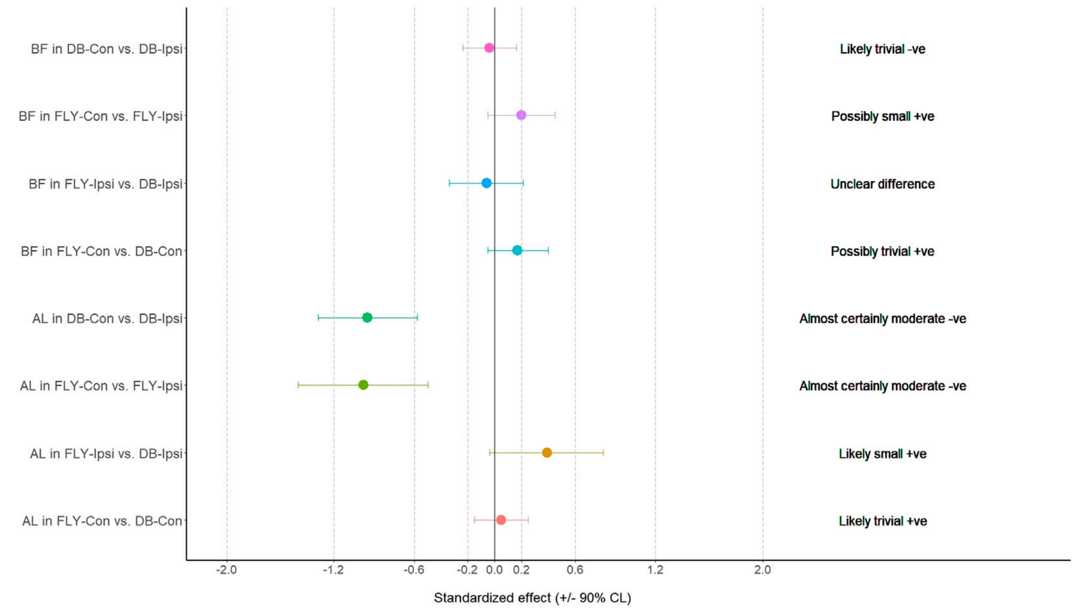

FIGURE 6
sEMG values of trunk and lower limb muscles of the 4 variations of single-leg Romanian deadlift during concentric phase EO-D: the dominant side of external oblique; EO-ND: the non-dominant side of external oblique; AL: adductor longus; GM: gluteus medius; ES-D: the dominant side of erector spinae; ES-ND: the non-dominant side of erector spinae; SGM: superior gluteus maximus; IGM: inferior gluteus maximus; BF: biceps femoris; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading; The red line represents the threshold for effective strengthening effect with a very high muscle activity (>60%) and the green line presents the high muscle activity (>40%).

This study was not without limitations. The cross-talk might occur due to the very tight and close electrode placements and the overlapped abdominal or gluteal muscles. As SLRDL is a functional strength exercise highly challenging on neuromuscular control and balance, the determination of maximum strength using one or six repetition maximum was almost impossible. Therefore, the relative load to the corresponding maximum strength of each subject in performing SLRDL was not assessed.

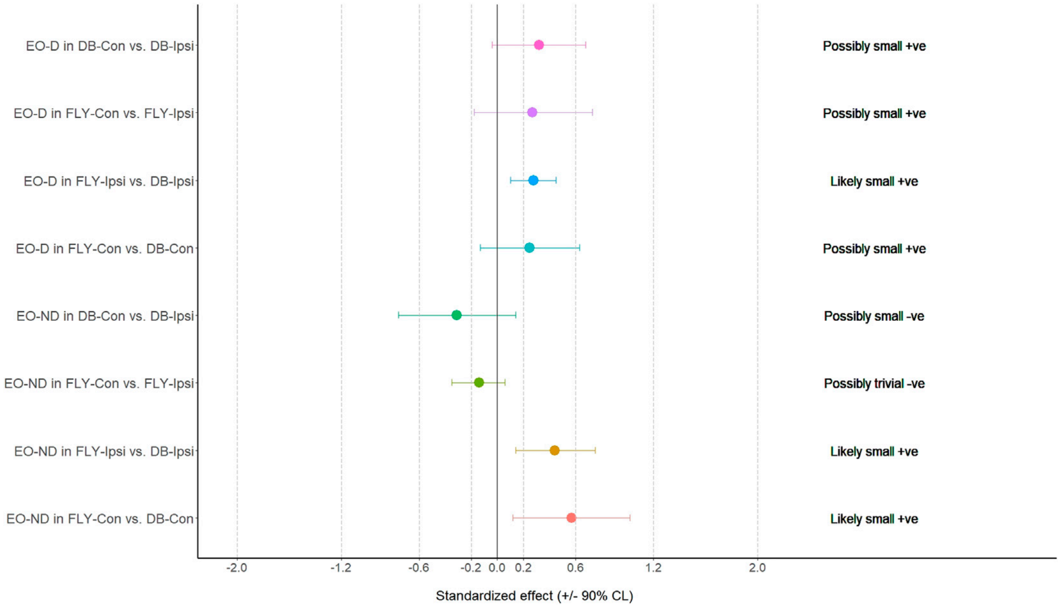

FIGURE 7
sEMG values of trunk and lower limb muscles of the 4 variations of single-leg Romanian deadlift during eccentric phase EO-D: the dominant side of external oblique; EO-ND: the non-dominant side of external oblique; AL: adductor longus; GM: gluteus medius; ES-D: the dominant side of erector spinae; ES-ND: the non-dominant side of erector spinae; SGM: superior gluteus maximus; IGM: inferior gluteus maximus; BF: biceps femoris; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading; The red line represents the threshold for effective strengthening effect with a very high muscle activity (>60%) and the green line presents the high muscle activity (>40%).

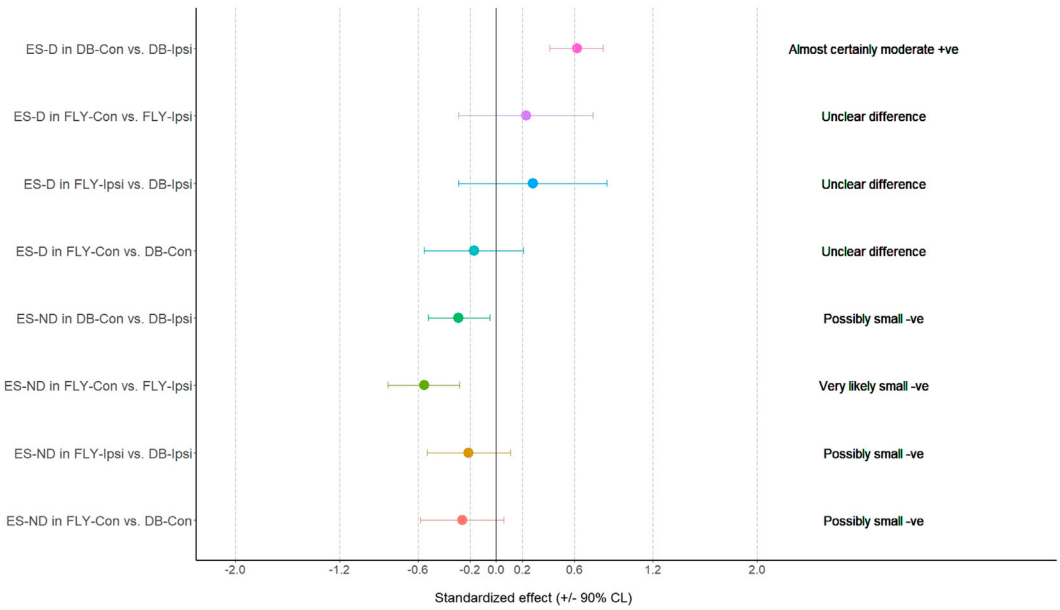

FIGURE 8
The results of magnitude-based decision for external oblique muscle during the concentric phase EO-D: the dominant side of external oblique; EO-ND: the non-dominant side of external oblique; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading.

5 Practical applications

The findings of the present study provide strength coaches and clinicians with empirical evidence for better exercise selection and implementation. Whenever strength coaches and clinicians look for using RDL exercise to strengthen the hip extensors, SLRDL using a dumbbell or flywheel with contralateral loading position is highly recommended to effectively strengthen the BF, SGM, IGM, GM, ES-

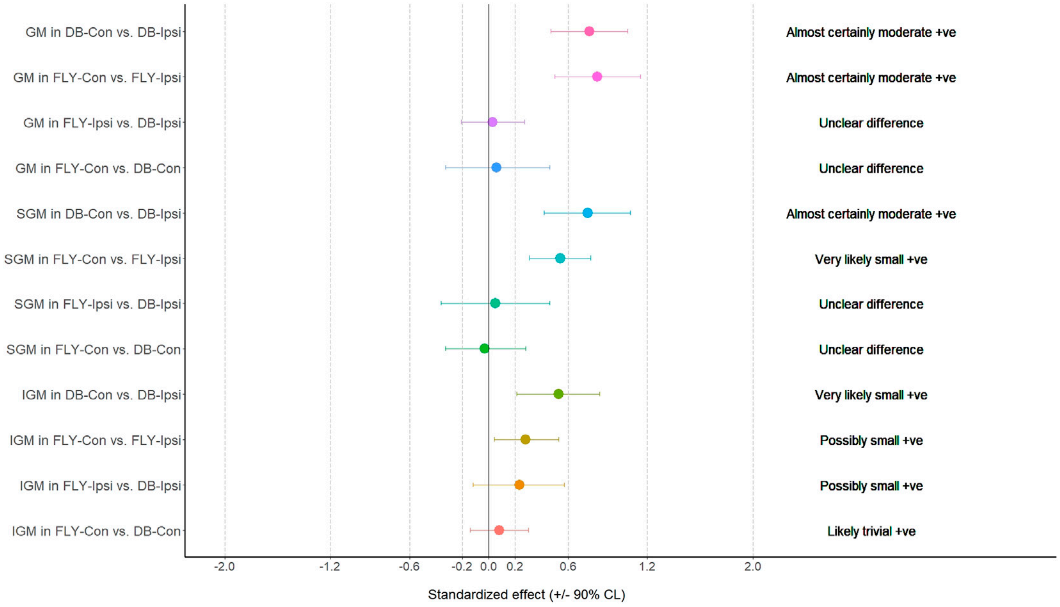

FIGURE 9
The results of magnitude-based decision for erector spinae muscle during the concentric phase ES-D: the dominant side of erector spinae; ES-ND: the non-dominant side of erector spinae; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading.

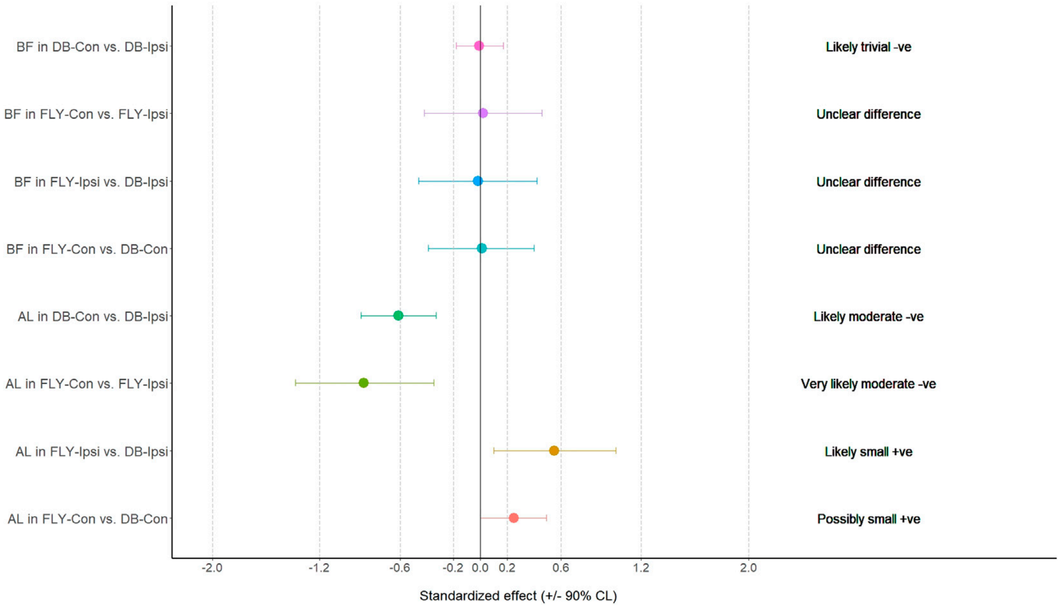

FIGURE 10
The results of magnitude-based decision for gluteal muscles during the concentric phase GM: gluteus medius; SGM: superior gluteus maximus; IGM: inferior gluteus maximus; FLY-Con: flywheel with contralateral loading; FLY-Ipsi: flywheel with ipsilateral loading; DB-Con: dumbbell with contralateral loading; DB-Ipsi: dumbbell with ipsilateral loading.

D, and ES-ND muscles. Meanwhile, it also enhances the activation of trunk and pelvic stabilization muscles concurrently. Therefore, it can be a good option to potentially produce dual strengthening effects for both hip extensors and pelvic stabilizers. Given very high BF activation during the eccentric phase in FLY or DB conditions, SLRDL is potentially an effective method to enhance the eccentric strength for reducing the risk of hamstring tear. Coaches may also consider adding SLRDL drills into the warm-up routine to activate multiple trunk and hip muscles for better neuromuscular control before high-intensity training.

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 Technological and Higher Education Institute of Hong Kong. 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

RM: Data curation, Formal Analysis, Investigation, Methodology, Project administration, Writing–original draft. DN: Data curation, Investigation, Methodology, Project administration, Writing–original draft. CN: Data curation, Formal Analysis, Investigation, Methodology, Project administration, Writing–original draft. KS: Data curation, Formal Analysis, Investigation, Methodology, Project administration, Writing–original draft. JL: Conceptualization, Project administration, Supervision, Validation, Writing–review and editing. IH: Conceptualization, Data curation, Formal Analysis, Methodology, Supervision, Validation, Visualization, Writing–review and editing.

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Conflict of interest

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

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Quantifying technical load and physical activity in professional soccer players during pre-season matches with IMU technology

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This study aimed to record, analyze and quantify professional soccer players' technical (TL) and physical load (PL) in friendly matches to compare their records during the first and second halves and between players with different positions. Eighteen professional soccer players, 24.6 ± 2.7 years, 1.78 ± 0.3 height (m), 74.6 ± 4.5 body mass (kg), 9.8 ± 2.2 body fat (%), and 65.6 ± 2.7 maximal oxygen consumption (VO_{2max}, ml·kg^{-1}·min^{-1}) were monitored during six preseason friendly matches to analyze the activity profile using technical and physical variables through inertial measurement unit (IMU). No significant differences were found between the periods for the TL and PL. Significant differences were found between specific positions: Full Back (FB: n = 4), Central Defender (CD: n = 3), Midfielder (MD: n = 4), Winger (WG: n = 4), and Forward (FW: n = 3), both the TL and PL. We conclude that the PL profile based on his playing position is independent of the development of the PL shown during friendly matches. The monitoring, quantifying, and controlling of the TL added to the PL provides a more holistic vision of soccer players in friendly matches. The relative ease IMU application technology offers an alternative with less time-cost and more significant benefits than other types of technologies applied up to now.

KEYWORDS

soccer (football), monitoring, technical load, physical load, quantifying

Introduction

Soccer performance is multifactorial and requires training programs that combine technical, tactical, and psychological aspects (Stølen et al., 2005). That´s why the more incredible the information and control of these types of variables, the more informed decision-making by the members of the coaching staff, the greater the chances of improving the performance of soccer players and increasing the chances of success (Buchheit et al., 2014; Taberner et al., 2020). In matches, players typically transition between short, high-intensity efforts and long periods of low-intensity activities (Bangsbo et al., 2006). However, performance in soccer depends on these more physiological factors. Still, there are various factors, possibly more determinants, such as technical, tactical, or mental, which also greatly influence performance (Torreño, 2017). Currently, the design of soccer training sessions and tasks are based on technical-tactical and physical actions directly related to simulated game situations, to the detriment of analytical studies, due to the close relationship of these actions with the activity carried out in the matches (Carling, 2013; Barrett et al., 2020). However, the design and implementation of these training tasks can cause different results after their completion since there are endless variables that directly influence the development obtained, such as the dimension of the pitch, the number of participating players, the number of touches allowed, the tactical instructions to comply with or the work-rest ratios between series-repetitions (Akenhead and Nassis, 2016). In recent years, the means for monitoring and quantifying PL have proliferated, both in training sessions and matches using GPS technology (Barbero-Álvarez et al., 2009; Akenhead et al., 2013; Malone et al., 2015; Suarez-Arrones et al., 2015; Akenhead and Nassis, 2016; Barrett et al., 2020). However, this physical analysis does not demand special attention to the technical-tactical demands to which soccer players are subjected (Barnes et al., 2014) and is called TL. Until recently, TL data was obtained through complex infrastructures, such as video analysis and semi-automatic recording systems (Di Salvo et al., 2006; Castellano et al., 2014; Arjol-Serrano et al., 2021) or local positioning systems (Curtis et al., 2019). Recently, inertial measurement devices (IMU) have been designed (Edwards et al., 2019), which, placed in the soccer player´s boot, can represent a low-cost option that improves the task of monitoring the soccer player´s TL and PL. Some studies have shown the ability to monitor both TL and PL in English professional teams over an extended period of the season, analyzing the tasks of training sessions with male and female players (Barrett et al., 2020; Marris et al., 2021; Lewis et al., 2022; Myhill et al., 2022). Previous studies on monitoring TL and PL in soccer players have primarily focused on official matches or without considering TL (Barnes et al., 2014; Suarez-Arrones et al., 2015; Akenhead and Nassis, 2016), this is where we find a gap in information and knowledge, which P.S. Bradley (2020) himself questions, running from a "traditional" to an "integrated" approach to understanding the demands of the game. Therefore, there needs to be more research in understanding TL and PL profiles, specifically during preseason and friendly. The objectives are to record, analyzing and quantify the TL and PL of professional soccer players in friendly matches, compare their records during the first and second halves, and professional soccer players during friendly matches. Specifically, the study aims to compare TL and PL records between the first and second halves of and among players in different specific positions in the preseason. We hypothesize that there could be significant differences in TL and PL between the first and second halves of matches. Additionally, we expect to observe variations in TL and PL among players with different specific positions.

Material and methods

Participants

A total of 18 professional soccer players (n = 18) aged 24.6 ± 2.7 years, 1.78 ± 0.32 height (m), 74.6 ± 4.5 body mass (kg), 23.54 ± 2.7 body mass index (kg.m^2), 9.8% ± 2.2% body fat, and 65.6 ± 2.7 maximal oxygen consumption (VO_{2max}, ml·kg^{-1}·min^{-1}) belonging to the same team, took part in this study. The inclusion criteria were only data from outfield players who participated a minimum of 45 min in one of the two periods. In addition, participants were required to be in good health and free from any injuries that could affect their performance during the matches. At the same time, the exclusion criteria were one friendly match due to their extension of more than 90 min. Also, goalkeepers were excluded from the study to focus specifically on outfield players and their activity profiles. In the study, 103 records were made, 59 for the first period and 44 for the second one. The players were classified according to their specific position: Full Back (FB: n = 4), Central Defender (CD: n = 3), Midfielder (MD: n = 4), Winger (WG: n = 4), and Forward (FW: n = 3). All of them were previously informed about the object of study and provided their signed informed consent, following the indications of the Declaration of Helsinki (2013). Before starting the study, it was approved by the ethics committee of Pablo de Olavide University with code 0398-N17.

Sample size

To determine the sample size for this study, we employed G*Power software 3.1.9.7 (Faul et al., 2007) and conducted *a priori* calculations using the t-test family. We set the significance level (α) to 0.05, the desired power (1 - β error probability) to 0.80, and based on the effect size on previous studies (Nobari et al., 2021a; Nobari et al., 2021b), ranging from medium to high. The analysis indicated that a total sample size of 16 participants would yield an actual power of 81% for the present analysis.

Study design

The study employed a descriptive design, observing the methodology applied in data collection. Data were collected during friendly matches in the 2020-21 preseason (August-October) involving a professional soccer team competing in the third tier of Spanish soccer. The preseason period is characterized by a high PL for the players (Ade et al., 2016). Furthermore, the distribution of playing minutes in these friendly matches was evenly spread across all members of the team's squad. Throughout the 7-week preparatory period, the team conducted 38 training sessions and participated in 7 friendly matches (with one match excluded from this study). The matches were played 5–7 days apart in the morning, between 10 and 11 a.m., all of them belonging to the same competitive level as us. All anthropometric measurements, body composition and VO_{2max} were performed before the preseason.

Process and variables

Anthropometric, body composition and maximal oxygen consumption (VO_{2max})

The anthropometric, body composition and maximal oxygen consumption (VO_{2max}) measurements were performed by specialist at the Andalusian Sport Medicine Center (https://www.juntadeandalucia.es/organismos/turismoculturaydeporte/areas/deporte/medicina-deportiva/sedes-camd/paginas/camd-cadiz.html) during 24th

FIGURE 1
Timeline of the collecting data process using IMU technology (Playermaker™).

to 26th August 2020. Laboratory testing was conducted between 9 a.m. and 12 p.m. with ambient temperature between 22°C and 24°C. To measure height and body mass, the participants stood without shoes and with only shorts. For both measurements, a portable stadiometer (accuracy of ±5 mm) and balance weighting scales (accuracy of ±0. 1 kg) (Seca model 207, Germany) were used.

Body mass index (kg/m^2) was calculated using body mass/ height^2. Measuring the skinfold thickness at seven sites (chest, axilla, triceps, abdominal, subscapular, suprailiac and thigh) using a calliper (Holtain Skinfold Caliper, Holtain, UK). One experienced anthropometrist carried out all the anthropometric tests following the anthropometric measurement protocols established by the International Society for the Advancement of Kinanthropometry (ISAK). The percentage of body fat was calculated following Faulkner (1966).

A maximal exercise test on a treadmill (TM Trackmaster, United States) with a continuous and incremental protocol was made to calculate VO_{2max} designed by the components of the sports medicine service (Andalusian Sport Medicine Center). The initial speed was 9 km/h^{-1} for 3 min, then increased by 1 km/h every minute until exhaustion occurred within 10–15 min for all subjects. Maximal oxygen uptake was measured during both tests via a breath-by-breath gas analyzing system (Quark b2, Cosmed Co., Rome, Italy). The VO_{2max} with the highest VO_2 was calculated when a plateau in O_2 consumption was reported despite an increased workload. All these measures are considered as dependent variables in this study.

Monitoring technical load (TL) and physical load (PL)

The players' demands during friendly matches were monitored using an IMU technology-based data collection instrument (Figure 1). Smart motion devices (Playermaker™, Tel Aviv, Israel) were directly mounted on the soccer players' boots to quantify TL and PL. Each IMU device incorporated two components from the MPU-9150 multi-chip (InvenSense, California, United States), which included a 16 g triaxial accelerometer and a 2000°/sec-1 triaxial gyroscope. Previous studies have demonstrated the excellent inter-unit reliability of these devices for all PL variables compared to GPS devices (Waldron et al., 2021). Similarly, when comparing TL variables with video analysis, these units have shown validity and reliability (Marris et al. (2021). Prior to the start of each match, following the completion of warm-up activities, each player was provided with an IMU device inserted into a silicone flange, which was placed beneath the lateral malleolus of their foot. Subsequently, after each match, the devices were placed in a docking box connected via Bluetooth to an iPad (Apple Inc., California). In this setup, each device downloaded the recorded data into Playermaker™ Dashboard software (v.3.22.0.02) for subsequent processing and analysis.

The TL variables analyzed have been: Total Touches (TT: number (#) of times the ball hits the player's feet); Releases (REL: number (#) of times the player throws the ball with his foot); Total Possessions (TP: number (#) of times the player maintains possession of the ball); One touch (1T: number (#) of times the player contacts the ball without reception); Short Possessions (SP: number (#) of times the player maintains possession of the ball for no more than 2.5 s); Long Possessions (LP: number (#) of times the player retains control of the ball for more than 2.5 s); Receptions (RC: number (#) of times the player receives the ball); Release Velocity (RV: speed quantified in meters per second (m/s), with which the player performs the mechanical gesture at the moment of hitting the ball); Release Index (RI: is an indicator that combines the volume and intensity of each hit by the player and is presented as a single value (Arbitrary Units, AU, numeric) (Lewis et al., 2022).

The PL variables analyzed have been: Top Speed (TS: highest speed peak (m/s) reached by a player); Distance Covered (DC: amount of total distance (m) traveled in meters); Work Rate (WR: indicator (m/min) of load measured in amount of distance traveled in meters (m) between the time measured in minutes (min); High Intensity Distance Covered (HIDC: total amount of distance (m) covered in a speed range greater than 4.1 m/s; Sprint Distance Covered (SDC: total distance (m) traveled in a range greater than speed of 5.83 m/s); Number of Sprints (SP: number (#) of times the player reaches a speed greater than 5.83 m/s); Distance Traveled Zone 1 (DTZ1: total amount of distance (m) traveled in meters in a speed range of 0.0–2.5 m/s); Distance Traveled Zone 2 (DTZ2: Total amount of distance (m) traveled in meters in a speed range of 2.5–4.17 m/s); Distance Traveled Zone 3 (DTZ3: total amount of distance (m) traveled in meters in a speed range of 4.17–5.0 m/s); Zone 4 Distance Traveled Zone 4 (DTZ4: total amount of distance (m) traveled in meters in a speed range of 5.0–5.83 m/s), Distance Traveled Zone 5 (DTZ5: amount of total distance (m) traveled in

TABLE 1 Descriptive analysis of TL variables in absolutes (#) and relatives (#/min) values concerning time and speed releases (m/s).

TL variables	1st half	2nd half	t-test (p)	ES (d)	%Dif
TT (#)	47.0 ± 18.5	48.7 ± 26.4	0.57	−0.08	−3.62
TT (#/min)	1.03 ± 0.40	1.03 ± 0.51	0.92	0.00	0.00
REL (#)	16.4 ± 9.6	15.6 ± 10.7	0.77	0.12	7.15
REL (#/min)	0.36 ± 0.21	0.33 ± 0.23	0.55	0.18	11.11
TP (#)	17.7 ± 9.4	19.3 ± 10.4	0.47	−0.13	−7.08
TP (#/min)	0.39 ± 0.20	0.41 ± 0.23	0.68	−0.05	−2.56
1T (#)	6.0 ± 3.7	6.5 ± 3.2	0.36	−0.16	−9.24
1T (#/min)	0.13 ± 0.08	0.14 ± 0.07	0.55	−0.13	−7.69
SP (#)	4.8 ± 3.7	5.1 ± 3.9	0.48	−0.06	−4.97
SP (#/min)	0.11 ± 0.08	0.11 ± 0.08	0.66	0.00	0.00
LP (#)	6.9 ± 4.3	7.4 ± 5.1	0.44	−0.11	−7.12
LP (#/min)	0.15 ± 0.09	0.16 ± 0.11	0.66	−0.10	−6.67
RC (#)	11.7 ± 6.7	12.4 ± 8.1	0.41	−0.10	−6.23
RC (#/min)	0.26 ± 0.15	0.27 ± 0.17	0.15	−0.06	−3.85
RV Avg (m/s)	13.6 ± 1.1	13.7 ± 1.4	0.90	−0.11	−1.03
RV Max (m/s)	19.0 ± 1.5	19.3 ± 1.5	0.90	−0.20	−1.53
RI	22.6 ± 13.0	21.1 ± 14.6	0.96	0.08	4.82
RI/min	0.48 ± 0.29	0.46 ± 0.33	0.72	0.07	4.17

Note: TT: total touches; REL: releases; TP: total possessions; 1T: one touch; SP: short possession; LP: long; RC: receptions; RV: release velocity; RI: Release Index. Data are shown as mean ± standard deviation.

meters in a speed range of 5.83–6.66 m/s); Distance Traveled Zone 6 (DTZ6: amount of total distance (m) traveled in meters in a speed range greater than 6.66 m/s); Acceleration/Deceleration Actions (ADA: number (#) of times the player performs an intense change of direction and speed variation, in an accelerated or decelerated manner, in a speed range greater than 2.6 m/s^2).

The data corresponding to TL variables: TT, LAN, REL, 1T, SP, LP, RC and RV and, to PL variables: HIDC, SDC, SP and ADA, are presented both in absolute values and relative to the time of game. For this, the data obtained in the first half's friendly matches (average and standard deviation) are differentiated from those of the second period.

Statistical analysis

All variables were presented as mean values and standard deviations. The normal distribution of the data sets was assessed using the Shapiro-Wilk normality test. To analyze the differences between the first and second halves of technical load (TL) and physical load (PL), paired sample t-tests were performed. Additionally, a one-way analysis of variance (ANOVA) was utilized to compare the mentioned variables among playing positions during the preseason and a Bonferroni *post hoc* test was conducted to further investigate significant differences. A significance level of 95% was employed to determine statistical significance.

The effect size (ES) for the difference between variables was evaluated using Cohen's d (Cohen, 1998). A value of d < 0.1, 0.1 to 0.20, 0.20 to 0.50, 0.50 to 0.80, and >0.80 was considered trivial or no effect, small, moderate, large, and very large, respectively. The SPSS software for Windows (v. 26; IBM, Chicago, United States) was used for data analysis.

Results

The results obtained for the variables TL and PL are shown in Tables 1, 2, respectively. When comparing the TL for the first and second periods, no significant differences were observed in any of the variables analyzed. In the analysis of the PL variables, we found that WR (m/min) (p = ≤ 0.001, ES: 0.92), DC (m) (p = 0.02, ES: 0.57), HIDC (m) (p = 0.01, ES: 0.27), HIDC (m/min) (p = ≤ 0.001, ES: 0.36), SDC (m) (p = 0.02, ES: 0.21), SDC (m/min) (p = 0.01, ES: 0.23), SP (#) (p = 0.04, ES: 0.29), SP (#/min) (p = 0.01, ES: 0.37), DTZ3 (p = 0.01, ES: 0.31), DTZ4 (p = 0.01, ES: 0.26) and DTZ5 (p = 0.02, ES: 0.24), generate significantly higher values in the first part than in the second.

Tables 3, 4 show the results for each TL and PL variable, respectively, attending to the different positions for players who completed the first half. Significant differences by position are observed for both TL variables and PL variables. Considering TL variables by specific positions, the MDs are the ones that generated a more excellent record of TT without reaching significant differences with CD (p = 0.84) but obtaining significant differences with FB (p = 0.01) and with FW ($p \leq 0.001$).

TABLE 2 Descriptive analysis of PL variables in absolutes (#; m) and relatives (#/min; m/min) values, concerning time.

PL variables	1st half	2nd half	t-test (p)	ES (d)	%Diff
TS (m/s)	7.4 ± 0.5	7.5 ± 0.4	0.65	−0.20	−1.22
DC (m)	4968.2 ± 477.0	4600.7 ± 828.2	0.02*	0.57	7.40
WR (m/min)	108.6 ± 10.5	96.5 ± 16.2	≤0.001*	0.92	11.16
HIDC (m)	1255.4 ± 967.1	1027.8 ± 651.8	0.01*	0.27	18.13
HIDC (m/min)	27.4 ± 21.0	21.7 ± 14.4	≤0.001*	0.36	23.91
SDC (m)	298.0 ± 364.6	232.0 ± 229.2	0.02*	0.21	22.14
SDC (m/min)	6.5 ± 7.9	4.9 ± 5.0	0.01*	0.23	24.46
SP (#)	20.3 ± 9.8	17.7 ± 7.3	0.04*	0.29	12.68
SP (#/min)	0.44 ± 0.22	0.37 ± 0.15	0.01*	0.37	15.91
DTZ1 (m)	2106.6 ± 436.0	2107.6 ± 513.0	0.24	0.00	−0.03
DTZ2 (m)	1606.8 ± 592.6	1464.6 ± 586.3	0.52	0.24	8.85
DTZ3 (m)	573.5 ± 299.5	490.6 ± 229.4	0.01*	0.31	14.44
DTZ4 (m)	383.9 ± 347.4	305.2 ± 239.0	0.01*	0.26	20.52
DTZ5 (m)	222.5 ± 282.5	165.5 ± 167.1	0.02*	0.24	25.62
DTZ6 (m)	75.5 ± 93.7	66.5 ± 73.0	0.13	0.11	11.87
ADA (#)	27.6 ± 7.6	25.2 ± 9.8	0.24	0.28	8.66
ADA (#/min)	0.60 ± 0.16	0.53 ± 0.20	0.07	0.40	11.67

Note: TS: top speed; DC: distance covered; WR: work rate; HIDC: high intensity distance covered; SDC: sprint distance covered; SP: number of sprints; DTZ1: Distance Traveled Zone 1; DTZ2: Distance Traveled Zone 2; DTZ3: Distance Traveled Zone 3; DTZ4: Distance Traveled Zone 4; DTZ5: Distance Traveled Zone 5; DTZ6: Distance Traveled Zone 6; ADA: Acceleration/ Deceleration Actions. Data are shown as mean ± standard deviation. * Significant differences between the first and second half.

In the same way, MD also generates the best record for 1T, reaching significant differences with WG ($p \leq 0.001$) and FW ($p = 0.01$). In contrast, they do not differ significantly with CD ($p = 0.87$) or FB ($p = 0.80$), respectively. In the same way, CD generates the best record for REL without reaching significant differences with FB ($p = 0.09$) or with MD ($p = 0.34$) but obtaining significant differences with FW ($p \leq 0.001$). CD also generates the best record for TP, with substantial differences with FB ($p = 0.04$), WG ($p = 0.02$) and FW ($p \leq 0.001$), while no significant differences were found with MD ($p = 0.12$). In the same way, CD generates the best records for SP, LP, RC, RV and RI.

On the other hand, considering PL variables, the highest values by position are found for FB in TS, reaching significant differences with CD ($p \leq 0.001$), MD ($p \leq 0.001$) and FW ($p = 0.03$). In contrast, they do not reach significant differences with WG ($p = 0.92$). In the same way, the MD are those that reach the highest records in DC, with significant differences with CD ($p \leq 0.001$), FB ($p \leq 0.001$) and WG ($p = 0.03$); WR being the significant differences with CD ($p \leq 0.001$), FB ($p \leq 0.001$), WG ($p = 0.03$) and FW ($p \leq 0.001$); DTZ2 being the significant differences with CD ($p \leq 0.001$), FB ($p \leq 0.001$), WG ($p \leq 0.001$) and FW ($p \leq 0.001$); DTZ3 being the significant differences with CD ($p \leq 0.001$), FB ($p \leq 0.001$) and FW ($p \leq 0.001$); Similarly, the WG reach the highest records in the following variables: HIDC (finding significant differences with CD ($p = 0.01$), FB ($p \leq 0.001$) and FW ($p = 0.02$); DS (finding significant differences with CD ($p = 0.01$), FB ($p = 0.01$), MD ($p = 0.01$) and FW ($p = 0.02$)); SP (finding significant differences with CD ($p = 0.01$), FB ($p = 0.01$), MD ($p = 0.01$) and FW ($p = 0.02$)); DTZ4 (finding significant differences with CD ($p = 0.02$), FB ($p = 0.01$) and FW ($p = 0.03$)); DTZ5 (finding significant differences with CD ($p = 0.01$), FB ($p = 0.01$) and FW ($p = 0.03$)); and finally in DTZ6 (finding significant differences with CD ($p \leq 0.001$), MD ($p \leq 0.001$) and FW ($p = 0.01$)); and finally, for FW in DTZ1 (finding significant differences with MD ($p = 0.03$) and WG ($p = 0.04$). The number of accelerations (ADA) and accelerations per minute (ADA/min) are the only variables that did not manifest differences by positions.

Discussion

This study aimed to analyze the activity profile of professional soccer players during friendly matches using TL and PL variables. The main findings include the first-ever description of the TL profile based on players' positions during matches. Secondly, an intriguing observation emerged from the analysis of TL and PL. Despite significant modifications in the PL profile between the first and second halves of the matches, the TL profile remained remarkably consistent. This suggests that the technical demands placed on players, as reflected by TL variables, are relatively independent of the overall physical load experienced during the match. This finding underscores the complexity of soccer performance, where the interplay between technical and physical elements may not necessarily exhibit a direct correspondence. These results emphasize the independent nature of TL from PL and provide

TABLE 3 Descriptive analysis of TL variables by playing positions.

TL variables	FB (4 players)	CD (3 players)	MD (4 players)	WG (4 players)	FW (3 players)
TT (#)	43.48 ± 15.99^{b,c,d,e}	54.86 ± 22.47^{a,e}	56.29 ± 18.33^{a,e}	49.17 ± 15.82^{a,e}	30.50 ± 13.17^{a,b,c,e}
TT (#/min)	0.95 ± 0.34^{c,d,e}	1.18 ± 0.50^{e}	1.23 ± 0.40^{a,e}	1.26 ± 1.50^{a,e}	0.66 ± 0.27^{a,b,c,e}
REL (#)	15.87 ± 7.36^{c,e}	22.10 ± 12.76^{d,e}	20.93 ± 9.01^{a,d,e}	12.75 ± 6.05^{b,c}	7.20 ± 6.23^{a,b,c}
REL (#/min)	0.34 ± 0.16^{c,e}	0.48 ± 0.28^{d,e}	0.46 ± 0.19^{a,d,e}	0.28 ± 0.12^{b,c}	0.15 ± 0.13^{a,b,c}
TP (#)	18.65 ± 8.03^{b,e}	24.62 ± 11.51^{d,e}	21.86 ± 8.96^{d,e}	15.42 ± 6.27^{b,c,e}	8.00 ± 6.60^{a,b,c,d}
TP (#/min)	0.41 ± 0.17^{e}	0.52 ± 0.25^{d,e}	0.48 ± 0.19^{d,e}	0.33 ± 0.13^{b,c,e}	0.17 ± 0.14^{a,b,c,d}
1T (#)	7.09 ± 3.30^{e}	7.05 ± 3.34^{e}	7.64 ± 3.79^{d,e}	5.33 ± 3.45^{c}	2.40 ± 2.07^{a,b,c}
1T (#/min)	7.09 ± 3.30^{e}	7.05 ± 3.34^{e}	7.64 ± 3.79^{d,e}	5.33 ± 3.45^{c}	2.40 ± 2.07^{a,b,c}
SP (#)	4.70 ± 3.42^{b,e}	7.24 ± 4.01^{a,d,e}	6.07 ± 3.20^{d,e}	3.00 ± 2.66^{b,c}	1.70 ± 2.06^{a,b,c}
SP (#/min)	0.10 ± 0.07^{b,e}	0.16 ± 0.09^{a,d,e}	0.13 ± 0.07^{d,e}	0.06 ± 0.06^{b,c}	0.04 ± 0.04^{a,b,c}
LP (#)	6.09 ± 3.36^{b,d}	9.57 ± 5.83^{a,e}	8.14 ± 4.66^{e}	7.08 ± 2.68^{a}	2.90 ± 3.81^{b,c}
LP (#/min)	0.13 ± 0.07^{b,d,e}	0.21 ± 0.13^{a,e}	0.18 ± 0.10^{e}	0.15 ± 0.06^{a}	0.08 ± 0.08^{a,b,c}
RC (#)	10.78 ± 4.80^{b,c,e}	16.81 ± 9.31^{a,d,e}	14.21 ± 5.83^{a,d,e}	10.08 ± 4.21^{b,c}	5.60 ± 5.15^{a,b,c}
RC (#/min)	0.24 ± 0.10^{c,e}	0.70 ± 1.54^{d,e}	0.31 ± 0.12^{a,d,e}	0.22 ± 0.09^{b,c}	0.12 ± 0.11^{a,b,e}
RV Avg (m/s)	13.63 ± 0.77^{bi}	14.47 ± 0.62^{a,c,e}	13.48 ± 0.91^{b}	13.86 ± 1.08^{b}	13.05 ± 1.00^{b}
RV Max (m/s)	19.59 ± 1.34^{c}	20.09 ± 1.96^{c}	18.55 ± 1.03^{a,b}	19.01 ± 2.05	17.83 ± 1.06
RI	21.34 ± 9.26^{b,c,e}	32.01 ± 18.61^{a,d,e}	28.04 ± 11.71^{a,d,e}	17.49 ± 7.77^{b,c,e}	9.22 ± 7.85^{a,b,c,d}
RI/min	0.47 ± 0.21^{b,c,e}	0.71 ± 0.41^{a,d,e}	0.62 ± 0.26^{a,d,e}	0.39 ± 0.17^{b,c,e}	0.20 ± 0.17^{a,b,c,d}

[a](significant differences from FB).
[b](significant differences from CD).
[c](significant differences from MD).
[d](significant differences from WG).
[e](significant differences from FW). TT: total touches; REL: releases; TP: total possessions; 1T: one touch; SP: short possession; LP: long; RC: receptions; RV: release velocity; RI: release index.

valuable insights into the technical demands of players in different positions during matches. In our study, the ES associated with the significant differences in various PL variables help us better understand the practical significance of these findings. For example, the large effect size (ES: 0.92) for WR (m/min) in the first period highlights a substantial difference in the work rate during this match phase. These effect sizes demonstrate that the observed changes in performance metrics are not only statistically significant but also of practical importance. On the same way, large effect size (ES: 0.57) for DC (m). Additionally, it is worth noting that the effect sizes can provide valuable context when comparing our results to those of previous studies. For instance, the differences in Total Touches and Releases between our study and the work by Yi et al. (2019) may be partially explained by the effect sizes associated with these variables, shedding light on the magnitude of the variations observed.

This is one of the first studies that shed light on providing information on the activity profile based on TL variables of the soccer player in (friendly) matches applying IMU technology. In our study, we have recorded that the soccer player during each part of a friendly match performs an average of 47.0 ± 18.5 and 48.7 ± 26.4 Total Touches and 16.4 ± 9.6 and 15.6 ± 10.7 Releases, respectively. These values are higher for Total Touches and lower for Releases, compared to those obtained by Yi et al. (2019) in a study that analyzed technical performance in the five major European leagues, accounting for the technical actions carried out by outfield players who complete the official match but using semi-automatic cameras. These differences in terms of Total Touches may be due to a greater intensity of the game, with fewer interruptions in the game in higher category matches and fewer necessary touches (Yi et al., 2020), while for Releases, the lower records found in our study may be due to a more excellent combinative game in competitions of a higher competitive level (Yi et al., 2020).

Previous research has shown that players show lower PL records on Match Day-1, contrary to what occurs with TL in the study conducted by Marris et al. (2021). This may be due to an orientation of the training objectives with a more technical-tactical nature (Martín-García et al., 2018; Walker and Hawkins, 2018). Considering these 2 TL variables but focusing on specific positions, the MDs reach the best records for Total Touches. In contrast, the Central Defenders are the ones that reach the highest values for Releases. These values compared to those obtained in the study by Marris et al. (2021), also with IMU technology, are lower, although in said research TL is analyzed within the training microcycle, with Match Day obtaining the highest records for both variables. high, so we found that this specific position was also very prominent in our study. In the same way, analyzing an indicator that combines the volume and intensity of each hit by the player (Release Index), the findings of our study provide absolute

TABLE 4 Descriptive analysis of PL variables by playing positions.

PL variables	FB (4 players)	CD (3 players)	MD (4 players)	WG (4 players)	FW (3 players)
TS (m/s)	7.78 ± 0.42[b,c,e]	7.20 ± 0.45[a,d]	7.01 ± 0.31[a,d,e]	7.75 ± 0.38[b,c,e]	7.40 ± 0.40[a,c,d]
DC (m)	4579.10 ± 228.17[c,d]	4436.52 ± 750.83[c]	5509.29 ± 229.52[a,b,d,e]	5235.17 ± 457.54[a,c]	4618.90 ± 235.00[c]
WR (m/min)	96.62 ± 14.30[c,d]	97.74 ± 6.89[c]	120.83 ± 6.01[a,b,d,e]	113.99 ± 8.47[a,c,e]	100.56 ± 6.50[c,d]
HIDC (m)	1031.65 ± 674.31[c,d]	931.86 ± 836.44[c,d]	1481.50 ± 1055.23[a,b,e]	1699.42 ± 1177.15[a,b,e]	919.20 ± 645.44[c,d]
HIDC (m/min)	22.93 ± 14.98[c,d]	20.71 ± 18.59[c,d]	32.92 ± 23.45[a,b,e]	37.76 ± 26.16[a,b,e]	20.43 ± 14.34[c,d]
SDC (m)	283.52 ± 248.50[b,d]	183.00 ± 226.61[a,d]	290.43 ± 422.60[d]	495.42 ± 501.61[a,b,c,e]	189.40 ± 211.62[d]
SDC (m/min)	6.30 ± 5.52[b,d]	4.07 ± 5.04[a,d]	6.45 ± 9.39[d]	11.01 ± 11.15[a,b,c,e]	4.21 ± 4.70[d]
SP (#)	22.78 ± 8.12[b,c,d]	11.00 ± 4.53[a,c,d,e]	18.64 ± 6.77[a,b,d]	29.42 ± 10.36[a,b,c,e]	19.00 ± 6.80[b,e]
SP (#/min)	0.50 ± 0.18[b,c]	0.23 ± 0.10[a,c,d,e]	0.41 ± 0.14[a,b,d]	0.64 ± 0.23[b,c,e]	0.42 ± 0.15[b,d]
DTZ1 (m)	2080.17 ± 520.83	2247.76 ± 506.20[c,d]	1959.93 ± 377.01[b,e]	1977.58 ± 485.29[b,e]	2305.50 ± 371.83[c,d]
DTZ2 (m)	1326.61 ± 437.59[c]	1400.38 ± 458.67[c]	2067.29 ± 717.29[a,b,d,e]	1556.17 ± 665.86[c]	1394.30 ± 321.25[c]
DTZ3 (m)	448.30 ± 231.43[c,d]	478.33 ± 353.57[c]	709.93 ± 208.31[a,b,e]	684.33 ± 306.94[a,e]	460.30 ± 219.13[c,d]
DTZ4 (m)	299.83 ± 214.08[c,d]	270.52 ± 272.16[c,d]	481.14 ± 451.49[a,b,e]	519.67 ± 393.96[a,b,e]	269.50 ± 227.99[c,d]
DTZ5 (m)	177.91 ± 160.53[d]	141.10 ± 179.67[d]	248.43 ± 361.59	356.67 ± 371.66[a,b,e]	146.00 ± 171.86[d]
DTZ6 (m)	105.61 ± 94.71[b,c,e]	41.90 ± 50.24[a,d]	42.00 ± 71.40[a,d]	138.75 ± 132.37[b,c,e]	43.40 ± 41.08[a,d]
ADA (#)	25.78 ± 8.58	24.05 ± 9.47	29.00 ± 39.00	28.00 ± 28.00	27.90 ± 6.97
ADA (#/min)	0.56 ± 0.18	0.51 ± 0.20	0.66 ± 0.87	0.64 ± 0.64	0.61 ± 0.15

[a](significant differences FB).
[b](significant differences from CD).
[c](significant differences from MD).
[d](significant differences from WG).
[e](significant differences from FW). TS: top speed; DC: distance covered; WR: work rate; HIDC: high intensity distance covered; DS: distance sprint; SDC: sprint distance covered; SP: number of sprints; DTZ1: Distance Traveled Zone 1; DTZ2: Distance Traveled Zone 2; DTZ3: Distance Traveled Zone 3; DTZ4: Distance Traveled Zone 4; DTZ5: Distance Traveled Zone 5; DTZ6: Distance Traveled Zone 6; ADA: Acceleration/Deceleration Actions.

values of 22.6 ± 13.0 for the first period and 21.1 ± 14.6 for the second, being lower than those provided by Lewis et al. (2022) in their study with English professional players in training sessions for 25 weeks. The highest values are found in Match Day-4 (128.6 ± 35.7) and Match Day+1 (145 ± 45.2), justifying this great difference with those obtained in our research, firstly, at a distance in time of day of competition and, secondly, to the characteristics of the tasks for Match Day-4, and on the other hand, in Match Day+1, due to the compensation training carried out by the players who have played the fewest minutes and, also, to the characteristics of the training tasks (Arjol-Serrano et al., 2021; Lewis et al., 2022).

Taking this TL indicator (RI) to the analysis by specific positions, the Central Defenders in our study reach the highest values, followed by the Midfielders. These particular positions in the study carried out by Lewis et al. (2022) with IMU technology, but analyzing training tasks by categories, distinguishing: Warm-up; Possessions; Small-Side Game; Tactical Training; Specific Training and Technical Training also find findings that for both positions, the highest values for RI in the Possessions and Tactical Training tasks. Emmonds et al. (2022), in another line of work applying this technology to women's soccer, also obtain TL values of specific positions during different types of training, distinguishing: Possessions; Intensive Small-Side Games; Extensive Small-Side Games; Tactical Training and Technical Training. These authors show their results without differentiating with the specific positions but find that Total Touches (#), and Total Touches (#/min), reach the highest values during Possession and Tactical Training. In contrast, for Releases (#), Releases (#/min), find them during Tactical Training and Technical Training. The findings in our study and in previous studies mentioned in this article confirm the high degree of specificity reached by training sessions with a high content of technical-tactical components, confirming the need for more research on TL during matches, friendlies and competition to meet the requirements.

Regarding the analysis of the PL, we found in our study results of Work Rate (m/min) similar to those obtained with GPS technology (Torreño, 2017), both at the average level for all positions in the first period (GPS: 113 m/min; IMU: 108.6 m/min), as well as by specific positions Full Back (GPS: 112.8 m/min; IMU: 96.62 m/min), Central Defender (GPS: 103.7 m/min; IMU: 97.74 m/min), Midfielder (GPS: 122.6 m/min; IMU:120.83 m/min), Winger (GPS: 125.6 m/min; IMU: 113.99 m/min) and Fordward (GPS: 119.1 m/min; IMU: 100.56 m/min). The same occurs with Top Speed (m/s), where we obtain that Full Back (7.78 m/s) and Winger (7.75 m/s) are the ones that reach the highest speed peak during a friendly match. In previous studies with GPS technology, it is obtained that Winger (8.6 m/s) is the one that reaches the highest maximum speed during an official match (Suarez-Arrones et al., 2015). Such as in previous studies with other technologies (Carling, 2013; Barnes et al., 2014;

Suarez-Arrones et al., 2015; Arjol-Serrano et al., 2021; Teixeira et al., 2021), we found a reduction in High-Intensity Distance Covered/min, and Sprint Distance Covered/min. These results make us assume that the sample with which the TL information has been obtained in this study has a PL behavior very similar to other samples of a higher competitive level, both in friendly and official matches, so it would be interesting to analyze the variables TL in a competitive match to confirm or not the TL profile described in this study and thus obtain a better understanding of the demands of this sport (Marris et al., 2021).

This study has the following limitations: Firstly, the study's sample size was limited to a single professional team, which may affect the generalizability of the findings to a broader population of soccer players. Including multiple teams from different levels of play would enhance the representativeness and reliability of the results. Secondly, the study focused on friendly matches during the preseason, which may only partially capture the intensity and competitive nature of official matches. The findings might differ in different match contexts, such as league matches or cup competitions. Lastly, it is important to note that this study did not consider other potential factors that could influence TL and PL, such as mental conditions (e.g., stress level, started or not started players, motivation, mental toughness), environmental conditions (e.g., weather, pitch conditions), tactical data (e.g., through passing matrix about the game system, interaction between them) or individual player characteristics (e.g., fitness level, playing style). Future studies could incorporate these variables to provide a more comprehensive understanding of the factors influencing TL and PL in soccer matches.

Conclusion

The TL profile of professional soccer players, based on their playing position, is found to be independent of the development of PL observed during friendly matches. This profile appears strongly influenced by the game system and the specific role assigned to each position. Therefore, monitoring, quantifying, and controlling TL and PL of soccer players offers a more comprehensive and holistic understanding of the demands in friendly matches compared to solely analyzing PL. Assessing TL during friendly matches enables the differentiation of actions based on players' positions, which can optimize performance during training sessions.

The practical applications that this entails are.

- Designing training tasks with the TL component depending on the player's specific position.
- Adapting the volume and intensity of these variables to the needs of the training session within the microcycle, ensuring adequate tapering for the competition day, as is done with PL.
- IMU technology in this context offers a convenient and time-efficient alternative with significant benefits over other existing technologies.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Pablo de Olavide University with code 0398-N17. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin because Professional football players has signed a informed consent in the beginning of the season.

Author contributions

JL-B: Conceptualization, Investigation, Methodology, Writing–original draft, Data curation, Formal Analysis. FN-Z: Supervision, Writing–review and editing. JB-A: Conceptualization, Data curation, Formal Analysis, Writing–original draft, Writing–review and editing.

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Conflict of interest

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

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