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A physiologically-based approach to study different types of locomotion in association with core performance

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A physiologically-based approach to study different types of locomotion in association with core performance

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Topic Editor Tomas Maly is the holder of 2 domestic and 1 International EU patents for a device for lower extremity muscle force measurement in isokinetic movement conditions and the procedure for the measurement carried out on the device.

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Editorial: A physiologically-based approach to study different types of locomotion in association with core performance

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Editorial on the Research Topic
A physiologically-based approach to study different types of locomotion in association with core performance

Good posture and strong core muscles are essential for most athletic movements (Kibler et al., 2006) but also for daily life activities (Hibbs et al., 2008). Among them, walking and running require lumbo-pelvic stability and mobility for efficient movement and high-level performance (Fredericson and Moore, 2005) as well as prevention of lower limb injuries (Leetun et al., 2004). This is especially important during extensive trunk motions while changing the direction of movement (Horníková and Zemková), an abrupt walk to run transition, or extreme uphill and downhill walking or running. Such repetitive trunk loading over time may contribute to occurence of back problems and lower limbs injuries. The main biomechanical risk factors leading to back problems in athletes are maladaptive spinal, spinopelvic and lower limb kinematics, side-to-side imbalances in axial strength and hip rotation range of motion, spinal overloading and deficits in movement pattern, whilst neurophysiological risk factors include neuromuscular imbalance, increased muscle fatigability, muscle dysfunction and impaired motor control (Zemková et al., 2023). Fatigue of the trunk muscles induced by excessive loading of the spine is one of the sources of back problems in athletes (Zemková et al., 2020). In particular, high training volume and repetitive motions are responsible for the high prevalence rates (Zemková et al., 2020). Lumbar muscle fatigue causes changes in the lumbar spinal curvature and this is functionally relevant in explaining the impaired ability to maintain balance after externally induced perturbations (Zemková et al., 2021). Core stability of the lumbopelvic hip complex can prevent buckling and help return to equilibrium after perturbation (Willson et al., 2005). On the other hand, reduced core stability can impair performance but also predispose to injury.

To avoid these unwanted effects requires a novel approach for studying the physiology of locomotion in association with the spine motion and balance function. This may provide a basis for designing the exercise programs specifically tailored for competitive athletes

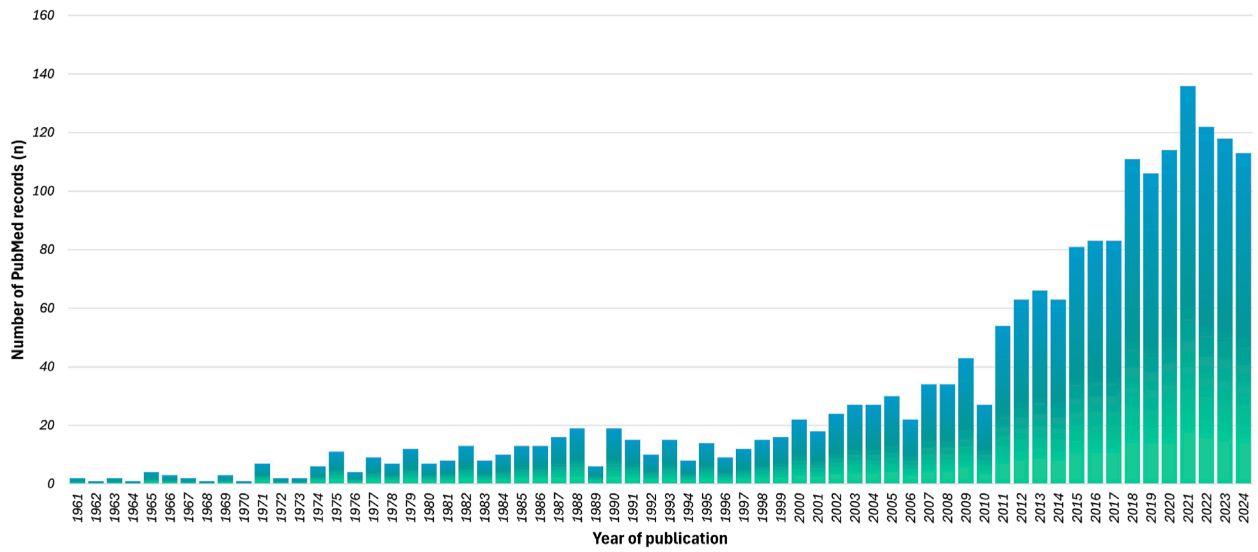

FIGURE 1
The results of a systematic search in PubMed according to the following Boolean search syntax: ["core performance" (All Fields)] OR ["core strength" (All Fields)] OR ["core stability" (All Fields)] AND ["locomotion" (All Fields)] OR ["walking" (All Fields)] OR ["running" (All Fields)] AND ["physiological mechanisms" (All Fields)] OR ["neurophysiological mechanisms" (All Fields)].

(Hibbs et al., 2008), healthy general population, as well as those suffering from movement disorders. Better neuromuscular control of postural and core stability contribute to more efficient functional movements specific to particular sports (Zemková and Zapletalová, 2022). Core stabilization and core strengthening exercises, alone or in combination with athlete training, contribute to increasing the performance, as well as reducing back pain in athletes (Zemková and Zapletalová, 2021). Specifically, ground-based free weight movements are effective for developing core strength and power due to the demands on force, velocity, and core stabilization that are similar to those of athletic skills (Willardson, 2007). Core strength has a significant effect on an athlete's ability to generate and transfer forces to the limbs (Shinkle et al., 2012). This is also evidenced by the clear relationship between trunk muscle activity and lower extremity movement (Willson et al., 2005).

So far, much effort has been devoted to investigate biomechanical and physiological variations of locomotion, including walking, running, swimming or hopping. However, a surprising evidence gap is to what extent core strength contribute to effective locomotor performance and healthy back. Therefore, studying neurophysiological mechanisms underlying postural and core stability with special reference to locomotion is of great importance.

The fact that this issue is of great interest among researchers and practitioners is also evidenced by the exponentially increasing number of articles in the last decade. The Figure 1 illustrates the results of a systematic search in PubMed according to the Boolean search syntax: "core performance" OR "core strength" OR "core stability" AND "locomotion" OR "walking" OR "running" AND "physiological mechanisms" OR "neurophysiological mechanisms." It includes 1747 items over 72 years.

Within this collection, 20 articles were submitted, of which 7 were rejected and 13 accepted. Actually, this Research Topic presents a collection of thirteen papers that exhibit substantial diversity in both content and methodological approaches.

Five of the studies focus on training interventions, employing various training methods. For instance, one study explores the effects of plyometric training on specific motor skills in young tennis players, while another examines the influence of horizontal plyometric training on volleyball-specific performance in post-peak-height-velocity female athletes. These studies offer valuable insights for coaches aiming to enhance athletic performance in youth populations. Another investigation tracks individual performance adaptations over 2 years of training in an elite 22-year-old aerobic gymnast, comparing outcomes between successive European Aerobics Championships, thereby providing detailed insights into performance variability at the elite level.

Two additional studies involve distinct populations—children and elderly women. The first is a 16-week school-based physical activity intervention targeting physical fitness in 8- to 9-year-olds, while the second assesses the effects of sensorimotor training on muscle strength and postural control in active elderly women aged 65–75 years. Both studies demonstrate significant intervention benefits, with potential implications for public health promotion.

Regarding training adaptations, another study employs a meta-analytic approach to evaluate the effects of blood flow restriction training on muscle activation and post-activation potentiation, illustrating how this method can effectively enhance lower extremity muscle engagement and post-activation performance.

The remaining papers address various performance dimensions across different sports and populations. One paper analyzes performance in young tennis players, highlighting motor skill differences across age categories, which could inform injury prevention strategies and training preparation. Another study explores several parameters of strength, morphological traits, and neuromuscular asymmetries in competitive soccer players, offering practical insights for trunk strength monitoring and development.

In relation to trunk strength, another study compares trunk rotational strength with shoulder rotational strength in athletes from mixed martial arts, tennis, swimming, and baseball. Both studies are critical for advancing knowledge on injury prevention strategies in sports.

Fatigue, a key focus area in sports physiology, is addressed in two studies: one investigates how fatigue impacts lower limb biomechanics during a forward lunge, while another evaluates the effect of molecular hydrogen supplementation on muscle performance, damage, and perceived soreness following two consecutive strenuous training sessions in elite fin swimmers, revealing potential benefits for muscle recovery.

Finally, two studies emphasize strength-related parameters. One compares the effects of various stimuli on maximal strength and power during bench press exercises, providing evidence for the most effective stimuli for improving both strength and power. The last study, a narrative review, synthesizes current research on the relationship between core strength and change of direction performance, highlighting the significance of core training for enhancing change of direction ability—a key performance indicator across many sports, making this area of interest highly relevant to performance physiology.

In the 2nd volume entitled "Neurophysiological basis of the relationship between core stability and human movement: Implications for sport and rehabilitation" we will continue to provide more information on this issue, focusing on the application of findings both in sports practice and clinical medicine. Then it is necessary to take into account the fact that research carried out in the rehabilitation settings cannot be applied to the sporting environment due to differing demands on the core musculature during sporting (dynamic movements, high loads) and everyday activities (slow movements, low loads) (Hibbs et al., 2008). Much evidence supports neurophysiological adaptations in body control induced by general conditioning exercises, however, little effort has been made to explain balance and locomotor adaptations induced by sport-specific exercises and their effects on athletic performance (Zemková and Kováčiková, 2023). While an enhancement in athletic performance is often attributed to an improvement of neuromuscular functions induced by sport-specific balance exercises, it can be equally well ascribed to their improvement by general body conditioning exercises. We believe that new contributions will address the complexity of this specific topic and present new insights into the knowledge and justification of research investigating the relationship between various movements and stability of the core musculature.

Author contributions

EZ: Conceptualization, Writing–original draft, Writing–review and editing. MM: Writing–original draft, Writing–review and editing. TM: 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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The plyometric treatment effects on change of direction speed and reactive agility in young tennis players: a randomized controlled trial

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Aim: The aim of this paper is to determine the effect of 6 weeks of plyometric training on speed, explosive power, pre-planned agility, and reactive agility in young tennis players.

Methods: The participants in this study included 35 male tennis players (age 12.14 ± 1.3 years, height 157.35 ± 9.53 cm and body mass 45.84 ± 8.43 kg at the beginning of the experiment). The biological age was calculated and determined for all participants. 18 of the participants were randomly assigned to the control group, and 17 were assigned to the experimental group. Running speed (sprints at 5, 10, and 20 m), change of direction speed (4 × 10, 20 yards, *t*-test, TENCODS), reactive agility (TENRAG), and explosive power (long jump, single leg triple jump, countermovement jump, squat jump, and single leg countermovement jump) were all tested. The Mixed model (2 × 2) ANOVA was used to determine the interactions and influence of a training program on test results. Furthermore, Bonferroni *post hoc* test was performed on variables with significant time*group interactions.

Results: The results of this research indicate that an experimental training program affected results in a set time period, i.e. 5 out of total 15 variables showed significant improvement after experimental protocol when final testing was conducted. The experimental group showed significantly improved results in the 5 m sprint test in the final testing phase compared to the initial testing phase, this was also the case in comparison to the control group in both measurements. Furthermore, the experimental group showed significant improvement in the single leg countermovement jump in the final test, as well as in comparison to the control group in both measurements. The change of direction speed and reactive agility test also exhibited significant improvement in the final testing phase of the experimental group.

Conclusion: The results of this research indicated that a 6-week program dominated by plyometric training can have a significant effect on the improvement of specific motor abilities within younger competitive categories. These results offer valuable insights for coaches in designing diverse tennis-specific scenarios to enhance overall performance, particularly focusing on the neuromuscular fitness of their players.

KEYWORDS

tennis, specific agility, experimental protocol, neuromuscular training, motor abilities

1 Introduction

Tennis, as a complex activity, is characterized by a number of specific movement structures that alternate depending on the situation and predominantly require maximum speed over a given period of time (Milanović et al., 2005). Due to the reactive requirements of the game, the total duration of a match, the basis on which it is played and the energy consumption required during a match, it can be said that one of the main goals of training tennis players must be directed towards the development and maintenance of speed, agility and explosive power (Milanović et al., 2005). Pre-planned change of direction speed (CODS) is characterized by a change in the direction of movement that is already known in advance, it is planned and players do not need to react to a certain stimulus. On the other hand, reactive agility (RAG) includes cognitive processing, observational skills, and decision-making factors (Sekulić et al., 2017). In the area of RAG, players most often need to react to a visual stimulus, which is crucial in the field of sports since athletes usually perform agile movements based on visual observation of either the opponent's motion or the trajectory of the ball (Sekulić et al., 2020). Given that movement in tennis is highly specific, CODS and RAG are considered to be crucial motor abilities (Sekulić et al., 2017; Sekulić et al., 2020).

Regardless of the importance of CODS and RAG in tennis, there are only a few scientific studies dealing with these motor abilities, especially under specific conditions. So far, these abilities have mostly been measured by standardized basic tests. This study will use a reliable and valid tennis-specific change of direction speed test (TENCODS) and a tennis specific reactive agility test (TENRAG) under specific conditions (Sinkovic et al., 2022).

We are increasingly faced with the fact that conditioning training is effective even in the prepubescent phase (Čanaki and Birkić, 2009). Prepuberty should be seen as a time of early anatomical adjustment of the heart, lungs, joints, and muscles to prolonged physical activity (Čanaki and Birkić, 2009). This should serve as the foundation upon which athletes will build aerobic and anaerobic fitness during the specialization and peak performance phase (Čanaki and Birkić, 2009). Although prepubescent conditioning training must be approached with caution, it is clear that dedicating more time to the development ability of changing direction and agility during prepuberty and early puberty increases the chances of fully exploiting this ability's potential in later stages of sports development (Čanaki and Birkić, 2009). Additionally, it is important to adapt the plan and program of conditioning training during prepubescence and early puberty phases, specifically for the younger competitive categories of tennis players (U-12 and U-14).

Plyometric training offers the necessary stimuli for developing the stretch-shortening cycle (SSC) mechanism and has the potential to improve explosive contractions in both prepubertal and pubertal individuals (Fernandez-Fernandez et al., 2016). In other words, plyometric training focuses on combining strength with speed of movement to generate power (Fernandez-Fernandez et al., 2016). Nowadays, there is increasing exploration of the influence of plyometric training on motor abilities, as well as biomechanical and physiological parameters in tennis (Salonikidis and Zafeiridis, 2008; Kilit and Arslan, 2019). Literature reviews show that plyometric training has the potential to enhance maximal serve velocity and various physical performance components, such as sprint speed, lower extremity muscular power and agility among healthy tennis players (Davies et al., 2015; Novak et al., 2023). Nevertheless, further research is warranted to gather more high-quality evidence regarding the effects of plyometric training on the skill and physical performance of tennis players (Davies et al., 2015). Some studies suggest that regular use of plyometrics in tennis training for younger players has a significant impact on CODS tests (Antekolović et al., 2003; Vuong et al., 2022). The main challenge lies in the lack of appropriate testing mechanisms, as most of the CODS in tennis has been assessed using standardized basic tests or modifications of existing ones, such as the "*t*-test," "505 test," and "Spider drill test" (Sinkovic et al., 2022). Additionally, one of the main problems is the lack of research investigating the effect of plyometric training on CODS and RAG in young tennis players, this being something that this study aims to provide answers to. It has been found that CODS is the most influential factor for tennis performance and is strongly influenced by linear speed and jumping power (Vuong et al., 2022). Therefore, it can be concluded that the tests were primarily designed to measure pre-planned agility, where changes in movement direction are planned in advance. It is crucial to emphasize that this study will utilize a specific test to assess reactive agility, which is a key factor for success in tennis.

In accordance with the above, the aim of this paper is to determine the effect of two plyometric, explosive power, pre-planned agility, and reactive agility sessions per week for tennis players from the younger competition categories (U-12 and U-14) in prepuberty and early puberty.

2 Methods

2.1 Participants

The sample included 35 young male tennis players (age 12.14 ± 1.3 years, height 157.35 ± 9.53 cm and body mass 45.84 ± 8.43 kg at the beginning of the experiment) who were ranked in the top 50 in the National Tennis Association rankings, as well the top 300 on the international "Tennis Europe" rankings. The G-Power program (version 3.1.9.2; Heinrich Heine University, Dusseldorf, Germany) was used to estimate the appropriate number of participants, with an expected effect power of f = 0.33, an alpha level of 0.05, and a statistical power of 0.90. 18 participants were randomly assigned to the control group (CG), and 17 participants were assigned to the

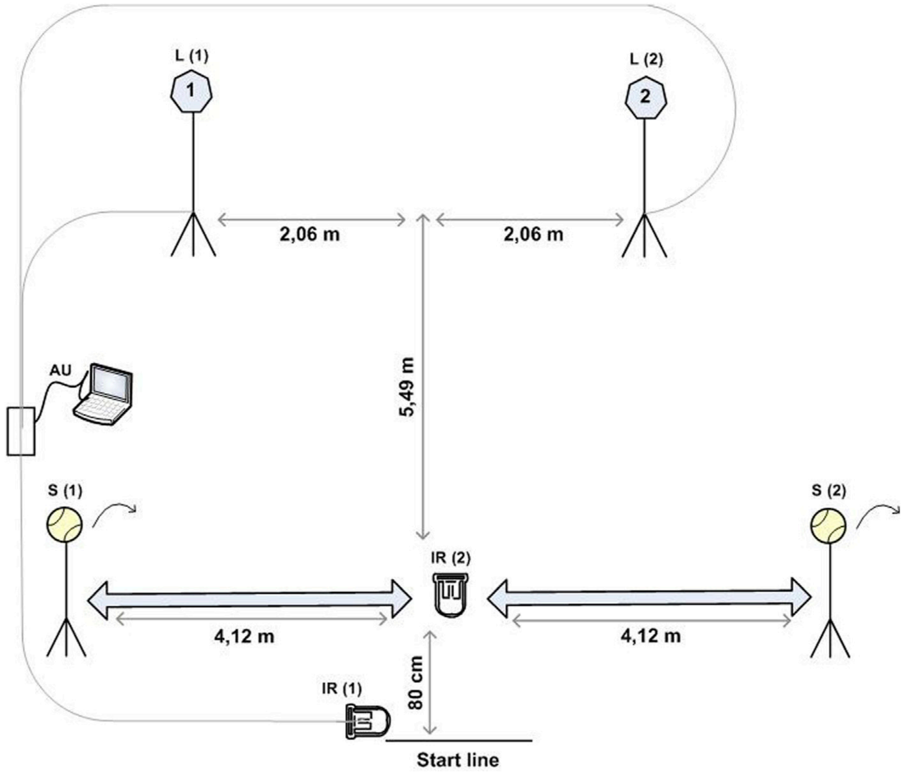

FIGURE 1
TENCODS and TENRAG test.

experimental group (EG). The biological age was calculated and determined for all participants. To participate in the study, all participants had to meet certain inclusion criteria, including being physically active players who trained for at least 6 hours a week and competed in regional, national, or international tournaments. According to the level of trainability, all participants were at least intermediate or advanced athletes. Exclusion criteria included any injury that would affect tennis play and physical performance at the start of the study. The study was conducted in accordance with the Helsinki Declaration and approved by the Ethics Committee of the Faculty of Kinesiology, University of Zagreb (protocol code 34; date of approval: 13 December 2021). All participants were informed of the research's purpose and the conditions for participation, and both they and their parents provided prior written consent to participate. The complete testing protocol was explained to them in detail, with a special emphasis on the additional effort required for the research and the risk of injury, which was the same level as during standard training or competition.

2.2 Measurements and procedure

The biological age of the participants was assessed through body height (cm), sitting height (cm), body mass (kg), leg length (cm), and chronological age (years). The data obtained was then entered into a specific regression equation for boys to determine PHV maturity offset: −9.236 + (0.0002708 x leg length x sitting height) + (−0.001663 x chronological age x leg length) + (0.007216 x chronological age x sitting height) + (0.02292 x ratio of body mass to body height) (Sinkovic et al., 2023). Therefore, a maturity offset of −1.0 indicates that the player was measured 1 year before peak height velocity, a maturity offset of 0 indicates that the player was measured at the time of peak height velocity, and a maturity offset of +1.0 indicates that the athlete was measured 1 year after peak height velocity. In accordance with this, age at peak high velocity (APHV) was calculated from an estimation between peak height velocity maturity offset and chronological age. The chronological age of the participants (years) was calculated by subtracting the date of birth from the date of measurement. Standing body height (cm) and sitting height (cm) were measured using a portable altimeter (Seca 213; seca gmbh, Hamburg, Germany). Leg length (cm) was calculated by subtracting the sitting height (cm) from the standing height (cm). Body mass (kg) was measured using a portable digital scale (Seca V/700; seca gmbh, Hamburg, Germany), while body fat percentage (%) was measured using the MALTRON BF 900 analyser (Maltron International Ltd., Rayleigh, United Kingdom).

The participants underwent a series of tests to evaluate their speed, agility, and explosive power. Speed assessments included 5, 10, and 20-m sprints, while agility was measured using tests such as the 20-yard run, 4 × 10-yard run, *t*-test, TENCODS, and TENRAG. Explosive power was evaluated through exercises such as the countermovement jump (CMJ), single-leg countermovement jump (CMJ_L, R), squat jump (SJ), long jump (L_JUMP), and single-leg triple jump (SLTJ_L, R). The Powertimer system

TABLE 1 Basic conditioning training program.

Training week	Exercise	Sets x reps	Pause (s)
1	Plank	3 × 30 s	30–60/90–120
	Leg raises	3 × 10	30–60/90–120
	Squat jumps	3 × 10	30–60/90–120
	Push-ups	3 × 10	30–60/90–120
2	Countermovement jump	3 × 6	30–60/90–120
	Hurdle hops forward (20–30 cm)	3 × 6	30–60/90–120
	Sprint 20 m	4 × 1	30–60/90–120
	Sprint 40 m	4 × 1	30–60/90–120
3	Plank	3 × 30 s	15–30/90
	Lunges: 3 sets x 10 reps (each leg)	3 × 10 (each leg)	15–30/90
	High knees	3 × 20 s	15–30/90
	Russian twists	3 × 10 (each side)	15–30/90
4	Squats	3 × 8	30–60/90–120
	Assisted pull ups	3 × 6	30–60/90–120
	Dumbbell bicep curls	3 × 10	30–60/90–120
	Bicycle crunches	3 × 15 (each side)	30–60/90–120
5	Agility ladder drills	3 × 10	30–60/90–120
	Shuttle runs	3 × 4	30–60/90–120
	Vertical jumps	3 × 4	30–60/90–120
	Medicine ball slams	3 × 8	30–60/90–120
6	Plank	3 × 30 s	15–30/90
	Mountain climbers	3 × 10	15–30/90
	Box jumps	3 × 4	15–30/90
	Tricep dips	3 × 8	15–30/90

(Newtest Oy, Oulu, Finland) was used to measure speed, the SportReact system (SportReact, Zagreb, Croatia) for agility, and the Optojump system (Microgate, Bolzano, Italy) for assessing explosive power during jumps. Each test was conducted three times, and the average of the three trials was then calculated for further analysis.

Before the testing session, all participants completed a standardized warm-up specific to tennis. The warm-up consisted of various activities, including light-intensity running covering a distance of 10 × 20 m. Following the running component, participants engaged in dynamic stretching exercises for a total duration of 15 min. These dynamic stretches involved lateral movements, skipping, jumping, lunges, and concluding with four repetitions of sub-maximum acceleration. Subsequently, the participants underwent tests to assess their speed (5, 10, and 20-m sprints), agility (20 yards, 4 × 10 yards, *t*-test, TENCODS, and TENRAG), and explosive power (countermovement jump, one-leg countermovement jump, squat jump, long jump, and one-leg triple jump).

2.2.1 Linear sprint speed tests

For the linear sprint speed tests, three electronic timing gates were positioned at predetermined distances of 5, 10, and 20 m from a designated starting line. Participants were instructed to their preferred foot positioning, placed on a marked line on the floor, and initiate the sprint from a stationary standing start. Their objective was to cover the 20-m distance as quickly as possible. Timing measurements were recorded at the 5-m mark (using the first electronic timing gate), the 10-m mark (using the second electronic timing gate), and the 20-m mark (using the third electronic timing gate). Each participant performed three trials, with a 3–4-min rest period between each trial. The mean value of the three trials was calculated for further analysis (Sinkovic et al., 2023).

2.2.2 Explosive power tests

During the countermovement and single-leg countermovement jump tests, participants kept their hands positioned on their hips to minimize any impact from the upper body on jump performance.

TABLE 2 Six-week plyometric training program.

Training week	Exercise	Sets x reps	Pause (s)
1	Ankle cone hops	3 × 10	15–30/90
	Ankle cone hops side to side	3 × 10	15–30/90
	Countermovement jumps	4 × 5	15–30/90
	Broad jumps	4 × 5	15–30/90
2	1-leg ankle hops forward	3 × 10	30–60/90–120
	Countermovement jumps	3 × 8	30–60/90–120
	Continious broad jumps	3 × 2 × 3	30–60/90–120
	Lateral bounds + stick	3 × 6	30–60/90–120
	2–1 Hurdle hops forward (20–30 cm)	3 × 10	30–60/90–120
3	1-leg ankle hops lateral	3 × 10	30–60/90–120
	Countermovement jump	3 × 10	30–60/90–120
	1:2 broad jumps	3 × 4	30–60/90–120
	Zig zag bounds + stick	3 × 8	30–60/90–120
	2–1 Hurdle hops lateral (20–30 cm)	3 × 10	30–60/90–120
4	1-leg square ankle hops	3 × 8	30–60/90–120
	1-leg Countermovement jump	3 × 5	30–60/90–120
	Continious broad jumps	3 × 3 × 3	30–60/90–120
	Lateral bounds (1-1-stick)	3 × 8	30–60/90–120
	2–1 Multidirectional hurdle hops	3 × 10	30–60/90–120
5	1-leg square ankle hops	3 × 12	30–60/90–120
	1-leg Countermovement jump	3 × 5	30–60/90–120
	1:2 Broad jumps	3 × 8	30–60/90–120
	Zig zag bounds (1-1-stick)	3 × 10	30–60/90–120
	2–1 Multidirectional hurdle hop	3 × 10	30–60/90–120
6	Ankle cone hops	3 × 10	15–30/90
	Ankle cone hops side to side	3 × 10	15–30/90
	Countermovement jump Broad jumps	4 × 5	15–30/90
	Broad jumps	4 × 5	15–30/90

Starting from a standing position with knees straight, participants performed a squat motion, lowering themselves to approximately a 90°, and then rapidly accelerated in a vertical direction using both legs or a single leg. Each participant completed three trials of the tests, with a 1-min rest period between each trial. The mean value of the three trials was then calculated for further analysis (Sinkovic et al., 2023).

In the squat jump test, participants started with a knee flexion angle of 90°, maintaining a straight torso, hands on hips, and feet positioned shoulder-width apart. They held this position for 2 s before initiating the jump. The push-off phase of the jump was performed without any form of countermovement. During the highest point of the jump, participants fully extended their legs. The landing phase involved both feet landing together in an upright position, with knees fully extended. Each participant completed three trials of the test, with a 1-min rest period between each trial. The mean value of the three trials was then calculated for further analysis (Sinkovic et al., 2023).

In the long jump test, participants were provided with standardized instructions to perform a long jump starting from a standing position. They were allowed to initiate the jump with bent knees and utilize arm swinging for assistance. A marked line on a hard surface served as the starting point, and the length of the jump was measured using a tape affixed to the floor. Each participant completed three trials of the test, with a 1-min rest period between each trial. The mean value of the three trials was then calculated for further analysis (Sinkovic et al., 2023).

TABLE 3 Results (Mean ± SD) of Intervention Group and Control Group Before and After the intervention Using 2 × 2 Mixed Analysis of Variance (ANOVA).

Variable	Control group		Experimental group		Interaction Time*Group			Post hoc bonferroni test	
	Initial testing	Final testing	Initial testing	Final testing					
	x̄ ±SD	x̄ ±SD	x̄ ±SD	x̄ ±SD	F	p	Partial η2	Comparison	p
Sprint 5 m (s)	1.27 ± 0.05	1.27 ± 0.09	1.27 ± 0.07	1.19 ± 0.06	7.8	0.01	0.2	CG > EG	0.01
Sprint 10 m (s)	2.12 ± 0.09	2.12 ± 0.12	2.14 ± 0.1	2.07 ± 0.1	5.76	0.02	0.15	CG > EG	0.23
Sprint 20 m (s)	3.71 ± 0.15	3.63 ± 0.24	3.79 ± 0.21	3.68 ± 0.21	0.12	0.74	0.00	-	-
CODS 4 × 10 yards (s)	10.62 ± 0.63	10.46 ± 0.49	10.64 ± 0.55	10.29 ± 0.45	1.57	0.22	0.05	-	-
CODS 20 yards (s)	5.65 ± 0.29	5.6 ± 0.28	5.62 ± 0.35	5.46 ± 0.25	2.26	0.14	0.07	-	-
CODS *t*-test (s)	12.22 ± 0.64	11.87 ± 0.63	12.14 ± 0.8	11.56 ± 0.69	3.28	0.08	0.09	-	-
Long jump (cm)	162.85 ± 16.48	165.2 ± 16.95	155.55 ± 18.18	172.8 ± 20.23	33.03	0.00	0.51	CG < EG	0.236
Triple jump_L (cm)	459.76 ± 57.44	462.93 ± 51.7	427.35 ± 65.32	461.04 ± 66.14	15.1	0.00	0.32	CG < EG	0.925
Triple jump_R (cm)	454.11 ± 56.26	451.24 ± 60.06	442.67 ± 66.39	471.14 ± 65.24	28.34	0.00	0.47	CG < EG	0.35
CMJ (cm)	23.3 ± 3.37	23.58 ± 3.34	21.56 ± 3.31	24.41 ± 3.57	28.96	0.00	0.48	CG < EG	0.48
SJ (cm)	23.1 ± 3.81	23.31 ± 3.91	21.48 ± 3.87	23.61 ± 3.86	15.9	0.00	0.33	CG < EG	0.82
CMJ_L (cm)	11.52 ± 1.57	11.73 ± 1.52	10.79 ± 1.13	12.97 ± 1.82	17.37	0.00	0.35	CG < EG	0.04
CMJ_R (cm)	11.54 ± 1.11	11.37 ± 1.37	11.21 ± 1.71	13.01 ± 2.01	22.39	0.00	0.41	CG < EG	0.01
TENCODS (s)	3.2 ± 0.17	3.18 ± 0.15	3.23 ± 0.16	3.04 ± 0.11	26.5	0.00	0.45	CG > EG	0.01
TENRAG (s)	3.38 ± 0.19	3.34 ± 0.19	3.36 ± 0.13	3.16 ± 0.17	19.08	0.00	0.37	CG > EG	0.01

Legend: CMJ (cm)—countermovement jump with arms set on hips; SJ (cm)—squat jump; CMJ_L (cm)—single leg (left) countermovement jump with arms set on hips; CMJ_R (cm)—single leg (right) countermovement jump with arms set on hips; TENCODS (s)—change of direction speed test; TENRAG (s)—reactive agility test; *—significant interaction ($p < 0.05$).

In the single-leg triple jump test, participants began by standing on one designated leg, with their toe positioned on the starting line. When ready, they performed three consecutive maximal jumps forward using the designated leg. Upper extremity movement during the single-leg horizontal hop was not restricted, although participants were instructed to land firmly on the last jump. After practice trials, three test trials were conducted on each leg in alternating order. A 30-s rest period was allowed between practice and test trials. The mean distance of the three test trials for each leg was then calculated for further analysis (Sinkovic et al., 2023).

2.2.3 Change of direction speed and reactive agility tests

In the 20-yard test, participants assumed a three-point stance and sprinted 5 yards in one direction, followed by a 10-yard sprint in the opposite direction, and then returned to the starting point. This test evaluates lateral speed and coordination. The timing commenced upon a sound of the signal and concluded when the participant crossed the timing gate upon their return. The time was measured in hundredths of a second (Sinkovic et al., 2023).

In the 4 × 10 yard test, parallel lines were marked on the floor with a distance of 10 yards between them. Participants were required to shuttle back and forth four times between the starting line and the other line as fast as possible, ensuring that both feet crossed each line during each run. The timing started upon a sound of the signal and ceased when the participant crossed the timing gate upon their return. The time was measured in hundredths of a second (Sinkovic et al., 2023).

In the *t*-test, a configuration of four cones was arranged in the shape of a "T." The starting cone was placed 9.14 m away from the first cone, and two additional cones were positioned 4.57 m from either side of the second cone. An electronic timing gate measuring 0.75 m in height and 3 m in width was set up in alignment with the marked starting point. Participants were instructed to sprint forward from the start line to the first cone (9.14 m) and touch it with their right hand. They then shuffled 4.57 m to the left to the second cone, touching it with their left hand. Next, they shuffled 9.14 m to the right to the third cone, touching it with their right hand, and then shuffled 4.57 m back to the middle cone, touching it with their left hand. Finally, they backpedaled to the start line. The timing commenced upon a sound of the signal and concluded when the participant crossed the timing gate upon their return. Trials were considered unsuccessful if participants did not touch a designated cone, crossed their legs during shuffling, or failed to face forward throughout the test. The time was measured in hundredths of a second (Sinkovic et al., 2023).

The change of direction speed (TENCODS) and reactive agility (TENRAG) variables were assessed using tests that exhibit excellent metric properties and are both reliable and valid (Sinkovic et al., 2022). The reliability of the pre-planned agility tests is slightly higher (CA = 0.92 and 0.92; ICC = 0.86 and 0.82) compared to the reactive agility tests (CA = 0.90 and 0.89; ICC = 0.74 and 0.72) (Sinkovic et al., 2022). The SportReact system (SportReact, Zagreb, Croatia)

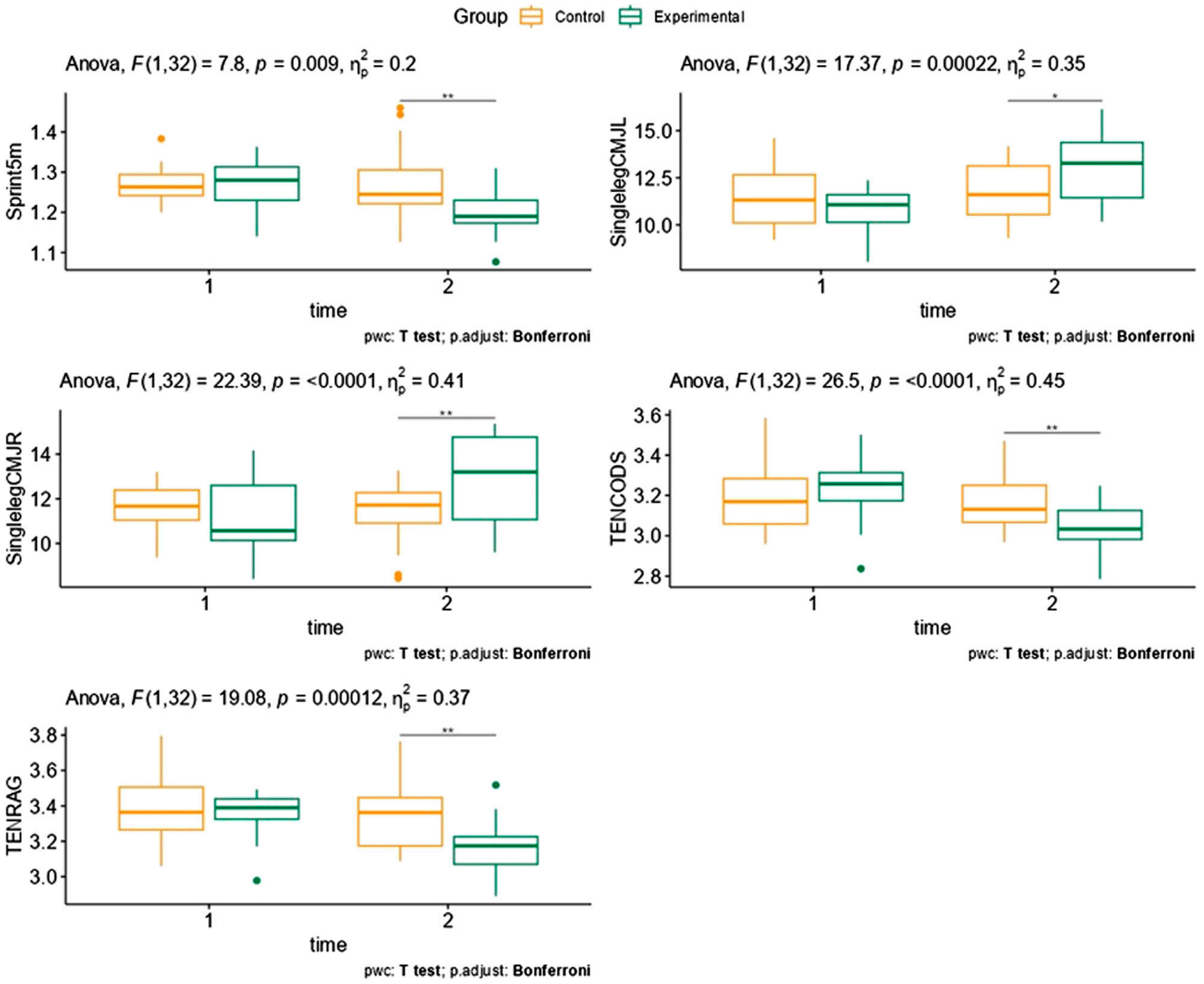

FIGURE 2
Box plots of selected variables that indicated statistically significant for 2 × 2 Mixed Analysis of Variance (ANOVA) and paired T tests.

was used to measure these tests, which consists of laser tape sensors and LED screens displaying differing signs and colors (Sinkovic et al., 2022). The TENCODS and TENRAG tests are designed to simulate specific movements in tennis (Figure 1). Participants start from a predetermined starting line, and the timing begins when the infrared signal (IR1) next to the starting line is interrupted by the "split step." At this point, one of the two lights (L1 or L2) illuminates, the participant must identify which light is lit, and perform a run with overstepping and a lateral side-to-side technique to reach a stand with a ball (S1 or S2) and hit the ball with a forehand or backhand stroke in front of their body with sufficient force for the ball to hit the ground. After playing the shot, the player should quickly return to the device in front of the starting line, interrupting the infrared signal (IR2), which stops the measurement. In the TENCODS test, participants are aware in advance of which light will illuminate, allowing them to plan their running and shot execution. Each test was performed nine times, with a 60-s break between measurement repetitions, and the mean value of the measurements was then used for further analysis (Sinkovic et al., 2022).

2.3 Study design

After the initial testing of the participants motor abilities, the control group (CG), in addition to standard technical-tactical training, continued with regular conditioning training that included a combination of strength exercises, plyometrics and agility drills. There were four standard technical-tactical training sessions and two conditioning training sessions per week. All participants were familiarized with the tests prior to the main test session. The exercises are arranged in a way that allows for a proper warm-up, progression, and targeted muscle group activation (Table 1). The experimental group (EG) underwent a 6-week plyometric training program in addition to their regular technical-tactical training sessions (Table 2). This combination ensured that both groups had an equal total load volume, the same number of training sessions, and an equal duration of training. To ensure that the participants followed the same training program, despite belonging to different clubs, licensed tennis coaches were involved in the study. The study design

TABLE 4 Heterogeneity by intervention status (*n* = 35).

Variable	Intervention group	Control group	Difference in variance
Sprint 5 m (s)	0.003 [0.001; 0.005]	0.009 [0.003; 0.015]	−0.006
Sprint 10 m (s)	0.004 [0.002; 0.006]	0.01 [0.004; 0.016]	−0.006
Sprint 20 m (s)	0.005 [0.001; 0.009]	0.045 [0.014; 0.076]	−0.040
CODS 4 × 10 yards (s)	0.109 [0.031; 0.187]	0.153 [0.049; 0.257]	−0.044
CODS 20 yards (s)	0.028 [0.008; 0.048]	0.047 [0.012; 0.082]	−0.019
CODS *t*-test (s)	0.131 [0.035; 0.227]	0.094 [0.023; 0.165]	0.037
Long jump (cm)	99.085 [34.236; 163.934]	37.726 [13.455; 61.997]	61.359
Triple jump_L (cm)	779.875 [212.82; 1346.93]	242.289 [87.394; 397.184]	537.586
Triple jump_R (cm)	322.594 [122.892; 522.296]	387.5 [164.476; 610.524]	−64.906
CMJ (cm)	3.825 [1.542; 6.108]	0.789 [0.266; 1.312]	3.036
SJ (cm)	3.292 [0.587; 5.997]	1.015 [0.325; 1.705]	2.277
CMJ_L (cm)	2.855 [0.985; 4.725]	0.98 [0.27; 1.69]	1.875
CMJ_R (cm)	2.316 [0.85; 3.782]	1.168 [0.37; 1.966]	1.148
TENCODS (s)	0.009 [0.003; 0.015]	0.007 [0.001; 0.013]	0.002
TENRAG (s)	0.015 [0.005; 0.025]	0.005 [0.001; 0.009]	0.010

Legend: CMJ (cm)—countermovement jump with arms set on hips; SJ (cm)—squat jump; CMJ_L (cm)—single leg (left) countermovement jump with arms set on hips; CMJ_R (cm)—single leg (right) countermovement jump with arms set on hips; TENCODS (s)—change of direction speed test; TENRAG (s)—reactive agility test.

incorporated the assistance and supervision of these coaches to ensure consistency in training implementation. To guarantee that both groups followed the same volume of training, the licensed tennis coaches closely monitored the training sessions of each group. They provided instructions and guidance to the participants, ensuring that the prescribed training volume was adhered to by both groups. The coaches maintained regular communication with the researchers to report any deviations or inconsistencies in training volume. By involving licensed tennis coaches, who were experienced and knowledgeable in training methodologies, the study aimed to minimize variations in training implementation and ensure that both groups received similar training volumes throughout the study period. Based on the expert literature, previous research and recommendations from licensed tennis coaches, the plyometric training exercises were selected for this program. The execution of the plyometric training exercises was carefully described and explained to the participants before the training sessions. Licensed tennis coaches provided detailed instructions on the technical execution of each exercise. They also used demonstrations and visual examples to show participants the correct technique. Participants were given the opportunity to practice each exercise under the supervision of the coaches to ensure proper execution of the movements and understanding of the technique. Coaches provided feedback and corrected any errors or deficiencies in exercise execution to ensure safe and effective implementation of the plyometric training. The training schedule, as shown in Table 1 and Table 2, outlined the number of weeks, exercise names, sets and repetitions, and rest periods. The participants typically performed 3 to 4 sets of 4–6 exercises, with each exercise consisting of 5–10 repetitions. They were instructed to exert maximum effort during all exercises. The rest periods between sets ranged from 15 to 60 s, while the rest periods between exercises varied from 60 to 120 s. The training sessions lasted between 30 and 45 min, including the warm-up period, and were supervised by a certified strength and conditioning coach (Novak et al., 2023). The plyometric program includes unilateral and bilateral jumps, both vertical and horizontal. The training plan was programmed based on the principle of a progressive increase in load volume, which was measured by the weekly increase in the number of jumps and the ratio between the number of bilateral and unilateral jumps per week. Each training session consisted of a preparatory, main, and final part, and there was a minimum of 48 h between two training sessions. At the end of the experiment, a final test was conducted to determine the effects of plyometric training on motor abilities, pre-planned change of direction speed, and reactive agility.

2.4 Statistical analysis

All statistical analysis was performed using R Statistical Software (version 4.2.2 R Foundation for Statistical Computing, Vienna, Austria). The normality of the distribution was tested with the Shapiro-Wilk W test. Descriptive statistics were used to determine the basic parameters of test results for each group (CG and EG) in initial and final testing phases (mean - $\bar{x}$; standard deviation—SD). Mixed model (2 × 2) ANOVA was used to determine interactions and the effect of the training program on test results. Maturity status calculated based on PHV maturity offset was included as a covariate. The partial η2 coefficient was used as an indicator of effect size. Furthermore, when the group effect was significant, the paired *t*-test with Bonferroni correction was used for a *post hoc* analysis. For the sensitivity analysis, a complex variance model was conducted to evaluate the heterogeneity of the intervention on 15 different outcomes. It means that the constant variance assumption was loosened to allow for differential variance in outcomes to be estimated by the intervention status. This modelling offers information about the magnitude and direction of the effect on variance. Complex variance models were fitted by partitioning the level-1 variance according to the intervention status (intervention group variance (σ^2_{e1}), and control group variance (σ^2_{e2})):

$$Y_i = \beta_0 + \beta_1 Intervention_i + e_{1i} Intervention_i + e_{2i} Control_i$$

For this model, the residual distribution of the specified model:

$$\begin{bmatrix} e_{1i} \\ e_{2i} \end{bmatrix} \sim N\left(0, \begin{bmatrix} \sigma^2_{e1} & \\ - & \sigma^2_{e2} \end{bmatrix}\right)$$

Where Y_i represents the 15 different outcomes, $Intervention_i$ is an indicator variable for the intervention group ($Intervention_i = 1$ if one was in the intervention group) and $Control_i$ is an indicator variable for the control group. Due to the limited number of observations, the point estimation was calculated through likelihood procedures (IGLS) and then applied parametric, bias-corrected bootstraps for the fitted models, with replicate set size set to 100, max iterations per replicate set to 25, and the maximum number of sets set to 5. This procedure ran by MLwiN Version 3.05. (Centre for Multilevel Modelling, University of Bristol). The level of statistical significance was set at $p < 0.05$ and the confidence interval was 95%.

3 Results

Basic descriptive parameters of the test results were calculated and are presented in Table 3. Additionally, time*group interactions were determined for all variables. Significant interactions were observed in the sprint test results for split times at 5 m (F = 7.80; p = 0.00) and 10 m (F = 5.76; p = 0.02), indicating differences between the groups over time. However, there were no significant interactions found in the 20 m sprint test results. The best average acceleration results at 5 and 10 m were obtained in the final testing of the, EG, while the best average results at 20 m were found in the final testing of the CG. The 4 × 10 yards and 20 yards CODS tests did not show significant interactions, with the best average results achieved in the final testing of the, EG.

In tests assessing horizontal jump performance (standing long jump, triple jump_L, triple jump_R), the lowest average results were measured in the initial testing, and the best results were achieved in the final testing of the, EG. Significant interactions were also observed for these tests (p = 0.00). Regarding vertical jump performance, the triple jump_L and triple jump_R tests showed the lowest values in the initial testing and the best average values in the final testing of jump height in the, EG. Significant interactions were determined for all vertical-oriented jump tests (p = 0.00). Single leg countermovement jump (CMJ) tests yielded better results when performed with the right leg (13.01 cm).

Furthermore, the change of direction speed (TENCODS) and reactive agility (TENRAG) results also exhibited significant interactions (TENCODS - F = 26.50; p = 0.00 and TENRAG—F = 19.08; p = 0.00), with the best results being measured in the final testing of the, EG.

In addition, for all variables that were significant in 2 × 2 (time*group) an ANOVA, Bonferroni *post hoc* test (Table 3) was performed to further determine differences in each variable. The, EG showed significantly improved results in the 5 m test in the final testing compared to the initial testing, as well as in comparison to the control group in both measurements. There were no significant differences in the 10 and 20 m sprint results between the initial and final testing within the, EG. T-tests revealed no significant differences between the initial and final testing for both the CG and the, EG. Significant differences were not observed in the, EG between the initial and final testing in tests focusing on horizontal jump ability (single leg triple jump) and vertical tests performed with both legs (countermovement jump and squat jump). Furthermore, the, EG showed significant improvement (p = 0.01) in the single leg countermovement jump in the final testing. The change of direction speed and reactive agility test also exhibited significant improvement in the final testing of the, EG (p = 0.01).

The results of this research indicate that an experimental training program affected results in a set time period, i.e. 5 out of total 15 variables showed significant improvement after experimental protocol when final testing was conducted. Moreover, modelling variance by intervention status revealed that plyometric intervention indeed improved the agility, meaning that substantial heterogeneity treatment effect exists and supporting results from 2*2 mixed ANOVA. (Figure 2). displays box plots of selected variables that showed statistically significant differences in the 2 × 2 Mixed Analysis of Variance (ANOVA) and paired t-tests.

Table 4 represents the results of partitioned variance in different outcomes when assuming different variances (heterogeneity) by intervention status (level-1). When we allow complex level-1 heterogeneity by intervention status, we observed everything bar two outcome variables (CMJ and sprint 20 m), the variance of the other outcomes did not differ by the intervention status. On the one hand, the CMJ variable indicated the presence of heterogeneous treatment effect ($\sigma^2_{Intervention\,Group}\,[\pm 1.96 * SE] = 3.825\,[1.542; 6.108]$, $\sigma^2_{Control\,Group}\,[\pm 1.96 * SE] = 0.789\,[0.266; 1.312]$). On the other hand, the sprint 20 m variable showed the treatment reached the control group heterogeneously rather than the intervention group ($\sigma^2_{Intervention\,Group}\,[\pm 1.96 * SE] = 0.005\,[0.001; 0.009]$, $\sigma^2_{Control\,Group}\,[\pm 1.96 * SE] = 0.045\,[0.014; 0.076]$). Lastly, since the ANOVA requires the homogeneity of variances, the sensitivity analysis suggests that the main analysis sufficed one of the primary assumptions in ANOVA.

4 Discussion

The findings of this study provide strong evidence for the positive effects of a 6-week plyometric training program on motor abilities in young tennis players. The, EG demonstrated significant improvements in various aspects compared to the CG, indicating the effectiveness of the training program. Specifically, the, EG showed enhanced sprint performance at 5 m, indicating improved acceleration and speed. These improvements in sprint times highlight the positive impact of the plyometric training program on the players' explosive power and running abilities. While no significant interactions were found in the 10 and 20 m sprint test, it is important to note that the, EG still achieved better average results in the final testing phase compared to the CG. The, EG also exhibited notable advancements in jump performance. Significant interactions were observed in horizontal jump tests, with the best results being achieved in the final testing phase. This indicates that the plyometric training enhanced the players' ability to effectively generate power and explosiveness in horizontal jumps. Additionally, significant interactions were found in vertical jump tests, particularly in the triple jump tests, where the, EG showed improved jump heights in the final stage of testing. The results suggest that the plyometric exercises positively influenced the players' vertical jump performance, contributing to their overall jumping abilities. Moreover, the, EG displayed significant improvements in change of direction speed and on the reactive agility tests. These findings indicate that the plyometric training program enhanced the players' ability to change direction quickly and react to unpredictable movements, both of which are crucial in tennis. Sensitivity analysis manifested the main analysis's assumption. Hence, it was an adequate analysis. Since pre-planned change of direction speed (CODS) and reactive agility (RAG) are distinct and separate abilities influenced by multiple factors, this study represents an innovative research effort in tennis, providing valuable insights into the effects of plyometric training on both aspects. Possible reasons for a slightly greater influence on CODS comes down to the simple fact that there is no decision-making factor in these tests. The movement structure is known in advance, so the participants are less susceptible to the influence of errors during execution. While on the other hand, the RAG test is considered more complex and more difficult to perform due to the greater demand on reaction speed. It is logical that the result will be somewhat weaker. It can be concluded that RAG is influenced not only by motor abilities but also by many other cognitive factors such as observation, perception, anticipation, or decision-making speed. The plyometric training program used in this research should be employed in tennis due to its potential benefits in enhancing specific physical qualities and skills required in the sport, such as improved power and explosiveness, enhanced agility and quickness, increased speed and acceleration, enhanced lower-body strength and injury prevention. Such plyometric training program can lead to several neuromuscular adaptations that contribute to improved athletic performance. These adaptations include enhanced motor unit recruitment and synchronization, improved intermuscular coordination, increased muscle fiber activation and force production, enhanced stretch-shortening cycle utilization, and improved proprioception and reactive capabilities. These neuromuscular adaptations can result in increased power output, greater force absorption and production during explosive movements, improved movement efficiency, and enhanced overall athletic performance (Fatouros et al., 2000; Chimera et al., 2004; Markovic et al., 2007).

Plyometric training is increasingly being researched as a beneficial tool for improving motor abilities in tennis players. Several studies have examined the effects of plyometric training on tennis players and have reported positive changes in their athletic performance. In a study conducted by Sadić et al. (2011), plyometric training was found to have a positive impact on the physical fitness of young tennis players. Improvements were observed in strength, speed, and agility. Granacher et al. (2016) also investigated the effects of plyometric training in prepubescent tennis players. The results showed that plyometric training led to improvements in physical fitness, including strength, speed, and agility.

In another study by Kovacs (2006), it was found that plyometric training can enhance serve performance in pubescent boys. This study highlights the potential of plyometric training in improving specific aspects of tennis gameplay. Plyometric training has also been studied in relation to maximal power output in tennis players. Other research has focused on the effects of plyometric training on acceleration and agility in young tennis players. Čavala et al. (2017) investigated the effects of plyometric training on acceleration and agility and found positive changes in these motor abilities in young tennis players. These studies suggest that plyometric training can have a positive influence on motor abilities in tennis players. Improvements have been observed in strength, speed, agility, and specific aspects of tennis gameplay such as serving. However, it is important to note that individual responses to training may vary, and it is necessary to tailor the training program to individual needs and goals of the tennis players. Similar results have been obtained in research carried out on young soccer players (10–14 years old) where plyometric training for 6 weeks significantly improved agility results (Ramírez-Campillo et al., 2015). Other studies have reported improvements in the Illinois Agility Test scores after 7 weeks of low-volume plyometric training (Ramírez-Campillo et al., 2014). Previous studies have also shown significant changes in the Illinois Agility Test score after 8 and 12 weeks of plyometric training in prepubescent soccer players (Negra et al., 2020). Some research studies have connected the plyometric training program with the ability to change direction, reporting improvements in agility test times after 6 weeks of training (Miller et al., 2006). Similar results have been observed in handball and basketball players with an average age 22.5 ± 0.4 years, where 8 weeks of plyometric training led to decreased agility test times (Bal et al., 2011; Rameshkannan and Chittibabu, 2014). Meta-analysis studies on pubertal and young athletes have reported improvements in agility indicators by 2%–5% after the implementation of plyometric training (Markovic and Mikulic, 2010). While the present study provides evidence for the positive effects of a 6-week plyometric training program on motor abilities in young tennis players, it is important to acknowledge that there are some contradictions with previous studies. Radnor et al. (2020) conducted a systematic review and meta-analysis on neuromuscular training interventions in youth sports, including plyometric training. While they acknowledged some positive effects, they also highlighted limited evidence and inconsistent findings in regards to motor ability improvements. Similarly, Khlifa et al. (2010) investigated the effects of plyometric training with and without added load on jumping ability in basketball players. Their findings suggested that plyometric training without added load did not result in significant improvements in jumping ability compared to the control group, indicating a lack of positive effects. Furthermore, Spurrs et al. (2003) explored the impact of plyometric training on distance running performance. Their study concluded that plyometric training alone may not significantly improve distance running performance, suggesting that the effects of plyometrics may vary depending on the specific motor ability being targeted. These studies present alternative findings and indicate that the effects of plyometric training may not be universally positive for all motor abilities and sports. It highlights the need for further research to understand the specific contexts and factors that influence the effectiveness of plyometric training. Despite these contradictions, it is worth noting that the overall body of research still supports the positive effects of plyometric training on motor abilities in various sports. However, individual responses and specific contexts should be considered when implementing plyometric training programs.

Summarizing the results of previous research, plyometric training aimed at developing the ability to change direction has been conducted with different age categories for durations ranging from 6 to 12 weeks. However, agility is now classified as consisting of two branches: pre-planned change of direction speed, where the change of movement direction is known in advance, and reactive agility, which includes a cognitive component involving observation and decision-making factors (Zeljko et al., 2020). With the advancement of sports science, more studies have focused on determining the reliability of tests for assessing pre-planned change of direction speed and reactive agility. These tests are often specific, aiming to replicate situations within a chosen sport. Such research has been conducted on various athlete samples including Australian football players (Henry et al., 2013), rugby players (Green et al., 2011), netball players (Farrow et al., 2005), basketball players (Sisic et al., 2016; Sekulić et al., 2017), soccer players (Knoop et al., 2013; Gilić et al., 2019; Krolo et al., 2020), and futsal players (Benvenuti et al., 2010; Sekulić et al., 2019; Sekulić et al., 2020; Zeljko et al., 2020).

This study has certain limitations that should be considered. Firstly, the participants in this research were young tennis players in a highly sensitive and crucial stage of development. Additionally, the motor tests were conducted using a convenience sample of subjects under controlled conditions. Therefore, further longitudinal investigations are needed to thoroughly examine the impact of biological age on motor abilities in young tennis players. This research suggests that coaches and practitioners can effectively use a plyometric training program to enhance the desired physical fitness in young tennis players. Specifically, the study demonstrated that plyometric training had a greater impact on pre-planned change of direction agility rather than reactive agility, highlighting the need for including cognitive training in the development of reactive agility. Coaches should take into consideration the variations in physical performance and the practical implications of maturation when planning the long-term development of young tennis players. Future research should aim to include participants of different genders and competition categories, subsequently enabling the acquisition of more precise and comprehensive data for an enhanced practical and scientific contribution. Such information would prove valuable to coaches in designing specific conditioning strategies to foster the motor characteristics of young tennis players.

5 Conclusion

The results of this research indicated that a 6-week program dominated by plyometric training can have a significant effect on the improvement of specific motor abilities in the younger competitive categories of tennis players (U-12 and U-14). It is especially important to emphasize how the training programs impacted both abilities, namely, change of direction speed and reactive agility. However, it is important to note that there are risks and dangers associated with plyometric training, particularly for young athletes in the prepubescent and early puberty stages. This primarily pertains to moderately complex plyometric exercises that may lead to acute injuries or various overexertion syndromes. Therefore, it is crucial to adhere to methodological principles and progressively advance from simpler to more complex exercises when implementing plyometric content. Our results offer valuable insights for coaches in designing diverse tennis-specific scenarios to enhance overall performance, particularly focusing on the neuromuscular fitness of their players. Further research is required to explore interventions that can effectively improve sport-specific neuromuscular fitness, with the ultimate aim of enhancing overall performance.

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 the Institutional Review Board of the Faculty of Kinesiology, University of Zagreb (Protocol Code 34; date of approval 13 December 2021). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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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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Biomechanical effects of exercise fatigue on the lower limbs of men during the forward lunge

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Background: During competition and training, exercises involving the lungs may occur throughout the sport, and fatigue is a major injury risk factor in sport, before and after fatigue studies of changes in the lungs are relatively sparse. This study is to investigate into how fatigue affects the lower limb's biomechanics during a forward lunge.

Methods: 15 healthy young men participate in this study before and after to exposed to a fatigue protocol then we tested the forward lunge to obtain kinematic, kinetic changing during the task, and to estimate the corresponding muscles' strength changes in the hip, knee, and ankle joints. The measurement data before and after the fatigue protocol were compared with paired samples t-test.

Results: In the sagittal and horizontal planes of the hip and knee joints, in both, the peak angles and joint range of motion (ROM) increased, whereas the moments in the sagittal plane of the knee joint smaller. The ankle joint's maximum angle smaller after fatigue. Peak vertical ground reaction force (vGRF) and peak contact both significantly smaller after completing the fatigue protocol and the quadriceps mean and maximum muscular strength significantly increased.

Conclusion: After completing a fatigue protocol during lunge the hip, knee, and ankle joints become less stable in both sagittal and horizontal planes, hip and knee range of motion becomes greater. The quadriceps muscles are more susceptible to fatigue and reduced muscle force. Trainers should focus more on the thigh muscle groups.

KEYWORDS

forward lunge, kinetics, kinematics, fatigue, lower limb

1 Introduction

Lunge is an important part of a lower-limb muscle strength training and rehabilitation programs. This task is typically performed to enhance the lower limb muscles'-ability to generate higher force, especially in the quadriceps, and to minimize the risk of joint injury (Keogh, 1999), and develop functional postural balance (Ebben et al., 2009). Lunge requires more balance than the more commonly used deep squat thus it can be used more safely to strengthen the biarticular quadriceps and hamstrings muscles, which are necessary for appropriate rehabilitation of gait and daily living activities (Wilson et al., 2008; Dregney et al., 2023). Also, this task often makes sure that the athlete's lower body and trunk become strong, flexible, and stable enough to support safe and efficient augmentation training (Tippett and Voight, 1995).

While modest knee loads support the health of the joint cartilage (Griffin and Guilak, 2005), high-intensity loads or extended exercise might cause injuries in the knee (Ebben et al., 2009; Richmond et al., 2013). Repeated work exposure to bow steps may also raise the incidence of joint degenerations, especially in the knee joint (Amin et al., 2008). For instance, repetitive knee flexion during work duties can lead to excessive fatigue (Richmond et al., 2013). Furthermore, the risk of injury increases when the intensity of exercise increases and activation of certain muscles increases or even exceeds the activation of other muscles (Irish et al., 2010).

Muscle fatigue, which is characterized by decreased muscular efficiency and force production capacity after extended exposure to activity (Gandevia et al., 2006; Yamane et al., 2023), has repeatedly been proven to have a negative impact on performance (Pincivero et al., 2000). In female athletes doing single-leg landings, neuromuscular fatigue has been demonstrated to alter knee flexion, knee abduction, and hip internal rotation (McLean and Samorezov, 2009). Moreover, the muscles' diminished capacity for force production may affect their capacity to function as dynamic joint dampers (Pincivero et al., 2000) and may contribute to damage (Du and Fan, 2020). For instance, epidemiological research shows that greater incidence of badminton injuries are discovered during trainings because of muscle strength decreased (Shariff et al., 2009; Kondrič et al., 2011). In badminton, lunge is frequently employed as a fundamental step, and when players grow tired, they are more likely to suffer ankle injuries in addition to knee injuries during practice or competition (Herbaut et al., 2018). Garcia et al. (2012), however, showed the lunge squat is an exercise that accurately represents the tiredness process and enhances knee stability by equally activating the quadriceps and hamstring complexes, and this co-activation Weir et al. (1998) observed to occur simultaneously with fatigue. The fatigue process reduces the contraction force and muscle activation time of the quadriceps, which triggers an increase in hamstring muscle activity during fatigue (Garcia et al., 2012). By preventing external joint rotation, the quadriceps, hamstrings, and gastrocnemius muscles stabilize the knee (Winby et al., 2009). On the other hand, fatigue fractures are a common injury that typically arise from running exercise. Consequently, a vital initial step in guiding injury prevention research and informing injury screening is understanding how fatigue affects movement patterns in standard musculoskeletal screening procedures (Weeks et al., 2015).

Some studies have illustrated lunge and squat EMG and kinematic changes under different loading conditions (Stastny et al., 2015a; Stastny et al., 2015b), but fewer studies have been conducted after prolonged exercise or even fatigue. The muscle performance during extended exercise is unknown, although experienced gym athletes show greater muscular strength and better joint coordination compared to novice, which helps to minimize redundancy in force production through joint coordination and employing muscle power effectively (Phomsoupha and Laffaye, 2015).

There is a lack of many studies focusing on how fatigue induce kinematic and kinetics changing in lunge. There is a lack of information on the kinematics, kinetics, and changes in the force generation of the relevant muscle groups in the lunge before and after fatigue, despite the kinematic performance of the lunge in various directions (Comfort et al., 2015; Goulette et al., 2021; Park et al., 2021) and of closed chain exercises of the lower limb after fatigue (Gribble et al., 2007; Weeks et al., 2015; Du and Fan, 2020). Therefore, the aim of this study was to investigate the effects of fatigue on lower limb biomechanics during the anterior lunge before and after completing a fatigue protocol. Fatigue is a major contributor to injury risk, and relevant objective data provide the required understanding for understanding the cause of injury and to help improve injury prevention programs.

2 Materials and methods

2.1 Participants

The sample size was determined using data from previous studies (Nielsen et al., 2018; Liu et al., 2023). At least 15 participants were selected using G*Power3.1, Statistical test choosing Means: Wilcoxon signed-rank test (matched pairs) with tails of 2 and an alpha value of 0.05 and a power value of 0.80 and effect size of 0.80 (Faul et al., 2009). 15 young healthy males were recruited for this study, and relevant basic information is shown in Figure 1. The dominant leg was identified by self-declaration of the preferred leg during kicking which was defined as the dominant limb. Participants had no lower limb muscle or bone illness or injury 6 months prior to this testing session. Before the experiment, participants fasted for 2 h and were not allowed to drink any alcohol or caffeine for the following 24 h. To prevent shoes from influencing the experiment's outcomes, they all wore shoes of the same design. All participants signed an informed permission form before the experiment and were made aware of the importance and goal of the study as well as the testing methods. The Ethics Committee of Ningbo University Research Institute approved the experiment. (NO: RAGH202303073005.2).

2.2 Instruments

An eight-camera Vicon motion capture system (Vicon Metrics Ltd., Oxford UK) was used to capture the markers motion trajectories with a sampling frequency of 200 Hz. Simultaneously with motion capture an embedded Kistler 3D force plate (Kistler, Switzerland) was used to record ground reaction forces with 1000 Hz. Before the experiment, 38 reflective markers (diameter: 14 mm) were mounted onto their bodies (Figure 1).

The EMG signals of the rectus femoris (RF), biceps longus (BF), tibialis anterior (TA), and gastrocnemius (GA) were recorded simultaneously at 1000 Hz with a Delsys EMG test system (Delsys, Boston, MA, and United States) to validate the results of the model. Maximum voluntary isometric contractions (MVIC) were performed for the rectus femoris, biceps femoris long head, tibialis anterior, and gastrocnemius muscles using a dynamometer (CON-TREX MJ System, CMV, Dübendorf, Switzerland).

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A

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Age (years)	22.5±1.60
Height (m)	1.75±0.06
Weight (kg)	74.76±0.05
BMI (kg/m²)	24.03±1.29
Leg length (m)	0.89±0.06
Shoulder width (m)	0.40±0.02

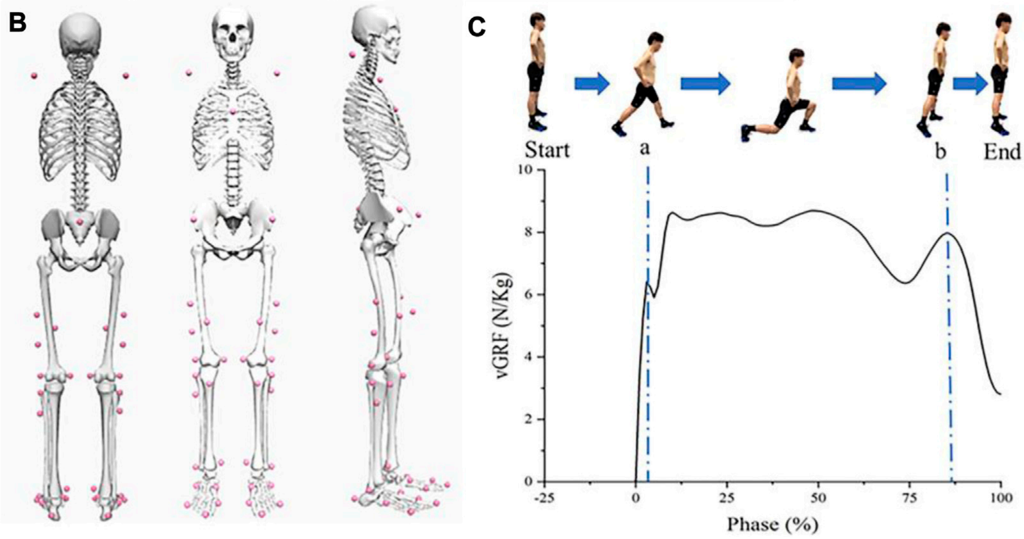

FIGURE 1
(A) Basic information of participants; **(B)** Back, front, and side view of the participant's reflective markers; **(C)** Forward lunge process and corresponding vGRF; a, Initial impact peak; b, Drive-off peak.

2.3 Procedures

First, participants warmed up with 5 min run on a stationary motorized treadmill (h/p/cosmos sports and medical GmbH, Nussdorf-Traunstein, Germany). The leg length of each participant was measured manually with a metric ruler. We defined step length as the 70% of the leg length. The lunging leg position was marked with tape on the force platform for both side and starting position was also marked with tape with the corresponding distance for each participant leg length.

To obtain maximal values of EMG signals, participants performed a 5-s MVIC on a dynamometer, and each participant performed 3 consecutive measurements for each muscle group with 1-min rest interval. The MVIC was tested according to the recommended setting of the dynamometer, which allows participants to power up to the maximum force possible (Bliss and Dekerle, 2019). Professionals were on hand to guide and protect the participants throughout the test and secured the athlete's trunk with a strap to avoid pronation. The participants were provided with concurrent visual feedback in the form of an isokinetic strength curve displayed on the dynamometer monitor. Verbal encouragement was also provided.

After skin preparation, shave off the body and clean the skin with alcohol. Bipolar surface electrodes were attached over four lower limb muscles. The sensor was placed over the muscle belly of the muscle parallel to the direction of the muscle fascicles. Bipolar surface electrodes (adhesive disposable electrode, 10 mm interelectrode distance) were taped parallel to muscle fascicles. Electrode placements was in accordance with the SENIAM recommendations (Hermens et al., 2000). The EMG signals of the RF, BF, TA, and GA muscles were collected at 1000 Hz using a wireless Delsys EMG test system.

Before the experiment, participants received specific instructions from an expert coach with several years of experience to make sure that participants were familiar with the task and that can perform the task properly. Proper executions had to meet the following criteria: 1) the body must remain upright and perpendicular to the horizontal at all times, with the arms crossed at the sides of the body; 2) the dominant leg's thigh must be perpendicular to the ground; and 3) the non-dominant leg's knee must be close to the ground but not touch it. Lunge started in a standing position with feet parallel to each other, at the previously marked starting location of the experiment. Then lunge was initiated by a verbal command. Based on the lunge forward of the dominant leg (right leg) to the mark on the force platform, participants were asked to moved their body weight downward to the upright leg and to maintain an upright posture. After the deepest position the non-dominant leg followed the dominant leg forward and settles parallel to the upright foot and stood on the corresponding ground marking, i.e., the body back into a standing position at the end. When a lunge is completed, the expert will indicate the quality of this movement, whether it reached the standard and how it can be improved. Unqualified movements are not included in the data.

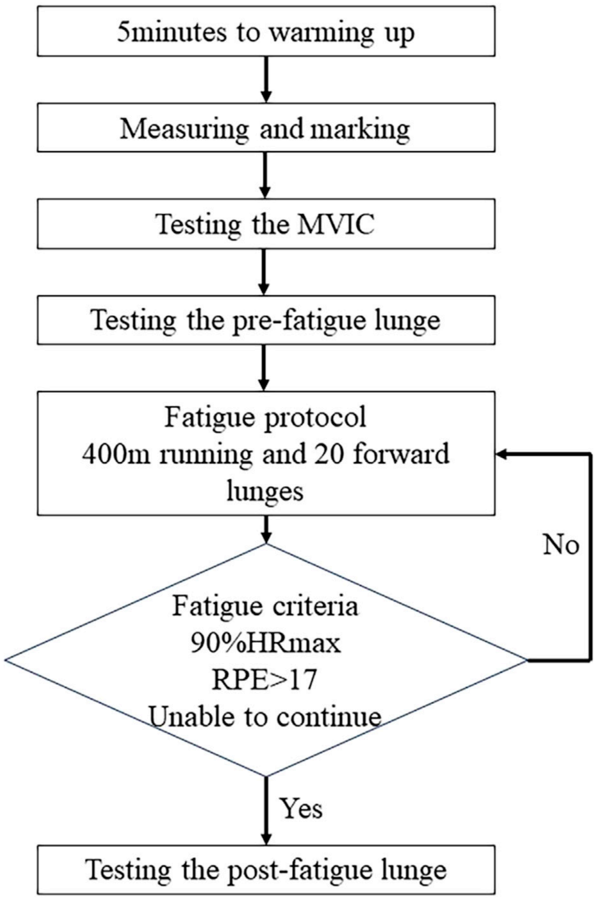

FIGURE 2
Flowchart of the study.

Prior completing the fatigue protocol participants were familiarized with the fatigue protocol and instructed in the use of the Borg Scale RPE 6–20 scale (Borg, 1982), to obtain the level of the subjective fatigue. In addition, heart rate was also measured with a portable detector (Polar RS100, Polar Electro Oy, Woodbury, NY, and United States) to monitor the changes in heart rate (HR) changes during the fatigue protocol. In to imitate lower limb movement patterns that might be seen in a sporting or recreational situation (Weeks et al., 2015), fatigue protocol consisted 20 repetitions of forward lunges (alternating forward lunges with the dominant and non-dominant leg) and a 400-m of running at an individually maximal running speed on a motorized treadmill. If fatigue level was minimal after one set of fatigue protocols, then the following set of procedures were carried out, and so on. HR and RPE data are used to quantify fatigue (Du and Fan, 2020). When the participants were unable to continue the fatigue protocol due to exhaustion, or their heart rates reached 90% of the maximum heart rate (HRmax = 220-age) predicted for their age, or if their Borg scale scores reached RPE >17 (very difficult), fatigue was considered to be occurred. Participants were not informed about the number of repetitions to avoid intentional halting to save energy.

After the fatigue protocol was completed, we repeated the measured lung test. 5 min were given for placing reflective markers on to the participants body. For each person, six repetition was requested, three trial included in the analysis, the flow chart is shown in Figure 2.

2.4 Data collection and processing

One lunge data period was defined as starting from the previous frame of the dominant leg contacting the force table to the end of the next stance position. By collecting kinematic and kinetic data from the hip, knee, and ankle joints in the sagittal and horizontal planes, as well as vertical ground reaction forces (vGRF), joint changes under fatigue were examined. Lunge can be divided lunges into five phases recommended by Kuntze et al. (2010). In this study we used the first and last peak of the ground reaction force as initial impact peak and drive-off peak (Figure 1).

Joint moment, vGRF, and muscular strength data were normalized to body weight, respectively. Joint angular data, moment, and vGRF data were time-normalized to lunge strides (1–101 points), then these strides were averaged in a group level.

The original EMG signal is first pre-processed, including 50 Hz trapping to remove the industrial frequency interference, then 30 Hz zero-phase-shift high-pass filtering to remove motion artefacts; finally, the signal is taken to its absolute value, and the negative half-axis of the signal is flipped to the positive half-axis. Processing EMG signals in the 10–500 Hz frequency range using a bandpass fourth-order Butterworth filter (Zhang et al., 2010). The amplitude analysis is carried out using root mean square (RMS) calculation. RMS values of the EMG signals were calculated with a window size of 50 m. Using the same method for the EMG signal at MVIC, EMG values during lunge were normalized to the peak MVIC activity for each corresponding muscles. The MVIC and standardized activity value of each action was output. The EMG activity was calculated from 0 (0, completely inactive) to 1 (100%, fully activated) through the test root mean square amplitude/MVIC root mean square amplitude.

Marker trajectories and ground reaction force were filtered by zero-latency fourth-order Butterworth low-pass filters at 12 and 30 Hz, respectively. A threshold of 20 N was used, and ground reaction force data to determine the instant of the ground contact. The filtered marker coordinate data were imported into OpenSim for data processing after being converted in Matlab R2018a (The MathWorks, MA, United States) to formats recognized by OpenSim 4.3 (.mot and. trc) (Zhou et al., 2021). The model Mei et al. (2022) used in this experiment was adapted from the original OpenSim model (Rajagopal et al., 2016) by Mei et al. (2022). The model was upgraded with additional ranges of motion in the coronal and horizontal planes of the knee joint. First, the model was scaled to the static calibration measurement data using the positions and weights of the subjects' marker points. Marker positions were manually corrected to reduce RMS error value (less than 0.02) between the experimental and virtual markers in the model. In order to reduce the error between the experimental and virtual markers, the joint angles were estimated using the inverse kinematics (IK) calculation tool in OpenSim. The findings were then optimized using least squares. The net moments of the hip, knee, and ankle joints are determined calculating inverse dynamics (ID) with a built in OpenSim algorithm. In order to determine the net forces and torques for each joint that creates the motion, the ID

TABLE 1 Hip, knee and ankle range of motion and maximum and minimum peak angles in the Sagittal plane and Horizontal plane before and after fatigue protocol.

Index		Pre		Post	
		S	H	S	H
Hip	Max	88.51 ± 12.36*	9.97 ± 6.54*	92.89 ± 9.23*	13.32 ± 2.56*
	Min	12.87 ± 11.72	0.46 ± 5.79*	16.80 ± 5.21	1.58 ± 2.09*
	Rom	75.64 ± 5.74	10.63 ± 2.76	76.10 ± 9.53	11.75 ± 3.38
Knee	Max	−120.45 ± 10.45*	13.44 ± 11.46*	−124.44 ± 8.34*	25.43 ± 5.07*
	Min	−20.90 ± 8.21	−12.15 ± 8.42	−19.14 ± 7.11	−10.48 ± 5.15
	Rom	99.55 ± 7.71*	25.59 ± 12.08*	105.30 ± 8.27*	35.91 ± 3.92*
Ankle	Max	32.05 ± 8.40*	—	24.56 ± 4.55*	—
	Min	−0.48 ± 5.83*	—	−8.22 ± 3.40*	—
	Rom	32.53 ± 4.40	—	32.78 ± 5.73	—

* indicates significant difference between pre and post, $p < 0.05$. pre, pre-fatigue; post, post-fatigue. S, sagittal plane; H, horizontal plane. (°).

tool solves the force and acceleration mathematical equations of classical mechanics in an inverse dynamics sense (Yamane et al., 2023). The next step involved estimating muscle forces and muscle activation using static optimization (SO) and minimization of the sum of squared muscle activity. The Delsys EMG test system measurements of standardized muscle electrical signals were used to validate the model, which was then compared to the OpenSim static optimization algorithm's output of the degree of muscle activation. The quadriceps, hamstrings, gastrocnemius, and tibialis anterior muscles were among the major muscle groups whose forces were estimated using static optimization.

2.5 Statistical analysis

Data are presented as the Mean Difference and Standard Deviations (MD±SD). To check the normality of each dataset we used Shapiro-Wilk normality test. Paired samples t-tests were used to compare joint ROM, peak joint angles, peak joint moments, peak vGRF, and two peaks (A and B) of the lunge test before and after the fatigue protocol. The direction of the movement was also marked as follows: 1; flexion (+)-extension (−) in the sagittal plane and internal rotation (+)-external rotation (−) in the horizontal plane, 2; knee joint was flexion (+)-extension (−) in the sagittal plane and internal rotation (+)-external rotation (−) in the horizontal plane. 3; ankle sagittal plane was dorsiflexion (+) and plantarflexion (−). IBM SPSS Statistics 26 (IBM Corporation, Armonk, NY) was used to calculate all statistical analysis. The alpha level was set at 5%.

3 Results

3.1 Hip, knee, and ankle joint angles

As can be seen in Table 1, there was a significant difference in the hip's maximum angle both in the sagittal plane and horizontal plane before and after fatigue ($p = 0.007$ and $p = 0.017$), representing an increase of 4.38° and 3.35°. And hip minimum peak joint angle was significantly lower ($p = 0.011$) in the horizontal plane after fatigue. There was a 5.75° increase in ROM and a significant difference in maximal and ROM at the knee joint (both $p = 0.001$) in the sagittal plane. And for the knee in the horizontal plane after fatigue, the maximum value has, increased by 11.99°, a significantly higher ($p < 0.001$), ROM also differed significantly before and after fatigue ($p = 0.001$), with an increase of 10.32°. The maximum and minimum values in the ankle were significantly different (both $p < 0.001$). The ROM was nearly unchanged, while the maximum value decreased by 7.49° and the minimum value dropped by 7.74°.

3.2 Hip, hip, and ankle joint moments

As shown in Table 2, there was a significant difference in the peak sagittal plane moment at the hip joint before and after fatigue ($p < 0.001$), with an increase in moment of 0.39 Nm/kg. There was also a significant increase in the horizontal plane ($p = 0.003$) as well. The moment at the knee joint significantly decreased in the sagittal plane by 0.24 Nm/kg ($p = 0.004$). At the ankle joint, the sagittal plane moment was statistically significant after fatigue ($p = 0.023$). At the ankle joint, the post-fatigue sagittal moment was statistically significant ($p = 0.023$).

3.3 Hip, hip, and ankle joint moments

Table 3 shows that only the initial contact peak (A) for vGRF before and after fatigue had a statistically significant decline of 0.49 N/kg ($p = 0.014$). The mean peak and the drive-off peak (B) were not statistically significant, but the mean peak increases while the drive-off peak decreases.

3.4 Model validation and muscle force

According to Figure 3, muscle activity during lunge using the OpenSim SO tool matched the experimentally obtained EMG

TABLE 2 Peak joint moments in the sagittal and horizontal plane before and after fatigue protocol.

Index		Pre	Post
Hip	S	−1.95 ± 0.53*	−2.34 ± 0.17*
	H	0.38 ± 0.10*	0.48 ± 0.08*
Knee	S	1.54 ± 0.68*	1.30 ± 0.30*
	H	−10.98 ± 1.38	−11.48 ± 2.15
Ankle	S	−1.12 ± 0.13*	−1.06 ± 0.14*

* indicates significant difference between pre and post, $p < 0.05$. pre, pre-fatigue; post, post-fatigue. S, sagittal plane; H, Horizontal plane. (Nm/kg).

TABLE 3 Peak vGRF, of the first peak and last peak before and after fatigue protocol.

Index	Pre	Post
vGRF	9.77 ± 0.38	9.26 ± 1.95
A	7.15 ± 0.80*	6.66 ± 0.59*
B	8.39 ± 1.22	8.51 ± 1.13

* indicates significant difference between pre and post, $p < 0.05$; A, initial impact peak; B, Drive-off peak. pre, pre-fatigue; post, post-fatigue. (N/kg).

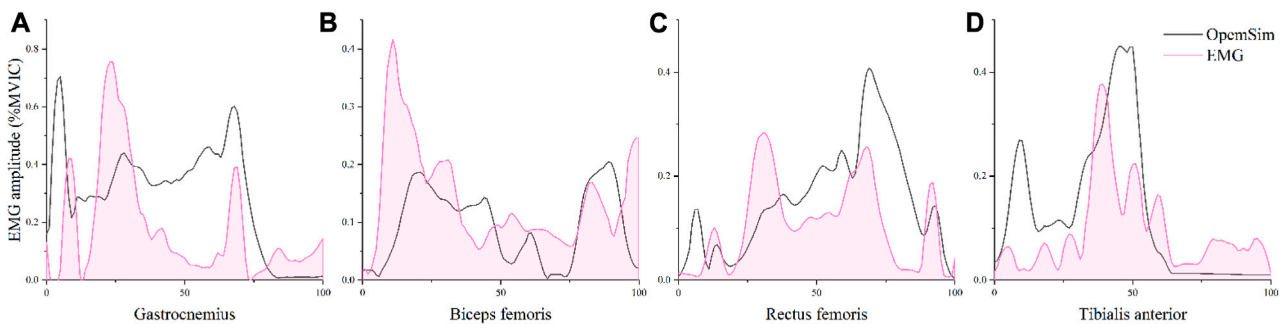

FIGURE 3
The comparison of gastrocnemius **(A)**, biceps femoris **(B)**, rectus femoris **(C)**, and tibialis anterior **(D)** EMG activity levels obtained using the EMG signal and the estimated values from the OpenSim optimization algorithm.

activity signal trends, proving that the data from the OpenSim model in this study is reliable (Hamner and Delp, 2013). When compared to muscle forces before fatigue (Figure 4), the biceps femoris and gastrocnemius both had lower average and maximal muscle force after fatigue protocol. The quadriceps and tibialis anterior muscles generated more force on average and at their maximal force output was also higher. The average muscle force of the tibialis anterior muscle was increased by 1.56 N/kg compared to after fatigue, it has a significant difference (p = 0.001); its maximum muscle force increased by 3.00 N/kg, also a significant difference, (p = 0.046). The mean muscle force of the biceps femoris decreased by 4.19 N/kg ($p < 0.001$). The maximum muscle force was significantly different, decreasing by 12.76 N/kg (p = 0.005). For the quadriceps, mean muscle force significantly increased by 13.16 N/kg (p = 0.002), and maximum muscle force increased by 19.78 N/kg ($p < 0.001$). Of the muscles explored, the quadriceps had the most significant increase in mean and maximum muscle force.

4 Discussion

The aim of this study is to investigate the changes of lunge biomechanics before and after completing a fatigue protocol in healthy young men. Our results provide the necessary insights by using our objective data to understand which aspects of the lower limb are specifically affected by fatigue, and help to prevent the injuries associated with fatigue based on previous research. Fatigue needs to be taken into account as part of a risk assessment for injuries where internal workload, cardiovascular fitness, and fatigue interact (Benjaminse et al., 2019; Song et al., 2023). Running and forward lunge a chosen as the fatigue protocol for this study because it more accurately simulates the fatigue brought on by performing exercise repeatedly.

In both the sagittal and horizontal planes of the hip joint, according to our research, the peak angle increased in the sagittal plane and horizontal plane. On both planes, ROM also increased differently. Peak angle and ROM in the sagittal plane both

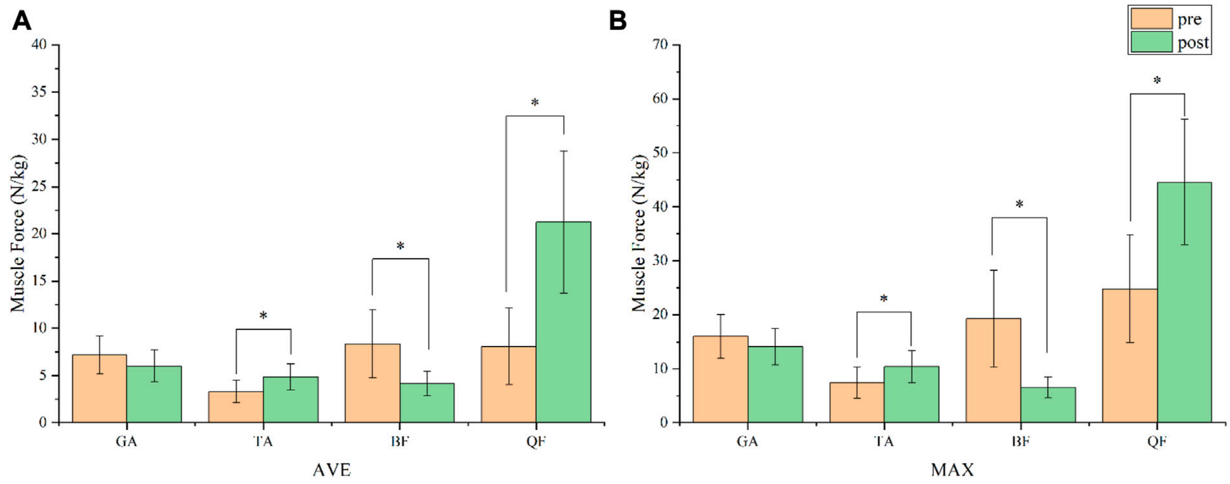

FIGURE 4
Comparison of the average **(A)** and maximal **(B)** estimated muscle force during lunge before and after fatigue protocol. GA, gastrocnemius; TA, tibialis anterior; BF, biceps femoris; QF, quadriceps femoris. *, $p < 0.05$.

significantly increased in the knee. The action of the knee joint and the motion of the hip joint during lunging are very similar. Greater knee flexion and forward trunk movement as a result of tiredness can also be used to explain increased hip flexion (Lin et al., 2015). The upper trunk's swing is enhanced by fatigue, and limb movements are necessarily less effective as maintaining the trunk becomes difficult. Similar findings were made by Weeks et al. (2015) who hypothesized that fatigue increases hip flexion, pelvic tilt, inclination, and rotation as well as trunk flexion and lateral rotation. As a result of fatigue, fatigue causes the trunk and pelvis ROM become greater. The position of the body's center of mass and the subsequent loading of the lower limb joints may be dramatically altered by the trunk because of its greater relative mass (Park et al., 2021). The peak knee joint angle and ROM increased significantly after the fatigue protocol compared to pre-fatigue in the sagittal plane. This shows that when we are exhausted or when the intensity of the exercise builds up over time, the knee joint tends to move farther forward from a vertical ground position. According to Zellmer et al. (2019), increased knee flexion may also increase the knee's tendency to move farther forward. And he also finds, peak knee joint stress, quadriceps force, knee moment, and knee flexion are higher when the knee is brought in front of the toes during the lunge. Less stretching force is placed on the patellar tendon when the knee is kept behind the toes (Escamilla et al., 2008). The plantar flexor and foot muscles involved more to take transfer the additional stress required to maintain the joint output when the hip and knee muscles are working less efficiently due to the fatigue effect. In the horizontal plane, the knee joint found a considerable shift as well, showing an increase in peak angle and ROM. This outcome, in our opinion, may be a result of greater toe external rotation movement in the upright foot during landing and more forward movement of the knee. Because fatigue has been shown to lead to reduced control of the stabilizing muscles in the hip and knee joints, resulting in altered joint kinematics (Webster et al., 2012). Different degrees of knee flexion may result in different levels of sports performance and joint impact forces. Athletes with knee injuries increase knee flexion during the lunge to reduce the impact of landing on the joint and increase their dynamic stability center of mass by reducing their knee height (Huang et al., 2014). And Huang et al. (2014) noted that to reduce the likelihood of damage, athletes may flex their knees more and conduct less physically demanding activities. This may be a neuromuscular protective mechanism. If athletes want to improve performance, adding greater weights is the most popular and important method of resistance training (Comfort et al., 2015). In addition, the increased external weight causes more mechanical work to be done at the hip and ankle joints (Riemann et al., 2012), muscle activation was significantly higher in the weight-bearing condition than in the self-weight condition.

While joint ROM did not vary significantly in the ankle joint, the peak angle did, with the maximum joint angle falling by almost 7.49° and the minimal angle increasing by 7.74°. This indicates that following fatigue, the ankle joint is more likely to be at a more plantarflexed position before landing. According to previous study, a considerable 10° increase in ankle plantarflexion increases the risk of injury owing to calf muscle fatigue and foot overuse and may also produce fatigue and injury to the Achilles tendon and anterior heel ligaments (Mei et al., 2017). Participants showed reduced dorsiflexion, possibly as a result of fatigue, leading to an insufficient dorsiflexion muscular force generation and relatively high plantarflexion muscle force. Additionally, the vGRF can also be used as a measure for resistance training, which can be used to improve performance, reduce injury risk, and increase strength (Dempster et al., 2021). According to our finding, peak vGRF falls down after fatigue, and peak contact reduces down to around 0.49 N/kg. A larger portion of the heel contact the ground and a better transmission of forces across the ankle muscles when the heel touches the ground are made possible by higher ankle plantarflexion, which can possibly reduce the risk of injury.

In terms of joint moment, the peak hip moment increased significantly in the sagittal plane and horizontal plane, while at the knee joint it decreased in the sagittal plane and increased in the horizontal plane. The ankle joint showed a significant reduction in the moment. According to previous research (Kovács et al., 2023), an increase in moment at the hip joint was linked to a change in kinematics, including an increase in flexion angle brought on by forward body lean. Fatigue reduces the activation of the vastus lateralis muscles during the lunge and the knee moment in the upright leg during the lunge. The quadriceps, hamstrings, and gastrocnemius are the primary tibiofemoral joint motor muscles. These muscle groups make up nearly all of the cross-sectional area of the knee muscular tissue, or 98% (Wilson et al., 2008). The co-activation of the quadriceps and hamstrings, as well as the activation of the biceps femoris and rectus femoris, were unaffected by fatigue. When becoming fatigued, lateral femoral muscle activation may decrease and hamstring co-activation may rise. This strategy may be intended to reduce knee flexion by increasing resistance to diagonal joint motion because co-activation between the lateral femoral and biceps femoris muscles has a tendency to increase after fatigue (Longpré et al., 2015). (Longpré et al., 2015) speculated that a significant decrease in knee moments may result from the vastus lateralis and biceps femoris muscles' ability to cooperate more when they are subjected to fatigued. An increase in plantarflexion and a decrease in the dorsiflexor muscles' force may be responsible for the drop in ankle net moments. Du's reported Du and Fan (2020) that there was a tendency for ankle plantarflexion to increase after fatigue, although the foot landed more flat position (i.e., greater contact area with the ground) at the ground. The findings of this study also indicate that better-performing athletes had stronger muscle strength and displayed higher knee and ankle moments, suggesting that the results of his experiment may be related to the participants' varying levels of activity.

The forward lunge is a great exercise to stimulate lower limb extensor muscles, including the hip and knee extensor muscles (Ross, 1997). The average and maximum muscle force of the biceps femoris and gastrocnemius muscles decreased based on the estimation of the OpenSim SO calculation. The quadriceps and tibialis anterior muscles experienced significant increases in both their average and maximal muscular forces. The quadriceps muscle showed the highest increase in maximum force increase by a 19.78 N/kg. This demonstrates that the quadriceps muscle gets the most work done and it is the most active muscle during forward lunge. Running fatigue throughout the fatigue protocol may have been the source of the decline in biceps femoris muscle strength. Moreover, the maximum muscle force of the biceps femoris decreased by 12.76 N/kg. In contrast, the increased force in the tibialis anterior muscle may be the result of the knee joint moving more forward after exhaustion. For the aim of inducing localized tiredness in the quadriceps and other lower limb muscles, the forward lunge in the fatigue protocol was used, and this is what the study explored. The results of this study help us to determine which of the investigated muscles that are heavily involved in the lunge movement during the post-fatigue and furthermore it can help us to design more specific training exercise for these muscles. According to Baker et al. (1998), a variety of exercises at a moderate speed should be performed than for a high resistance strength training can be started in order to gain additional muscle strength and muscle mass. Although high level of fatigue is believed to enhance these aspects of muscle function, thus increasing the amount of fatigue that working muscles experience may benefit in improving strength and hypertrophy (Rooney et al., 1994).

The front lunge has the advantages of increasing safety when it is properly executed, preventing potential knee injuries, and building strong postural muscles (Wilson et al., 2008). Certain forms of the lunge can also be added into the fitness regime if you want to improve your fitness. These movements can help to improve the dynamic flexibility of the lower limb joints and aiding in muscle hypertrophy and force development. Importantly, they can also be used to prevent injuries so that augmentation training can be carried out effectively and safely (Tippett and Voight, 1995). In general, it is important to perform all relevant exercises according to your condition to avoid unnecessary injuries caused by fatigue.

The methods we used in this study has limitation which needs to be addressed. First of all, although the biomechanical alterations in the forward lunge before and after fatigue protocol were investigated, they were not compared between different fatigue states. Secondly, The SO uses known movements of the model to solve for muscle activation forces, so the results may differ from the EMG test system, this means that there are limitations of the muscle force estimation we used. Thirdly, there is regional difference in muscle EMG activity and the location of measurements is not always the same for each participant, so EMG is also limited. Finally, we only tested the healthy young men, and we did not test other populations such as the athletic and injured populations, besides the protocol is limited.

5 Conclusion

In this study, we discovered that forward lung is affected by fatigue. After fatigue, the hip and knee joints have a greater ROM in the sagittal plane and an increased offset in the horizontal plane, with a tendency towards forward leaning. In addition to an increased amount of plantarflexion muscle activity in the ankle and unstable body postural performance. Additionally, the quadriceps muscles are the most affected after fatigue. To avoid injuries due to instability after fatigue, training people should focus more on strength training of the hip and knee muscles groups as a way to control joint motion more effectively.

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 the Ningbo University. The patients/participants provided their written informed consent to participate in this study.

Author contributions

All the authors contributed substantially to the manuscript. LG, JY, KB, and YG were responsible for the conceptualization. LG, JY, ZM, and ZR were responsible for investigation and methodology. LG, JY, KB, and YG were responsible for formal analysis and writing–original draft. JY, ZR, ZM, and YG were responsible for writing–review and editing and supervision. 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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The effects of blood flow restriction training on PAP and lower limb muscle activation: a meta-analysis

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Objective: This study aims to systematically evaluate the effects of blood flow restriction (BFR) training on lower limb muscle activation and post-activation potentiation (PAP) in athletes through a meta-analysis and discuss methods to improve instant muscle strength so as to provide a reference for training in this field.

Methods: Randomized controlled trials (RCTs) that examined the impact of BFR training on muscle activation and PAP were gathered through database searches, such as CNKI, Wanfang, Web of Science, PubMed, and others. The Cochrane risk of bias tool was used to include and exclude literature. Quality evaluation and statistical analysis were conducted using ReviewManager 5.3 software, STATA 16.0, and other software programs. The sensitivity analysis and funnel plots were employed to assess result stability and publication bias.

Results: In total, 18 literature studies were included with a total of 267 subjects. The meta-analysis showed that BFR could significantly improve the RMS value of lower limb muscles [*SMD* = 0.98, 95% *CI* (0.71, 1.24), and $p < 0.00001$]. BFR had a significant effect on the immediate explosive power of the lower limbs [*SMD* = 0.28, 95% *CI* (0.02, 0.53), and $p = 0.03$], but the heterogeneity was obvious (I^2 = 51%). The subgroup analysis showed that different training methods may be influencing factors that lead to the heterogeneity between studies. The measurement indexes were the counter movement jump (CMJ) [*SMD* = 0.45, 95% *CI* (0.20, 0.69), and $p = 0.0004$], training mode to overcome body weight [*SMD* = 0.57, 95% *CI* (0.33, 0.82), and $p < 0.00001$], and compressive strength of 40%–60% arterial occlusion pressure (AOP) [*SMD* = 0.57, 95% *CI* (0.31, 0.83), and $p < 0.0001$], which reached the maximum effect and was statistically significant.

Conclusion: BFR training can induce lower extremity muscle activation and PAP. Combining self-weight training with BFR exercises set at 40%–60% AOP appears to be particularly effective in inducing PAP, especially for enhancing CMJ. Furthermore, combining body-weight training with BFR is considered an effective warm-up method to improve CMJ.

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KEYWORDS

blood flow restriction training, muscle activation, post-activation potentiation, meta-analysis, lower limb muscle

1 Introduction

With increasing competitiveness in sports, traditional training methods often fall short of meeting athletes' demands for enhancing their competitive abilities. Developing explosive muscle power is a common objective for athletes participating in disciplines such as jumping, throwing, or sprinting. During their training, athletes often incorporate specialized exercises tailored to the unique characteristics of their sport, which may include augmentation or resistance exercises. Researchers have discovered that blood flow restriction (BFR) training can serve as a supplementary approach to high-intensity resistance training, effectively improving muscle contraction function and promoting muscle strength growth (Xu and Wang, 2013). It achieves this by applying pressure to the outer regions of the limbs, which causes occlusion of venous blood flow at the distal ends of the limbs. Subsequently, training is conducted at lower exercise intensities, thereby facilitating optimal muscle activation during the warm-up (Che et al., 2021). Studies have indicated that the combination of BFR training with low-intensity resistance training can improve the recruitment capacity of the lower limb muscles (Wang, 2021).

As a method for rapidly enhancing strength, post-activation potentiation (PAP) is achieved through controlled training, such as squats and deadlifts, which induce intense neuromuscular excitement and, consequently, rapidly improving muscle explosiveness within a short timeframe (Batista Mauro et al., 2011). High-intensity exercise is achieved through the rapid recruitment of muscle fibers by the nervous system. Consequently, enhancing muscle nerve activation before a competition holds significant importance for improving sports performance (Lin et al., 2017; Xu et al., 2020). Nevertheless, there is controversy surrounding the induction mode and timing of PAP. Most coaches tend to use maximum resistance exercise to induce PAP (Hanson et al., 2007; Mccann and Flanagan, 2010). However, this high-intensity and high-load training approach can lead to sports injuries and muscle fatigue. By contrast, BFR training is a low-energy consumption, high-efficiency exercise mode. By restricting blood flow to the limbs, metabolites accumulate, prompting the body to falsely simulate stress in muscle fibers by intensive exercising, thereby optimizing training (Hu, 2020).

Warm-up exercises have been extensively researched, and scientific warm-up routines can effectively enhance athletic performance. Studies have shown that the PAP effect can optimize warm-up programs for endurance sports, resulting in improved athletic achievements (Wu et al., 2020). However, the potential of utilizing BFR to enhance warm-up effects remains largely unexplored. In light of this, this study conducts a meta-analysis that summarizes the impact of BFR training combined with different exercise modalities on lower limb muscle activation and PAP, finding the optimal pressure intensity to induce an enhancement effect of lower limb activation and determining the appropriate exercise mode that can be combined with BFR training during warm-up. Our focus lies on the lower limb muscles below the iliac crest (Zhao et al., 2006). The selected experiments are all randomized controlled trials that aim to provide a reference for enhancing athletes' muscle recruitment capacity and explosiveness.

2 Materials and methods

2.1 Search strategy

A total of 159 documents were retrieved from the CNKI, Wanfang, VIP, PubMed, and Web of Science databases up to 4 February 2023. The English search terms used were as follows: ("blood flow restriction training" or "BFR" or "KAATSU training" or "pressure training") and ("Potentiation after activation" or "PAP" or "muscle recruitment" or "explosive power" or "lower extremity") and ("RCT").

2.2 Inclusion and exclusion criteria

2.2.1 Inclusion criteria

Type of study: All included literature were publicly published and involved randomized controlled trials (RCTs) that studied the effects of BFR training on muscle activation and post-activation enhancement effects. Study subjects: The study subjects included healthy adults, both with and without prior training experience. Interventions: The experimental group received BFR training, while the control group received either other training modalities or no training at all. Outcome measures: The primary outcome measure was related to the quantitative lower limb (below the point of the iliac crest) (Zhao et al., 2006), which included measures of muscle activation and PAP such as MVC moment, EMG value, and longitudinal jump height. Additional criteria: The studies should provide details about the experimental design and intensity of BFR training, among other relevant information. Source inclusion: To minimize the risk of bias in the included literature, this study considers only articles indexed in the SCI (Science Citation Index).

2.2.2 Exclusion criteria

Unclear research type: Studies lacking clear documentation of their research type were excluded. Non–BFR training: Studies that involved interventions other than BFR training were excluded. Duplicate publications: Repeatedly published articles for which full text could not be obtained and review articles were excluded. Lack of quantitative outcome data: Studies without quantitative outcome indicators or valid data were excluded. Animal experiments: Research that involved animal experiments were excluded.

2.3 Data Extraction

The collected literature were imported into EndNote software and underwent independent screening by two researchers. The steps of literature screening and inclusion are illustrated in Figure 1. Ultimately, 18 articles were included in this review.

Data extraction: Two researchers independently extracted information according to a custom-made form, which primarily encompassed the following categories:

1. General information: first author and year of publication.

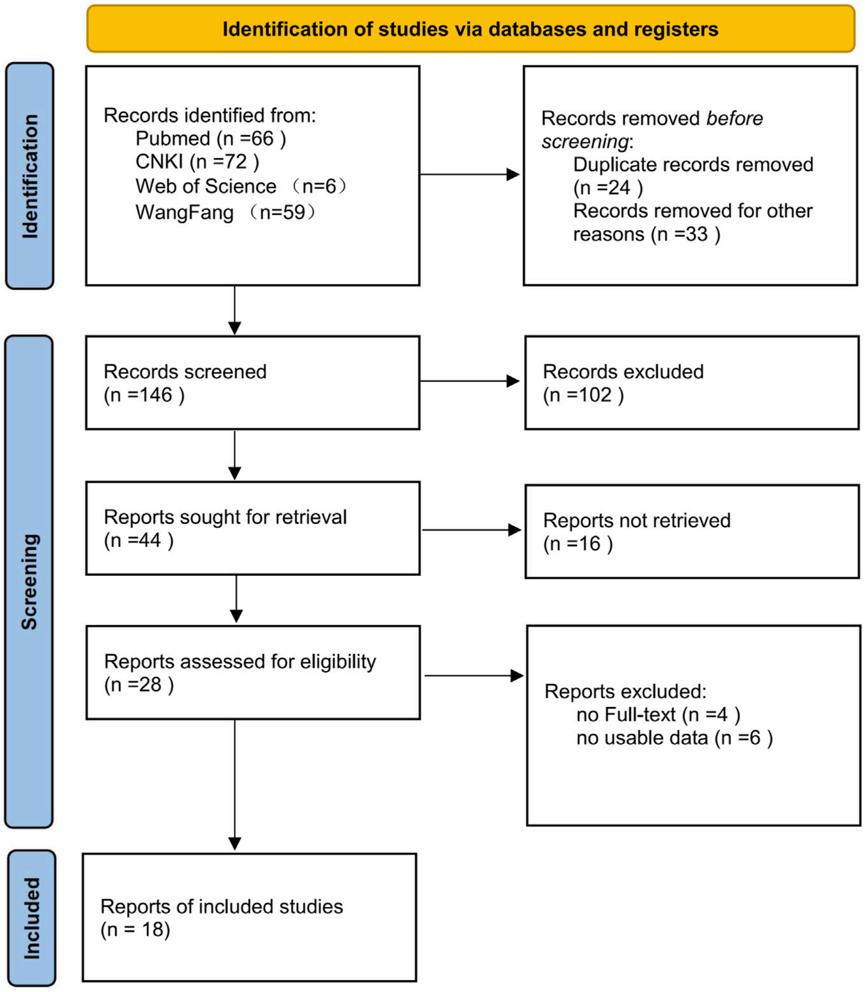


FIGURE 1
Flow diagram of literature selection.

2. Sample information: details about the research subjects such as age and sample sizes for both the experimental and control groups.
3. Characteristics of exercise intervention: information on intervention measures for both the experimental and control groups, and specifics of the intervention programs for the experimental group (such as training methods, training volume, and training intensity).
4. Outcome indicators: quantitative measures of lower limb muscle activation and test indicators related to PAP.

2.4 Statistical analysis

Statistical analysis was performed using ReviewManager 5.3 software. The outcome indicators included in the literature in this study were continuous variables, and standardized mean differences (*SMDs*) and 95% confidence intervals were chosen for effect sizes because of the different testing methods used for each indicator. The Cochrane risk bias assessment tool was referenced for literature quality assessment. The homogeneity test (Q test, test level a = 0.1) was used to test for heterogeneity, and I^2 values from 0% to 100%, $I^2 > 50\%$, and $P < a$ indicated the existence of heterogeneity, and the random effects model was selected. The random effects model was chosen for meta-analysis, while the fixed effects model was chosen for the opposite. The subgroup analysis was used for the treatment of heterogeneity and STATA 16.0 was used for sensitivity analysis to test the stability of the results. The Egger test and funnel map were used to check for the presence of publication bias.

3 Results

3.1 Study characteristics

A total of 18 publications were included in this study, all of which were RCTs, which included 267 subjects with mixed genders and an age range of 18–33 years, with the basic characteristics shown in Table 1.

TABLE 1 Characteristics of studies included in the systematic review and meta-analysis.

Study	Country	Age (years)	N (EG/CG)	Intervention (EG/CG)	Plan (BFR intensity)	Outcome extracted
Wang (2021)	China	19.65 ± 0.94	19/19	BFR/No BFR	Four groups of 30-15-15-15 times 30% 1RM knee extension resistance (40%)	RMS VM↑ MVC↓
Li et al. (2021)	China	20.3 ± 1.9	10/10	BFR/No BFR	Four groups of 30-15-15-15 times 30% 1RM knee extension resistance (40%)	RMS VM↑
Hu (2020)	China	18.3 ± 3.28	12/12	BFR/HRT, LRT	Two groups of 30 + 20 30% 1RM squats (bundled pressure 40 mmHg and inflation pressure 200 mmHg)	RMS VM↑ CMJ↑ MVC↑
Li (2020)	China	21.4 ± 3.2	10/10	BFR/No BFR	Four sets of 30-15-15-15 squats (40%)	RMS RF NS
Hongwen and Xiang (2022)	China	23.6 ± 1.51	27/27	BFR/No BFR	Two sets of 10 straight leg jumps + three sets of five consecutive obstacle jumps + five drop jumps (inflation pressure 160 mmHg)	CMJ↑ RCMJ NS
Yan and Guo (2018)	China	20.3 ± 2.3	20/20	BFR/No BFR	Five sets of 50% HRR and 2-min interval runs (inflation pressure 150 mmHg)	CMJ↑ MVC↑
Zhang (2021)	China	15.83 ± 1.0	12/12	BFR/No BFR	20 min cycling (inflation pressure 250 mmHg)	P(W) 10 s↑
Che et al. (2021)	China	17.57 ± 2.83	10/10	BFR/No BFR	Four groups of 30-15-15-15 times 30% 1RM half squats (bundled pressure 40 mmHg and inflation pressure 180 mmHg)	RMS GM↑
Sun et al. (2019)	China	33.5 ± 4.9	10/10	BFR/No BFR	Four groups of 30-15-15-15 times 20% 1RM hard pull (20 mmHg)	RMS BF↑
Pan et al. (2019)	China	21.14 ± 1.17	18/18	BFR/No BFR	Four groups of 30-15-15-15 1RM knee extension resistance exercises (40%, 60%, and 80%)	sEMG (uV)↑
Amani et al. (2019)	Iran	23 ± 2	6/6	BFR/No BFR	Three-player football training with BFR (80–100 mmHg)	RMS VM↑ MVC↑
Yun-Tsung et al. (2019)	China	22.7 ± 4.6	12/12	BFR/No BFR	Five sets of 50% HRR and 2 min runs (149.8 ± 5.0 mmHg)	MVC↑ RMS BF↑
Cleary Christopher and Cook Summer (2020)	United States	20.3 ± 0.9	15/15	BFR/No BFR	One set of thirty 30% 1RM back squats (60%)	VJ NS RMS VM NS
Doma et al. (2020)	Australia	22.9 ± 5.0	18/18	BFR/No BFR	Three sets of eight single-leg lunges, leg swings, high knees, and hip kicks each (130% systolic pressure)	VJ NS MJ↑
Pedro et al. (2016)	Portugal	24.8 ± 5.4	14/14	BFR/No BFR	Six groups each with 10 maximum knee extension eccentric movements (40%)	RMS RF↑ MVC↓
Gepfert et al. (2020)	Poland	28.4 ± 5.8	10/10	BFR/No BFR	Three sets of three 70% 1RM barbell squats (100%)	P(W)↑ V↑
Lauver et al. (2017)	United States	22.8 ± 2.3	24/24	BFR/No BFR	Four groups of 30-15-15-15 20% 1RM knee resistance exercises (130% systolic blood pressure)	MVIC↓ RMS VM↑
Miller et al. (2018)	United States	21.8 ± 2.6	20/20	BFR/No BFR	Three sets of 20-s WBV Three sets of MVC (charging pressure 160 mmHg)	CMJ↑

NS, no statistical significance; RMS, electromyographic standard value; MVC, maximum autonomous isometric contraction; VM, medial thigh muscle; RF, rectus femoris muscle; GM, gluteus maximus muscle; BF, biceps femoris muscle; R, rate. ↑ represents a significant increase; ↓ represents a significant decrease; WBV, whole body vibration; HRR, heart recovery rate; CMJ, counter movement jump; MVIC, maximal voluntary isometric contraction; V, velocity of Bench Press; P(W), maximum output power; RCMJ, rate of counter movement jump.

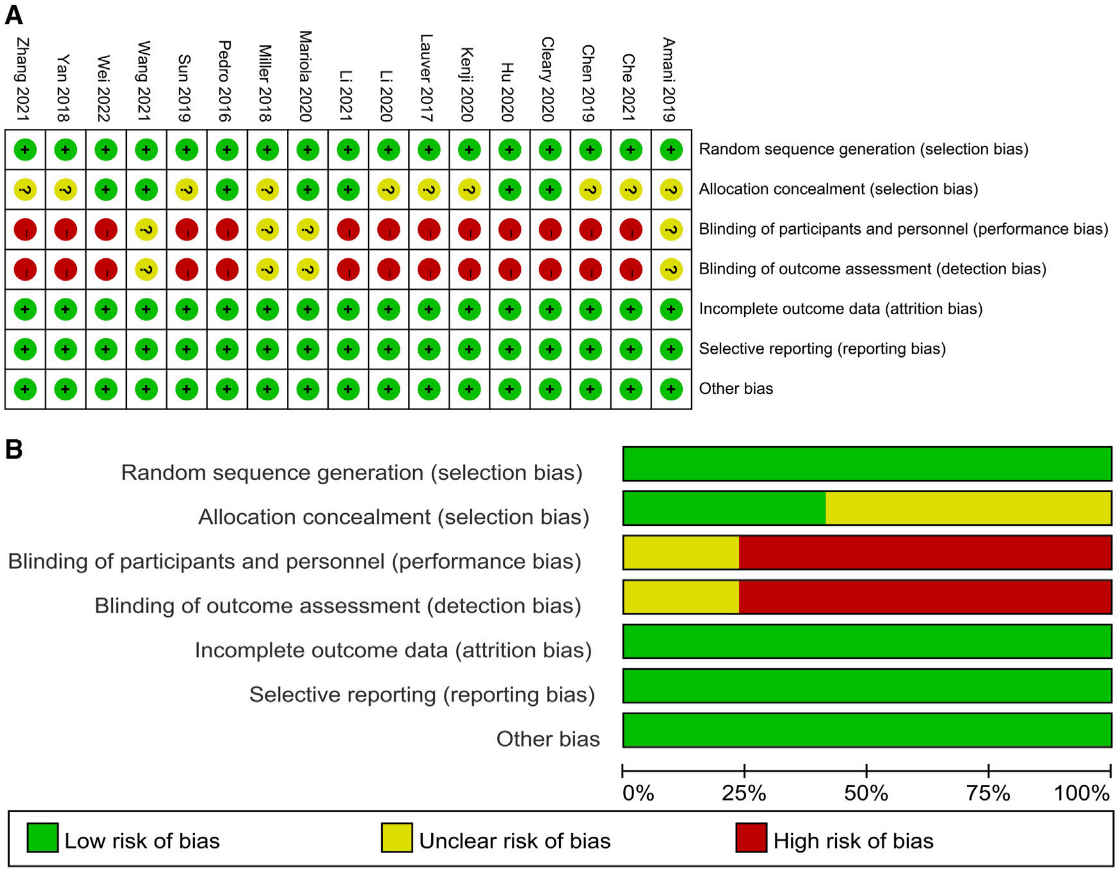
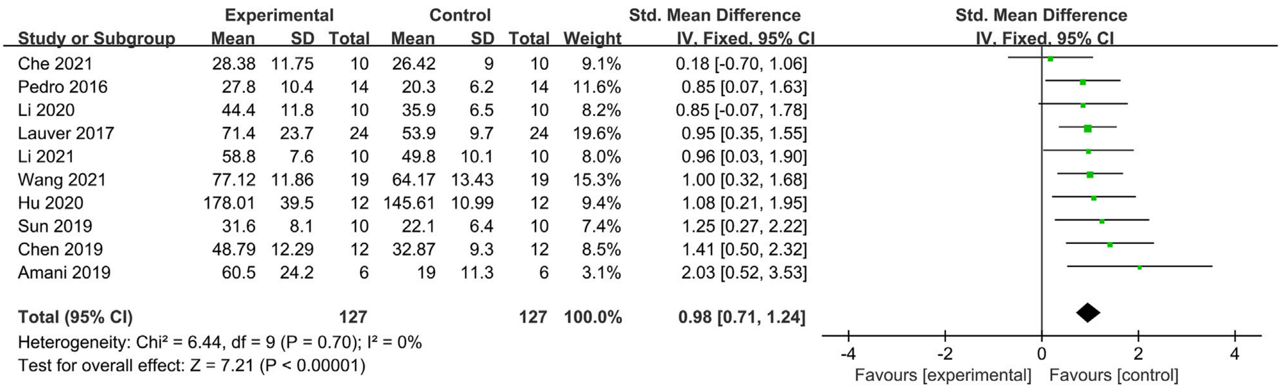


FIGURE 2
Methodological quality graph and summary of the included studies: **(A)** risk of bias summary and **(B)** risk of bias graph.



Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
Che 2021	28.38	11.75	10	26.42	9	10	9.1%	0.18 [-0.70, 1.06]
Pedro 2016	27.8	10.4	14	20.3	6.2	14	11.6%	0.85 [0.07, 1.63]
Li 2020	44.4	11.8	10	35.9	6.5	10	8.2%	0.85 [-0.07, 1.78]
Lauver 2017	71.4	23.7	24	53.9	9.7	24	19.6%	0.95 [0.35, 1.55]
Li 2021	58.8	7.6	10	49.8	10.1	10	8.0%	0.96 [0.03, 1.90]
Wang 2021	77.12	11.86	19	64.17	13.43	19	15.3%	1.00 [0.32, 1.68]
Hu 2020	178.01	39.5	12	145.61	10.99	12	9.4%	1.08 [0.21, 1.95]
Sun 2019	31.6	8.1	10	22.1	6.4	10	7.4%	1.25 [0.27, 2.22]
Chen 2019	48.79	12.29	12	32.87	9.3	12	8.5%	1.41 [0.50, 2.32]
Amani 2019	60.5	24.2	6	19	11.3	6	3.1%	2.03 [0.52, 3.53]
Total (95% CI)			**127**			**127**	**100.0%**	**0.98 [0.71, 1.24]**

Heterogeneity: Chi² = 6.44, df = 9 (P = 0.70); I² = 0%
Test for overall effect: Z = 7.21 (P < 0.00001)

FIGURE 3
Effect of BFR training on neuromuscular activation.

3.2 Study quality assessment

The quality of the collected literature was evaluated with reference to the Cochrane risk of bias assessment tool (Higgins and Altman, 2007). Review Manager 5.3 software was used to assess seven aspects, namely, the random allocation method, allocation scheme concealment, participant blinding, outcome blinding, completeness of outcome data, selective reporting of study results, and other sources of bias (Figures 2A, B). Twelve articles did not clearly describe whether the implementer of the assignment had strictly performed the random assignment, and 18 articles had a high risk of bias due to informed consent being signed before the experiment. Thus, there was a high risk of bias in the blinding.

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Lauver 2017	207	17.3	24	231.3	48.9	24	7.6%	-0.65 [-1.23, -0.07]
Pedro 2016	294.3	43.4	14	309.5	35.8	14	6.1%	-0.37 [-1.12, 0.38]
Wang 2021	167.57	14.28	19	169.42	21.2	19	7.1%	-0.10 [-0.74, 0.54]
Mariola 2020	2,129	309	10	2,134	428	10	5.1%	-0.01 [-0.89, 0.86]
Kenji 2020	58.3	7.9	18	57.1	10.2	18	6.9%	0.13 [-0.53, 0.78]
Miller 2018	60.2	8.1	20	58.7	7.6	20	7.2%	0.19 [-0.43, 0.81]
Miller 2018	59.4	8.1	20	57.7	7.9	20	7.2%	0.21 [-0.41, 0.83]
Hu 2020	36.65	5.29	12	35.38	4.97	12	5.6%	0.24 [-0.56, 1.04]
Zhang 2021	943.39	153.66	12	907.81	128.09	12	5.6%	0.24 [-0.56, 1.05]
Cleary 2020	61.9	4.9	15	60.7	4.6	15	6.3%	0.25 [-0.47, 0.96]
Hu 2020	29.31	6	12	26.67	5.39	12	5.5%	0.45 [-0.37, 1.26]
Yan 2018	161.34	21.21	20	150.67	18.35	20	7.1%	0.53 [-0.10, 1.16]
Chen 2019	154.05	29.88	12	136.25	29.75	12	5.5%	0.58 [-0.24, 1.40]
Yan 2018	43.56	3.56	20	40.89	3.02	20	7.0%	0.79 [0.15, 1.44]
Wei 2022	55.81	2.47	27	52.07	4.2	27	7.7%	1.07 [0.50, 1.64]
Amani 2019	30.9	8	6	14.9	7.5	6	2.4%	1.90 [0.44, 3.37]
Total (95% CI)			**261**			**261**	**100.0%**	**0.28 [0.02, 0.53]**

Heterogeneity: Tau² = 0.13; Chi² = 30.59, df = 15 (P = 0.010); I² = 51%

Test for overall effect: Z = 2.14 (P = 0.03)

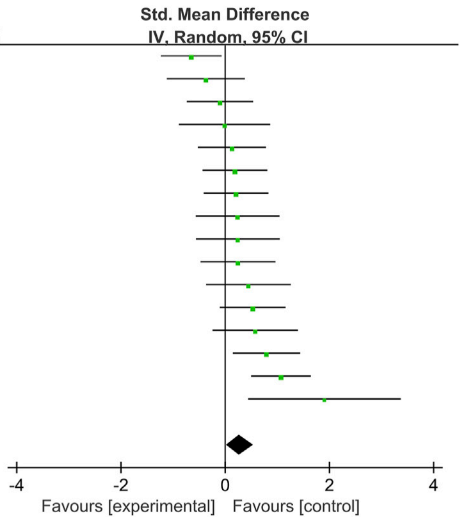


FIGURE 4
Forest plot of the impact of BFR training on PAP.

3.3 Lower limb muscle activation

Out of the 18 included articles, 10 compared 127 subject differences in RMS standard values before and after BFR training (Figure 3). After testing for heterogeneity, $I^2 = 0.0\% < 50\%$ and $p = 0.70 > 0.1$ for the Q test, suggesting no heterogeneity among the included literature. The fixed effects were selected for the meta-analysis. The *SMD* value for the pooled 10 studies was 0.98, with a 95% confidence interval from 0.71 to 1.224 and statistically significant, with $Z = 7.21$ and $p \leq 0.05$, indicating that BFR exercises can significantly improve RMS values in lower limb muscles.

3.4 PAP

For BFR training–induced PAP, 13 articles were included (16 studies with a total of 261 subjects) and were tested for heterogeneity, and $I^2 = 51\% > 50\%$ and Q-test of $p = 0.01 < 0.1$, indicating a strong heterogeneity among the included literature, and random effects models were selected. A meta-analysis was performed (Figure 4) and the results showed that the combined effect size was *SMD* = 0.28 and statistically significant ($Z = 2.13$ and $p = 0.03$), which indicates that BFR training could significantly induce the production of PAP when compared with the control group.

3.5 Subgroup analysis

Based on the data of this study, the authors suspect that the source of heterogeneity may be the inconsistency of PAP effect test indicators. Therefore, according to the test indicators of the PAP effect (MVC: torque, CMJ: longitudinal jump, and P(W): output power), 13 articles (16 studies) were divided into three groups for the subgroup analysis (Table 2). According to the exercise modality, the included studies were divided into three subgroups: ≤30% 1RM resistance exercises, ≥70% 1RM resistance exercises, and self-weight exercises. For compressive strength, the subgroups were categorized based on the arterial occlusion and thigh circumference, according to Loenneke Jeremy et al. (2015), and three subgroups were identified: 40% AOP and below, 40%–60% AOP, and 60% AOP and above.

The subgroup analysis of the outcome indicators showed that the heterogeneity of the three groups was 66%, 28%, and 0%. When compared with the overall combined effect ($I^2 = 51\%$),the within-group heterogeneity of the MVC moments had increased to 66%, which suggests strong heterogeneity among the studies with respect to the outcome indicator of the MVC moment. The heterogeneity within the literature on the outcome indicator of the MVC moment was strong. The CMJ longitudinal jump group had the highest effect size and was statistically significant (*SMD* = 0.45 and $p = 0.0004 < 0.01$). The available results suggest that BFR training can significantly improve CMJ performance. The available results also suggest that BFR training can significantly increase the vertical jump height of CMJ.

The subgroup analysis of exercise patterns showed that the heterogeneity of the three groups was 40%, 0%, and 33%, which is lower than the overall combined effect ($I^2 = 51\%$). It is speculated that different exercise methods may be the influencing factors that lead to the heterogeneity between studies. When compared to resistance exercises at 30% 1RM and below, as well as resistance exercises at 70% and above, self-weight exercise had the largest effect, with an *SMD* of 0.57, and it was statistically significant ($p < 0.01$). This indicates that BFR training combined with self-weight exercise can significantly induce the generation of PAP.

The subgroup analysis of pressure intensity revealed varying degrees of heterogeneity among the three groups: 73%, 19%, and 0%, respectively, in comparison to the overall combined effect ($I^2 = 51\%$). Notably, within the subgroup of compressive strength of 40% AOP and below, the intra-group heterogeneity increased to 73% ($I^2 = 73\%$), which indicates significant heterogeneity among the studies in this category. Among these, the effect

TABLE 2 Subgroup analysis of lower limb PAP induced by BFR training.

Research feature	Subgroup standard	Study (sample)	*SMD*	95% *CI*	*P*	I^2 (%)	*P* (heterogeneity)
Outcome extracted	MVC	7 (107)	0.07	−0.21,0.34	0.63	66	0.07
	CMJ	7 (132)	0.45	0.20,0.69	0.0004	28	0.21
	P(W)	2 (22)	0.13	0.47,0.72	0.68	0	0.67
Exercise mode	≤30% 1RM	5 (82)	−0.06	−0.37,0.25	0.69	40	0.15
	≥70% 1RM	3 (44)	−0.02	−0.44,0.39	0.91	0	0.51
	Self-weight	8 (135)	0.57	0.33,0.82	<0.0001	33	0.17
Compressive strength	≤40% AOP	4 (67)	−0.12	−0.47,0.23	0.50	73	0.01
	40%–60% AOP	6 (119)	0.57	0.31,0.83	<0.001	19	0.29
	≥60% AOP	6 (75)	0.13	−0.21.0.45	0.44	0	0.75

TABLE 3 Combined effects of lower limb muscle activation after excluding individual studies.

Study	*SMD*	95% *CI*	*P* (merge effect)	I^2 (%)
Che et al. (2021)	1.06	0.78, 1.33	<0.00001	0
Pedro et al. (2016)	0.99	0.71, 1.27	<0.00001	0
Li (2020)	0.99	0.71, 1.26	<0.00001	0
Lauver et al. (2017)	0.98	0.69, 1.28	<0.00001	0
Zhao et al. (2006)	0.98	0.70, 1.25	<0.00001	0
Wang (2021)	0.97	0.68, 1.26	<0.00001	0
Hu (2020)	0.97	0.69, 1.24	<0.00001	0
Sun et al. (2019)	0.95	0.68, 1.23	<0.00001	0
Yun-Tsung et al. (2019)	0.94	0.66, 1.21	<0.00001	0
Amani et al. (2019)	0.94	0.67, 1.21	<0.00001	0
Overall	0.98	0.71, 1.24	<0.00001	0

size of the 40%–60% AOP group was the highest and statistically significant (*SMD* = 0.57 and $p < 0.01$), which suggests that the pressurization intensity of BFR training at 40%–60% AOP significantly induces PAP production.

3.6 Sensitivity analysis

Sensitivity analysis was conducted on the included literature, both by including and excluding individual groups of studies, to assess heterogeneity.

In Table 3, the combined effect of BFR training on lower limb muscle activation, as included in all studies, resulted in an *SMD* of 0.98 ($p < 0.01$ and $I^2 = 0\%$). The *SMD* range from individual studies was from 0.94 to 1.06, with $I^2 = 0\%$, and all *p*-values were <0.01. There was no single literature that posed a threat to the meta-analysis results, which indicates the study's stability.

Table 4 presents the combined effect of BFR training on the PAP effect across all included studies, with an *SMD* of 0.28 ($p = 0.03$ and $I^2 = 51\%$). After excluding the studies by Hongwen and Xiang (2022) and Lauver et al. (2017), the combined effects were 0.09 and 0.002, respectively, with I^2 values of 37% and 31%. This resulted in a significant reduction in heterogeneity. The combined effect, after excluding other single studies, had an *SMD* of 0.02–0.07, with *p*-values < 0.1.

3.7 Publication bias

We conducted bias tests separately by drawing funnel plots within the subgroups to assess the publication bias of the included studies. The funnel plots exhibited symmetry, which indicates no publication bias, as illustrated in Figures 5A–D.

Furthermore, we continued to examine potential bias using the Egger test, and all *p*-values were found to be >0.05, as presented in Table 5. Therefore, it can be concluded that there is no publication bias present in the literature analyzed in this study.

4 Discussion

4.1 BFR training–induced muscle activation in the lower limbs

The induction method employed in this study is BFR training. By combining low-intensity resistance exercises (Lauver et al., 2017; Cleary Christopher and Cook Summer, 2020; Hu, 2020; Li, 2020; Che et al., 2021; Wang, 2021), high-intensity resistance exercises (Pedro et al., 2016; Pan et al., 2019), and aerobic activities such as running (Amani et al., 2019; Yun-Tsung et al., 2019), we assessed their impact on electromyography (EMG) readings of lower limb muscles. As for the criteria for evaluating lower limb muscles, specific sites below the iliac crest point (Wu et al., 2020) were selected, which primarily included the vastus medialis (VM), rectus femoris (RF), gluteus maximus (GM), biceps femoris (BF), and other muscle groups.

Muscle mass and strength development are governed by neural modulation and stimuli (Marcotte et al., 2015). The results of the meta-analysis indicate that the effect sizes from

TABLE 4 PAP merger effect after excluding individual studies.

Study	*SMD*	95% *CI*	*P* (merge effect)	I^2 (%)
Hongwen and Xiang (2022)	0.20	−0.03, 0.44	0.09	37
Yan and Guo (2018)	0.24	−0.02, 0.50	0.07	50
Yan and Guo (2018)	0.26	−0.01, 0.53	0.06	53
Hu (2020)	0.28	0.01, 0.55	0.04	54
Hu (2020)	0.27	−0.00, 0.54	0.05	54
Wang (2021)	0.31	0.04, 0.58	0.02	52
Zhang (2021)	0.28	0.01, 0.55	0.04	54
Pedro et al. (2016)	0.32	0.06, 0.58	0.02	49
Miller et al. (2018)	0.29	0.01, 0.56	0.04	54
Miller et al. (2018)	0.29	0.01, 0.56	0.04	54
Gepfert et al. (2020)	0.29	0.03, 0.56	0.03	54
Doma et al. (2020)	0.29	0.02, 0.57	0.04	54
Lauver et al. (2017)	0.35	0.13, 0.58	0.002	31
Cleary Christopher and Cook Summer (2020)	0.28	0.01, 0.56	0.04	54
Yun-Tsung et al. (2019)	0.26	−0.01, 0.53	0.06	53
Amani et al. (2019)	0.24	−0.00, 0.48	0.05	46
Overall	0.28	0.02, 0.53	0.03	51

The same literature name refers to different research results included in the same literature.

the overall effect tests in all 10 studies were consistently positive ($p < 0.01$). Therefore, BFR training significantly enhances the root mean square (RMS) values of lower limb muscles. The heterogeneity test results indicate complete homogeneity among the study outcomes ($I^2 = 0\%$), and the sensitivity analysis showed no significant changes in heterogeneity or combined effects when any single study was removed. This suggests that there are no differences related to participant characteristics, exercise methods, pressure intensity, etc., with all included studies pointing to the same outcome.

It is well known that high-intensity exercise is achieved through the recruitment of both fast and slow muscle fibers by the nervous system. Studies have demonstrated a positive correlation between the degree of muscle activation and number of nerve fibers (Westing et al., 1991). When compared to centrifugal exercise alone, combining centrifugal exercise with BFR leads to greater neuromuscular activation (Schoenfeld Brad, 2012). This increased neuromuscular activation observed during BFR exercises is attributed to reduced muscle oxygen availability due to compression, which inhibits α motor neurons. To meet the altered energy demands, more type II (fast-twitch) muscle fibers are recruited for participation in the exercise (Yasuda et al., 2015). In the literature within this study, the control group's intervention measures involved non-pressurized resistance exercises. Therefore, in comparison to traditional resistance exercises, BFR exercises may facilitate the recruitment of more fast-twitch muscle fibers. This recruitment potentially has a positive impact on improving explosive strength and muscle strength in athletes.

4.2 Possible mechanism of inducing PAP by BFR training

As a physiological phenomenon characterized by an acute increase in explosive force, methods aimed at inducing PAP are primarily based on heavy-load activities such as squats, bench presses, and high-intensity exercises (Zhuang, 2021). In this study, we conducted a meta-analysis of various explosive force measurement indices, such as MVC moment, CMJ vertical jump height, and P maximum output power, before and after BFR training. The results revealed an overall effect size of 0.28 ($p < 0.05$) across 16 studies, which indicates that BFR training can induce PAP.

Traditional PAP induction methods typically require heavy training equipment for short-term maximum or sub-maximum resistance training, which can pose a risk of sports injuries and subsequent muscle fatigue due to their high-intensity and heavy-load nature. By contrast, BFR training is characterized by low intensity and rapid recovery. Furthermore, creatine kinase (an index representing the degree of muscle damage) did not significantly increase during BFR training, suggesting that muscle fiber damage is lower than it is in high-intensity training (Xu et al., 2021).

In recent years, new warm-up programs based on the PAP effect have gained attention in the academic community. These programs combine resistance training with isometric training to enhance sports performance and have been adopted as pre-match warm-up routines to induce PAP (Yang and Huan, 2022). In summary, BFR training offers a relatively simple and convenient method for

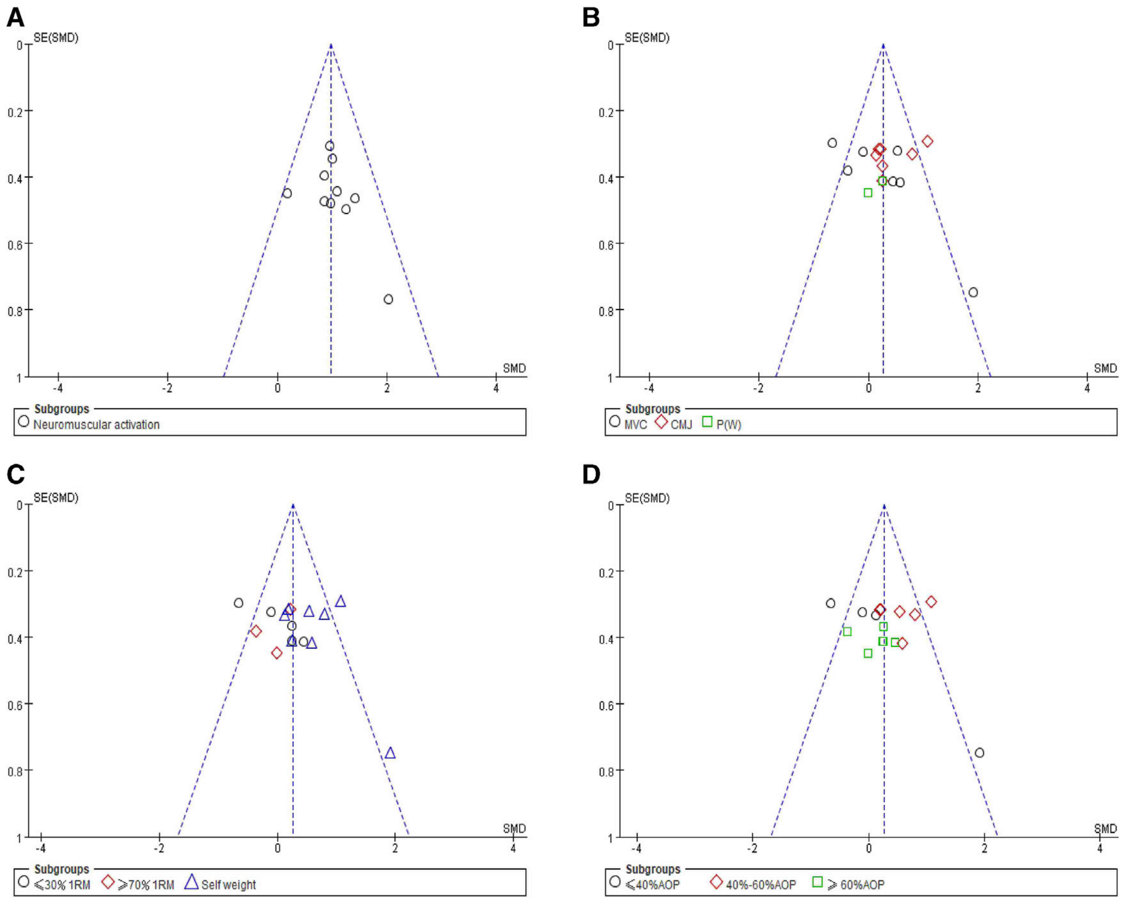


FIGURE 5
Funnel plots of meta-analysis: **(A)** neuromuscular activation, **(B)** outcome extracted, **(C)** resistance strength, and **(D)** compressive strength.

TABLE 5 Egger test results.

Research features	Subgroup standard	Coefficient	*t*	*Pr* > |z|
Neuromuscular activation	RMS	1.780	1.30	0.175
Outcome extracted	MVC	5.433	2.53	0.133
	CMJ	−5.578	−1.28	1.000
	P(W)	−7.119	N	1.000
Resistance strength	≤30% 1RM	8.400	4.29	0.086
	≥70% 1RM	−2.553	−0.60	1.000
	Self-weight	1.976	0.96	0.711
Compressive strength	≤40% AOP	5.852	3.43	0.089
	40%~60% AOP	−5.391	−1.12	1.000
	≥60% AOP	−2.184	−0.76	0.806

N, no value.

effectively inducing the PAP phenomenon when compared to traditional high-intensity resistance exercises.

The production of PAP is primarily attributed to factors such as muscle acidification, strengthening of the H-reflex, and changes in muscle fiber recruitment angles under load stimulation, which result in an increased number of recruited motor units due to motor nerve excitation (Chong et al., 2020). This phenomenon aligns with the neuromuscular activation observed in BFR exercises as mentioned

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earlier. Cleary Christopher and Cook Summer (2020) also found that EMG amplitudes in activated hamstrings were the highest under BFR conditions during blood restriction training, suggesting a potential link between lower limb muscle activation and BFR training–induced PAP.

4.2.1 Outcome indicators

Following the heterogeneity test (I^2 = 51%), we conducted a subgroup analysis to explore the reasons for variation among studies, focusing on the outcome indicators related to the PAP effect (Table 2). The results showed that 1) BFR training resulted in a significant increase in height of the CMJ vertical jump; 2) the MVC moment did not exhibit a significant effect on the combined results, which might be attributed to the high heterogeneity in the literature (I^2 = 66% and p = 0.07), with studies using the MVC moment as the outcome indicator, which is the primary source of heterogeneity; and 3) there are only two references on P (output power), and the results of the subgroup analysis also did not reach a significant level.

Three out of the seven studies, which used the MVC moment as the outcome indicator, reported negative effect sizes. The author found that these three studies when compared to the rest of the literature were all conducted on people with no athletic experience. Some researchers suggested that high-level athletes (track and field and rugby) may cause greater PAP than non-athletes (Hamada et al., 2000). Wilson et al. (2013) also demonstrated that athletes exhibited a larger effect size of PAP than non-athletes. The analysis suggests that athletes might display an enhanced response to PAP protocols due to their training adaptations. Therefore, the MVC moment test index in non-athletes may be insensitive to BFR exercises.

As an effective indicator of the PAP effect, CMJ vertical jump height is usually quantified by the following formula (Cleary Christopher and Cook Summer, 2020):

$$\mathrm{PAP}\,(\%) = \left[\frac{\text{post CMJ height (cm)}}{\text{pre CMJ height (cm)}} \times 100\right]. \qquad (1)$$

A value >100 indicates the generation of PAP. In the literature comprising seven studies on CMJ longitudinal jump, all reported positive effects, and there was no observed heterogeneity within this group (I^2 = 28%). This suggests that combining BFR exercises may further enhance the PAP effect and optimize the CMJ vertical jump index, thus aligning with Cleary's perspective.

4.2.2 Exercise mode

An analysis of subgroups based on different exercise methods found that when compared to combining BFR training with low-intensity resistance exercise and high-intensity resistance training, combining BFR with body-weight exercises is more likely to induce PAP.

In traditional resistance training, effective improvements in muscle absolute strength typically requires an intensity of ≥70% 1RM (Ratame et al., 2009). However, the occurrence of the PAP phenomenon depends on post-training fatigue levels (Boullosa et al., 2013). Consequently, determining the optimal method to induce PAP is challenging, and for various intensity resistance exercises combined with BFR, participants may experience levels of fatigue greater than that induced by PAP. Additionally, Che et al. (2021) found that the subjective fatigue level during pressurized low-intensity resistance exercises, measured using RPE, was more pronounced in the pressurized training state.

The recruitment of high-threshold motor units is one of the mechanisms proposed by PAP, as observed by Chen et al. (2022); we found that during a 120-s warm-up at varying intensities, the higher the exercise intensity, the more pronounced the warm-up effect. Although more muscle fibers are recruited, contributing to enhanced muscle strength (Sweeney et al., 1993), BFR exercises combined with light loads (such as self-weight) may also trigger similar responses as heavy-load exercises. For instance, Miller et al. (2018) discovered that in a study combining BFR with whole-body vibration, both whole-body vibration and maximum isometric contraction exercises significantly improved vertical jump height under BFR conditions. This indicates that BFR training can yield comparable effects to high-load training, even with lower training intensity, thereby reducing the risk of sports injuries and excessive exercise loads.

4.2.3 Compressive strength

With the change in pressure intensity, the induction degree of PAP is also different. When compared to no BFR training conducted conditions, lower limb occlusion above the brachial artery systolic pressure induced a significant amount of PAP stimulation. However, intramuscular hypoxia caused by high-intensity compression easily accelerated the fatigue response of muscle fibers (García-Pinillos et al., 2015).

A study also showed that low-intensity exercise with BFR pressure hardly induces the body's stress response (Wang, 2021). High-intensity BFR pressure can lead to anaerobic metabolism, which results in lactic acid accumulation and a significant decrease in muscle torque. On the other hand, excessive AOP can easily cause severe limb ischemia and cardiovascular adverse events due to muscle edema (Spranger et al., 2015). Therefore, it is recommended to use BFR exercise with 40%~60% AOP for immediate muscle strength growth.

4.3 Study limitations

The 18 articles included were not blinded and the methodology is limited in this respect. It is difficult to use blinding in this type of study because of the corresponding ethical requirement for human subjects to sign an informed consent form. In the few articles retrieved for this study, the authors could not be contacted to obtain the required data, which is theoretically biased, but the authors do not believe that this would have a subversive effect on the results of this study. Limitations in the research field and theme, such as the small number of studies evaluating lower extremity muscle function, the generally low sample sizes, and variations in intervals after BFR exercises among studies, may have introduced potential bias. Furthermore, despite extensive research, there remains a shortage of large-scale, high-quality studies on BFR training. Future studies should improve the credibility of the study by expanding the sample size as much as possible by improving the experimental design. For PAP induction, the effects of the training status, exercise interval time, and other factors on the PAP effect should be further clarified.

5 Conclusion

BFR exercises induce lower limb muscle activation and PAP effects to overcome self-weight. BFR exercises with 40%–60% AOP are more likely to induce PAP. BFR exercises in combination with a warm-up to overcome dead weight help improve the height of the CMJ vertical jump.

Data availability statement

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

Author contributions

JW, HL, and LJ: Conceptualization. JW: Methodology, resources, and supervision. HL and LJ: Software, formal analysis, and visualization. JW: Validation. LJ: Investigation. HL: Data curation. JW: Manuscript writing–original draft preparation. HL: Manuscript writing–review and editing. All authors contributed to the article and approved the submitted version.

Conflict of interest

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

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Measuring and assessing motor skills of selected Croatian U12, U14 and U16 tennis players

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Purpose: The aim of this research is to analyse and to determine the differences between tennis players in younger age categories (U12, U and U16) in certain motor skills.

Methods: A total of 60 tennis players ranked in the rankings of the Croatian Tennis Federation were measured by using 10 tests for assessing explosive strength in jump, speed, agility, and trunk strength. The tennis players were divided into three groups of 20 respondents, depending on the age category in which they compete. Statistically significant differences ($p < 0.05$) between all age categories were found in indicators of frontal and lateral agility, running speed in the 20-m shuttle run test, and explosive strength in jump and repetitive trunk strength.

Results: The results of the conducted tests indicate a linear development trend for the mentioned skills in relation with the increase of chronological age of the tennis players. Statistically significantly better results were shown between test subjects under 14 years compared to test subjects under 12 years in tests for the assessment of agility (SST,A9-3-6-3-9), in the 20 m sprint test, in tests of explosive strength of lower extremities (CMJ, CMJmax,SJ) and in the test of repetitive trunk strength (TF). Subjects under 16 years achieved significantly better results compared to subjects under 14 years in tests for assessing agility (SST, A9-3-6-3-9), speed (SRT5m, SRT10m, SRT20m) and explosiveness (CMJ, CMJmax, SJ). Players under 16 years recorded significantly better results in all tests for assessing agility (SST,A9-3-6-3-9), speed (SRT5m, SRT10m, SRT20m), explosiveness of the lower extremities (CMJ, CMJmax, SJ) and in the test for assessing repetitive trunk strength (TF). Statistically significant differences were not detected in tests of running speed in the 5-m and 10-m shuttle run tests among U12 and U14 tennis players, nor between U14 and U16 tennis players in the 60-s trunk flexion test. The highest heterogeneity of results in a single age category was determined in the test for assessing isometric trunk strength, and thus tennis players of different age categories do not differ significantly in this skill.

Conclusion: The results of this research point to the development of specific motor skills in accordance with the increase of game demands and chronological age, however, also refer to the problem of muscle imbalance between front and back trunk musculature. Physical conditioning of young tennis players should be multilaterally directed in order to enable injury prevention and adjustment of tennis players to competitive demands.

KEYWORDS

young tennis players, motor skills, multi-sided physical conditioning, tennis diagnostic, LtAD

1 Introduction

Tennis belongs to the group of complex polystructural sports which require athletes to have a high level of technical-tactical, physical conditioning and psychological preparation (Dobos and Nagykáldi, 2016; Fett et al., 2017). A high number of specific movement structures and match situations in the tennis game point to the fact that success of tennis players is determined by the level of multiple skills, knowledge, and characteristics. As a result of the afore-mentioned it is difficult to unambiguously determine success factors in the game of tennis. Planning and programming of sports trainings requires good knowledge of competitive demands in specific age categories and competition levels, as well as of player characteristics. Diagnostics of the training level enables detailed insight into the anthropological status of athletes, reveals potential risks of injury and presents the first step in creating an individualized training plan and programme (Ulbricht et al., 2013; Kramer et al., 2017). Regular implementation of diagnostics allows for control of athletes' development and efficiency of the training process. A detailed insight into the current state of physical conditioning of tennis players is a prerequisite for proper dosage of training and competition load, as well as a "guiding light" in defining objective short-term and long-term goals. Namely, it is precisely the lack of knowledge on the level of development of athletes that is the main cause of applying excessive intensity and load volume, as well as the appearance of overtraining, which often results in premature termination of playing competitive tennis (Strand and Samuelson, 2021).

Lately we have witnessed an increasingly rapid development of the tennis game. Technical-tactical preparedness of tennis players in top-level tennis is at a high level, thus without an optimal level of physical conditioning and movement technique tennis players are unable to use their full potential and be competent at the highest competition levels. Physical conditioning has a major impact on tennis performance even among younger age categories and presents one of the factors for predicting competitive success (Kovacs, 2007; Reid and Schneiker, 2008; Girard and Millet, 2009; Fett et al., 2017), and as a result of the aforementioned, and is taking on an increasing relevance in integral physical conditioning of young tennis players. Researches have shown that physical conditioning abilities in pre-puberty (up to the age of 12) are to the smallest extent in correlation with competitive success (Kovacs, 2007; Ulbricht et al., 2016; Kramer et al., 2017). In fact, in the mentioned period, success depends on the technical performance of strokes, as well as their efficiency and precision. After the age of 12, an accelerated physical growth and development takes place, and an increase in physical height and muscle mass occurs, thus physical conditioning becomes one of the factors which distinguish between successful and less successful tennis players.

Already in younger age categories, tennis players must be prepared to endure a high training load. Technical-tactical trainings for perspective junior players should be implemented in a fund of 15–20 h per week (Reid et al., 2007; Ulbricht et al., 2013) in order to allow them to achieve a high level of play and to participate in major competitions. It is thus clear that very little time remains for implementing physical conditioning trainings, and therefore it should be carried out in the most efficient manner, and tailored in accordance with the athlete's characteristics.

Specific characteristics of tennis performance should also be taken into consideration in the process of creating battery of tests for assessing motor and functional abilities of tennis players in order to meet the ecological validity of the tests. The aforementioned refers to the level of correspondence between real game situations in which the respondents manifest a certain ability with the situation in which the testing is conducted.

Movement in tennis is characterized by explosive starting velocities, short distance sprints, accelerations and decelerations, changes of direction of movement and performing strokes from various balance positions. It is precisely well-developed motor and functional abilities in flexibility, coordination, vigour and endurance, strength, agility, and speed that enable tennis players aged 12, 14, 16 to overcome different game situations on the tennis court in a strong, fast, long-lasting, precise or coordinated manner.

In this paper, motor skills of tennis players in the U12, U14, and U16 age categories were evaluated by using tests for assessing agility, explosive strength in speed, explosive strength in jump, as well as tests for assessing relative repetitive and static trunk strength.

Reactive agility, that is change of direction of movement conditioned by a reaction to visual stimulus, comes to the fore in the tennis game (Sheppard and Young, 2006; Young and Farrow, 2013). It allows the tennis player to reach the ball in time and to optimally set up for the stroke. Other motor skills, such as coordination, explosive strength, and speed, also have an impact on agility, however, likewise does the technique of changing the direction of movement, as well as perception of the environment and decision-making speed (Sheppard and Young, 2006).

In addition, tennis also demands explosive movements of the entire body. Explosive first steps enable tennis players to quickly arrive at an optimal position for the stroke, as well as allow for lower time-space pressure for playing the stroke. Both muscles of the upper and lower body are active in tennis and their synergy and timely activation of certain segments of the body allow for performing a biomechanically efficient stroke. Explosive strength of the arms and shoulder girdle allow the tennis player to accelerate with the racquet towards the point of contact with the ball, which thus results in a more powerful stroke. Whereas repetitive strength enables performing multiple repetitions of various movement structures and strokes over a longer period in the duration of a match.

The ability of speed is of great importance in the tennis game, as it allows tennis players to arrive at the ball in a timely manner, as well as to quickly perform certain tennis elements. It should be mentioned that there is also specific speed in tennis which is manifested in the ability to performtechnical-tactical elements or movements on the tennis court in the shortest possible time (Kovacs, 2009).

Several studies (Girard and Millet, 2009; Ulbricht et al., 2013; Lambrich and Muehlbauer, 2022) were conducted with the aim to identify the most important characteristics which determine competitive success in junior tennis players. Some of them indicate that motor and functional abilities do not enable predicting competitive success in younger age categories. Whereas other studies indicate that specific abilities and characteristics of younger tennis players, such as agility, speed, and vertical jump, are in correlation with competitive success. The systematic review and meta-analysis by Lambrich and Muehlbauer (2022) examined the impact of competition levels on physical fitness and stroke performance in tennis players, differentiating between elite and sub-elite players. The results indicated clear advantages in physical fitness and stroke

TABLE 1 Descriptive indicators of subject characteristics.

age category	n	Age	Height	Body mass
U12	20	12.12 ± 0.43	157.79 ± 8.49	45.07 ± 7.68
U14	20	13.95 ± 0.63	170.43 ± 9.86	56.56 ± 10.22
U16	20	15.89 ± 0.42	178.86 ± 7.79	66.85 ± 7.38

performance among elite players, particularly in terms of lower extremity muscle power, endurance, and agility. These findings emphasize the need to design targeted training programs, especially for sub-elite tennis players, to improve these essential physical attributes.

It is important to mention that younger age categories demand a professional and quality approach in planning and programming of the training process. Namely, young male and female tennis players are in a turbulent period of accelerated growth and development. It is precisely in that period that by means of a controlled and individualized training approach that the preconditions for a high level of playing tennis at a senior age are created. The starting point of any training process is diagnostics and analysis of the current training level of a tennis player. This provides insight into the level of development of individual abilities of a tennis player, and thus on the basis of comparison with modal values, provides guidelines for future planning and programming of the training process. The aim of this study is to determine the differences between groups of tennis players in younger age categories (U12, U14 and U16) in motor skills as indicators of physical conditioning.

2 Materials and methods

2.1 Sample of respondents

The sample of respondents is made of 60 Croatian male tennis players who are ranked in the official rankings of the Croatian Tennis Federation. The respondents were distributed into three groups of 20 tennis players according to their age category, as shown in Table 1. The inclusion criteria for this study involved selecting participants who were active tennis players regularly engaged in training. The participants needed to be within the specified age categories (U12, U14, and U16), aligning with the research objectives. Also, Selected participants were individuals who engaged in tennis training at least three times per week. Exclusion criteria included the exclusion of individuals with serious injuries that could affect their physical performance at the start of the study. This careful selection process aimed to ensure that the participants met the necessary requirements to contribute meaningfully to the research. Also, participants with a medical history or conditions that could potentially influence their physical abilities during the study were excluded. This criterion aimed to maintain the integrity of the results by ensuring that participants' performance was not influenced by underlying health factors. The recruitment process involved contacting and selecting tennis players who were part of the rankings administered by the Croatian Tennis Federation. These players were already engaged in competitive tennis, which made them suitable candidates for this investigation into motor skill differences among age categories in the sport.

2.2 Sample of variables

The respondents were tested by using a total of 10 tests for assessing motor skills, divided into 4 groups. The first group was made of tests for assessing the agility of tennis players: agility test with turn 93,639 (A9-3-6-3-9) and lateral side-step test (SST). The second group of variables was used for assessing explosive strength in sprint by means of the following tests: 5-m shuttle run test (5mSRT), 10-m shuttle run test (10mSRT) and 20-m shuttle run test (20mSRT). In the third group of variables, explosive strength in jump was evaluated with the following tests: countermovement jump (CMJ), countermovement jump–arm swing (CMJmax) and squat jump (SJ). The fourth group was composed of tests for assessing trunk strength: 60-s trunk flexion (TF) and static back-extension endurance test (BE).

2.3 Measurement protocol and study design

Measurements were conducted by educated measurers at the premises of the Sports Diagnostics Centre at the Faculty of Kinesiology University of Zagreb. All of the respondents were informed on the purpose and aim of the research, and they participated in the study with the consent of their parents/legal guardians. Before the testing session, all participants completed a standardized warm-up specific to tennis. The warm-up consisted of various activities, including light-intensity running covering a distance of 10 × 20 m. Following the running component, participants engaged in dynamic stretching exercises for a total duration of 15 min. These dynamic stretches involved lateral movements, skipping, jumping, lunges, and concluding with four repetitions of sub-maximum acceleration. Subsequently, the order of the various tests was predetermined and standardized. First, the participants underwent tests to assess agility, followed by tests for explosive strength in sprint, and finally, explosive strength in jump. After the final performance of the tests, all participants had an additional 5-min cool-down period, which consisted of light jogging and static stretching exercises to gradually reduce heart rate and promote muscular recovery. This structured warm-up and cool-down routine ensured that all participants were physically prepared for the study's assessments and that their physical condition returned to baseline.

Agility Test with Turn (A9-3-6-3-9): This test evaluates agility through a sequence of 9 steps forward, 3 steps backward, 6 steps forward, 3 steps backward, and 9 steps forward. The sequence challenges players' agility, footwork, and coordination. It comprises three trials with a 30-s rest between each trial and is conducted on a standard tennis court with no specific materials required.

Lateral Side-Step Test (SST): The SST assesses lateral agility as players side-step quickly to the left and right. It focuses on the ability to change direction rapidly, a crucial skill in tennis. The test includes three trials with a 30-s rest between each trial and is conducted on a standard tennis court, requiring no special materials.

5-m Shuttle Run Test (5mSRT): Players sprint back and forth over a 5-m distance in the 5mSRT, measuring their speed and quick acceleration. It comprises three trials with a 30-s rest between each trial and is conducted on a flat, non-slip surface.

10-m Shuttle Run Test (10mSRT): Similar to the 5mSRT, the 10mSRT evaluates players' speed and acceleration but over a longer 10-m distance. It includes three trials with a 30-s rest between trials and is performed on a flat surface.

20-m Shuttle Run Test (20mSRT): The 20mSRT assesses speed and endurance as players shuttle back and forth over a 20-m distance, necessitating sustained sprinting. The test comprises three trials with a 30-s rest between each trial.

Countermovement Jump (CMJ): In the CMJ test, players perform a vertical jump starting from a standing position. It assesses their explosive leg power. It includes three trials with a 30-s rest period between each trial.

Countermovement Jump–Arm Swing (CMJmax): Similar to the CMJ, the CMJmax test adds an arm swing to maximize vertical jump height. It further evaluates leg power with an emphasis on coordination. It comprises three trials with a 30-s rest between trials.

Squat Jump (SJ): The SJ test requires players to jump vertically from a squatting position, focusing on their leg power, coordination, and technique. It consists of three trials with a 30-s rest between each trial.

60-Second Trunk Flexion (TF): The TF test measures the endurance of the trunk flexor muscles as players perform continuous trunk flexion movements for 60 s. It is conducted on a flat surface, with no specific materials needed.

Static Back-Extension Endurance Test (BE): In the BE, players maintain a static back-extension position to evaluate the endurance of their lower back muscles. While the text does not specify the number of trials or rest periods for this test, it is performed on a flat surface without the need for additional materials.

2.4 Data processing methods

Data processing and statistical analysis was performed in the Statistica programme v14.0.0. For all of the variables parameters of descriptive statistics were calculated: arithmetic mean (AM), standard deviation (SD), as well as the measures of asymmetry and distortion of distribution - skewness (Skew) and kurtosis (Kurt). The Cohen's d coefficient as an indicator of effect size was calculated. Thresholds for effect size were statistically set to the following parameters: insignificant (<0.20), small (0.20–0.50), medium (0.50–0.80), and large (>0.80).

For determining statistically significant differences between the 3 groups of respondents in the measured variables, the ANOVA–univariant analysis of variance was used, as well as the Bonferroni Post-hoc method for analysis of differences, with the level of statistical difference of $p < 0.05$.

3 Results

3.1 Descriptive indicators of all variables and differences between age categories

3.1.1 Differences between tennis players in U12, U14 and U16 age categories in tests for assessing motor skills

In tests for lateral side steps (SST) and 93639 sprint with turn (A9-3-6-3-9) statistically significant differences were registered in all age categories, thus between U12 and U14, between U14 and U16, and between U12 and U16. It should be noted that there is a continuous improvement in the results of the aforementioned tests with the increase of chronological age of the respondents (A9-3-6-3-9 (AM) = 9.3117 s/8.6933 s/8.1481 s; SST (AM) = 10.130 s/9.058 s/8.2810 s), that is, the respondents require less and less time to complete the chosen test.

The obtained results show that all age categories statistically significantly differ in the 20-m shuttle run test (20mSRT (AM) = 4.12 s/3.89 s/3.56 s), as well as that with the increase of chronological age there is also an improvement of results for the 20-m shuttle run test. Upon analysis of the passing times at 5 m and 10 m, it is evident there are statistically significant differences as well among all age categories, except between U12 and U14 191 tennis players (5mSRT (AM) = 1.6833 s/1.6290 s/1.5190 s; 10mSRT (AM) = 2.5570,192 s/2.4537 s/2.2860 s).

Statistically significant differences were indicated between all age categories in the performance of the countermovement jump (CMJ (AM) = 32.603 cm/36.583 cm/43.795 cm), the countermovement jump with arm swing (CMJmax (AM) = 38.307 cm/44.365 cm/52.543 cm) and the squat jump (SJ (AM) = 31.067 cm/35.398 cm/41.710 cm). In all three of the mentioned variables, a linear progression of results was noted. Furthermore, the differences between the countermovement jump and the countermovement jump with arm swing were the greatest in the U16. age category, while it was the smallest in the U12 age category. The results achieved in the squat jump test were lower than the results of the countermovement jump in all of the groups of respondents, which is to be expected considering the method of performing in individual tests.

From the results achieved in the test for assessing repetitive trunk strength it is evident that there are statistically significant differences between all age categories, except between U14 and U16 tennis players (TF (AM) = 46.650 reps/56.200 reps/59.150 reps). There was no statistically significant difference found between the age categories in the test for assessing static trunk strength (BE 207 (AM) = 105.30 s/120.35 s/119.28 s).

Table 1 showes basic descriptive parameters of measured variables for assessing motor skills of tennis players in U12, U14 and U16 age categories. Furthermore, Table 2 shows high result dispersion in the trunk extension test, where some. respondents achieved significantly below-average results, whereas certain respondents had significantly above-average results.

4 Discussion

The conducted research showed statistically significant differences in the majority of the observed motor skills between tennis players in the U12, U14, and U16 age categories. Consequently, our assumption that such differences would be present has been confirmed. These results will be discussed in comparison with existing literature in the following text.

The obtained results point to a trend of development of certain motor skills with the increase in chronological age of tennis players. It should be noted that there is a linear increase in the observed abilities with the transition to a higher age category. In fact, the

TABLE 2 Basic descriptive parameters (AM, SD, p) and statistical significance of differences (p) and effect size (ES) between respondents in different age categories of measured variables.

Variables	U12	U14	U16	p; ES	p; ES	p; ES (U12:U16)
	AM ± SD	AM ± SD	AM ± SD	(U12:U14)	(U14:U16)	
A9-3-6-3-9	9.31 ± 0.63	8.69 ± 0.42	8.15 ± 0.49	0.001; 1.15	0.005; 1.18	0.001; 2.06
SST	10.13 ± 0.89	9.06 ± 0.67	8.28 ± 0.37	0.001; 1.36	0.002; 1.44	0.001; 2.71
5mSRT	1.68 ± 0.13	1.63 ± 0.11	1.52 ± 0.11	0.441; 0.42	0.013; 1.00	0.001; 1.33
10mSRT	2.56 ± 0.17	2.45 ± 0.14	2.29 ± 0.11	0.081; 0.71	0.002; 1.27	0.001; 1.89
20mSRT	4.12 ± 0.23	3.89 ± 0.17	3.56 ± 0.16	0.001; 1.14	0.001; 1.99	0.001; 2.82
CMJ	32.60 ± 4.13	36.58 ± 4.77	43.80 ± 4.52	0.020; 0.89	0.001; 1.56	0.001; 2,59
CMJmax	38.31 ± 4.22	44.37 ± 8.38	52.54 ± 4.29	0.006; 0.91	0.001; 1.22	0.001; 3.34
SJ	31.07 ± 3.86	35.40 ± 4.12	41.71 ± 3.91	0.003; 1.08	0.001; 1.57	0.001; 2.73
TF	46.65 ± 6.89	56.20 ± 4.55	59.15 ± 6.63	0.000; 1.64	0.398; 0.52	0.001; 1.85
BE	105.30 ± 36.65	120.35 ± 41.57	119.28 ± 40.17	0.700; 0.38	1.000; 0.03	0.803; 0.36

*Level of significance $p < 0.05$.

increase in chronological age is also followed by an increase of competitive demands, and thus physical conditioning of tennis players should be at an increasingly higher level. The development of individual abilities is a result of repeating training requirements and specific movement structures within tennis trainings and competitions, however, also of individual physical conditioning trainings. The observed age categories of respondents should be taken into account, as well as the fact that with entering into puberty and the accelerated growth and development phase physical conditioning becomes one of the factors which contributes to competitive success. It is precisely in this period that there is also an increase in longitudinal and transversal dimensionality of the skeleton, which is accompanied by an increase of muscle mass, and that all of the aforementioned has a positive effect on the development of certain motor skills (Kovacs, 2007; Dobos and Nagykáldi, 2016; Ulbricht et al., 2016; Kramer et al., 2017). Technical-tactical preparation and development of players in younger age categories is of crucial importance, however, multi-sided physical conditioning also enables players to keep up with training and competitive demands, as well as optimal tennis performance, and thus presents an indispensable component of a long-term training plan and programme.

4.1 Differences between tennis players in U12, U14 and U16 age categories in certain motor skills

4.1.1 Differences between tennis players in U12, U14 and U16 age categories in agility

Tennis movement is characterized by explosive accelerations and decelerations in short distances, as well as constant changes of direction of movement. Due to the aforementioned, lower-extremity explosive strength, starting acceleration and agility play an important role in physical conditioning of tennis players of all age categories (Reid and Schneiker, 2008; Munivrana et al., 2015; Dobos and Nagykáldi, 2016). Numerous research (Fernandez et al., 2006; Filipčić et al., 2010; Munivrana et al., 2015; Kramer et al., 2017; Galé-Ansodi et al., 2016; Fernandez-Fernandez et al., 2010) show a high level of correlation between agility and explosive strength in jump with competitive success and ranking position of tennis players in younger age categories. In the conducted research, statistically significant differences were determined between all age categories in tests of frontal and lateral agility. The results demonstrate a linear progression of this ability with chronological age of tennis players.

Agility is most often developed in individual physical conditioning trainings, however also within tennis trainings and appearances in numerous competitions. Since the process of maturation also results in an increase of longitudinal dimensionality of the skeleton and an increase of muscle mass, the aforementioned positively affects the strength of lower extremities and the speed of movement, and therefore agility as well. The results of this test depend on multiple abilities and motor skills of tennis players, to which attention should be paid in the development of agility. Tennis players with more efficient technique in changing the direction of movement, who are more explosive, and have greater eccentric strength of lower extremities, allowing them to decelerate more efficiently, shall also achieve better results in the agility assessment test (Sheppard and Young, 2006; Sekulic et al., 2017; Keller et al., 2020). In tennis we are referring to reactive agility because during the match a tennis player must quickly react to situations during a point, and accordingly, change positions on the tennis court. The aforementioned shows that by means of the conducted tests assessment is made of pre-planned agility due to the absence of external stimuli, which certainly does not comply with the demands of the tennis game. In order for the testing to come closer to real conditions on the tennis court, agility assessment tests should also include a component of reaction to external stimuli. This is precisely why certain authors proposed a standardized agility test that aside from the change of direction of movement also includes a cognitive component (perception), as well as specific performance of a task with the tennis racquet (Fernandez-Fernandez et al., 2014). In agility training, as well as in other abilities relevant for success in tennis, the transfer of abilities to specific conditions on the tennis court should also be taken into consideration. For this reason, the mentioned ability should be trained in short distances on the tennis court, with focus on lateral and frontal movements, and with connecting imitations or playing strokes.

4.1.2 Differences between tennis players in U12, U14 and U16 age categories in straight sprint speed ability

The increasing demands of the tennis game with transition to a higher age category must likewise be followed by an increase in training stimuli in order to reduce the risk of injury, as well as to improve performance on the court. A tennis player's speed plays an important role in predicting competitive success. An explosive first step and the ability of starting acceleration are required to efficiently perform strokes from various positions on the tennis court. Tennis players aged between 11 and 13 are capable of performing serves at the speed of approximately 125 km/h, which means that the player returning the serve has 0.69 s for perception, reaction, arrival at the ball, and preparing the stroke (Ferrauti and Bastiaens, 2007). Even small differences in running speed at 5 m can result in a significant advantage or disadvantage in the game. In fact, if a tennis player fails in taking an optimal position for the stroke, the efficiency of the stroke significantly reduces. Stroke velocities in younger age categories are quite high, and as court dimensions are relatively small (8.23 × 23.77 m), speed of movement in short distances in various directions represents one of the crucial success factors. Statistically significant differences in the test for passing time results at 5 and 10 m were not found between U12 and U14 tennis players. The reason for the aforementioned can be in the stagnation of strength development of lower extremity musculature between these two age categories, which is in correlation with the fact that tennis players have not yet reached their peak height velocity (PHV), when a significant increase in muscle mass also takes place. Since the result of the mentioned tests also depends on movement technique, acceleration, and the speed of starting reaction, it is possible that insufficient attention has been given to this segment of physical conditioning. The mentioned results should be discussed, as well as studies should be conducted in the direction that shall show the reasons for such results in the aforementioned parameter, in order for physical conditioning coaches to have the insight for programming trainings in the future for the development of the specific segment of performance which is key for such results. As tennis players run an average of 3–4 m between two strokes, and since they are not able to achieve maximum speed of movement (which occurs between 30 and 60 m in straight-line running) (Fernandez-Fernandez et al., 2014; Dobos and Nagykáldi, 2016), it is precisely the ability of accelerating and stopping at a short distance that is of key importance for tennis players. The passing time at 5 m provides insight into the speed of starting reaction and the first step, while the passing time at 10 m measures the acceleration of an athlete. Starting velocity and acceleration are specific for tennis demands, and therefore precisely the mentioned two tests are of key importance for assessing the specific speed of tennis players.

It is interesting that statistically significant differences were found between all age categories in the 20mSRT test. The mentioned test serves for evaluating maximum running speed, and thus it is not specific for tennis because tennis players do not run a 20-m straight line distance in any single game situation. The obtained results point to the fact that there is a noted increase in the running speed of tennis players between the U12 and U14 age categories, however that there is no progress in efficient starting and acceleration.

4.1.3 Differences between tennis players in U12, U14 and U16 age categories in explosive strength in jump ability

Explosive strength of the lower extremities is assessed by using different types of vertical and horizontal jumps. The vertical jump is a frequently present movement structure in most sports. In terms of movement biomechanics, a similar movement structure also occurs in acceleration, as well as in dynamic game situations (Fernandez-Fernandez et al., 2014). The results of tests for assessing explosive strength in jump demonstrate a linear progression in the mentioned ability with the increase in age category. Statistically significant differences between all age categories indicate a positive effect of growth and development, specific training, and the increase of muscle mass in lower extremities on explosive strength of the lower extremities. Better results with the increase of chronological age can be correlated with higher activation of motor units, better technique of movement performance and improved inter- and intra-muscular coordination (Munivrana et al., 2015). The mentioned ability is of great importance for success in tennis. It enables tennis players to have explosive starts and starting acceleration, it positively affects sprinting speed and agility, as well as participates in the performance of all strokes, as it is precisely the lower extremities which are the first link of the kinetic chain during the performance of all strokes (Dobos and Nagykáldi, 2016; Kramer et al., 2017).

The conclusion can be made that starting speed improves with the development of the mentioned motor ability, which can result with dominance in certain parameters that separate an average and a top-level player. The aforementioned is particularly important because of the relevance of explosive movements and accelerations which allow tennis players to arrive at the ball in a timely manner and to perform strokes from an optimal balance position. Tennis players who are capable of producing a large amount of force in the shortest possible time shall be able to move quickly on the court and perform strokes at high speeds. Improving explosive strength of the lower extremities is important in younger age categories as it allows the players to perform explosive starting acceleration more efficiently, as well as to accelerate in short distances and to produce a larger impulse of force which is thus transferred through other links of the kinetic chain into contact of the racquet with the ball.

The countermovement jump is closest by its performance characteristics to the specific musculature working regime of the lower extremities during tennis performance. Namely, the mentioned test evaluates explosive strength of elastic character, as after the eccentric phase and storage of elastic energy, it is then directed into the concentric phase of the jump. The described working regime is characteristic for the performance of all strokes in tennis, and it is perhaps the most visible during the performance of the serve.

4.1.4 Differences between tennis players in U12, U14 and U16 age categories in repetitive and static trunkstrength

Already in younger age categories, tennis players are exposed to high levels of stress on the locomotor system due to training and competitive load. As tennis includes repeated movements which dominantly activate one side of the body, muscle imbalance and risk of injury as a result ofoverexertion frequently occur. Strength and muscle endurance trainings should be included in the training plan and programme of young tennis players in order to improve the quality of stroke performance, as well as to reduce risk of injuries. A significant ncrease of muscle mass and strength is noted immediately after the period of PHV, which occurs around the age of 14 among boys (Dobos and Nagykáldi, 2016; Kramer et al., 2016; Ulbricht et al., 2016; Kramer et al., 2017).

Statistically significant differences between age categories were found in indicators of repetitive trunk strength, however not for static strength. A well-trained trunk musculature allows for adequate trunk stability during the performance of all strokes, which reduces risk of injury, while it increases stroke control and precision. Furthermore, the trunk represents the central part of the kinetic chain during the performance of strokes, and it is precisely the trunk that is the central link through which energy is transferred from the lower towards the upper extremities (Filipčić et al., 2010; Kovacs and Ellenbecker, 2011; Söğüt, 2016; Myers and Kibler, 2018). The large dispersion of results in the trunk extension test serves as a warning for neglecting the development of static trunk strength among tennis players in younger age categories. Since there were no differences found between the age categories, it is considered necessary to determine the reasons for this unsatisfactory trend. Due to the aforementioned results which show a certain imbalance in the level of development between the front and back side of the trunk, preventive and corrective exercises should be applied in order to reduce the possibility of injuries. The relevance of trunk strength is significantly demonstrated in the serve stroke where the trunk muscles present a key factor for the quality of performance. An optimal level of strength in all muscle-joint systems is very important, however, particular emphasis should be awarded to the muscles of the rotator cuff, forearm, wrist, lumbar part of the back and the trunk due to an increased load on the mentioned parts of the body (Strand and Samuelson, 2021). It should be discussed how much of an effect on the quality of the serve, and also of other strokes, does an insufficient static trunk strength have in younger age categories.

Exercises of concentric and eccentric working regime should be included into training contents for the development of strength, as it is shown that both result in an increase of stroke efficiency and speed (Kovacs, 2007). Furthermore, the aforementioned also reduces muscle imbalance and the possibility of injuries. The most efficient strength training in younger age categories is training in dynamic conditions by using multi-joint exercises with progressive increase of external load, and with emphasis on performance technique and similarity of movements to the technique of movement structures and strokes in tennis (Munivrana et al., 2015).

4.2 Strengths and limitations

Strengths of this study include its systematic and comprehensive approach to examining differences in physical fitness and stroke performance in tennis players across competition levels. The systematic review and meta-analysis considered a substantial number of studies and provided a quantified analysis of the differences, which enhances the robustness of the findings. Additionally, this research contributes to our understanding of competition-level differences and provides valuable insights into the physical attributes that distinguish elite and sub-elite tennis players. This study has certain limitations that should be considered. Firstly, the motor tests were conducted with a convenient sample of participants under controlled conditions. While this sample size is reasonable for a study of this nature, it might not fully represent the entire population of tennis players, and results may vary with a larger, more diverse sample. Secondly, the study focuses on tennis players within specific age categories (U12, U14, and U16). The findings may not be directly applicable to older or younger players or those in different competitive environments. Thirdly, a longitudinal study would be needed for a more comprehensive understanding. Also, the study employed specific tests to assess motor skills, and the choice of tests could impact the results. In future studies, it is crucial to acknowledge that different tests may yield varying outcomes, introducing the potential for bias based on test selection. Therefore, researchers should carefully consider the choice of tests to ensure a well-rounded evaluation of tennis players' abilities. Furthermore, future research endeavors could greatly benefit from continuous monitoring of the correlation between the development of motor and functional abilities, not only in male but also female tennis players, and other components of an individual's anthropological status in relation to competitive success within younger age categories. Particular attention should be given to selecting tests that closely replicate the demands of the tennis game, allowing for a consistent insight into the normative values of tennis players' abilities and characteristics that significantly contribute to success within specific age categories. Additionally, future studies could incorporate longitudinal monitoring of the anthropological status of both male and female tennis players, which would not only shed light on differences between age categories but also on the individual development trajectory of each player. These comprehensive research directions will provide invaluable insights into the intricate relationship between physical development, athletic performance, and competitive success in the realm of tennis. This would enable a more detailed view on the effect of age, maturation, and the training process on the anthropological status of tennis players. The aforementioned approach would offer a detailed insight into the development of significant abilities and characteristics of athletes, as well as allow for corrections of the training plan and programme.

5 Conclusions

The results obtained in this research indicate a linear progression trend in the development of most of the evaluated motor skills with the increase of age category of tennis players. Based on the results of this research, we can confirm our assumption that younger tennis players in the U12 category may exhibit significant differences in certain motor skills compared to those in the U14 and U16 categories. The observed age categories are of great importance as tennis players are at the beginning of their careers and in a phase of intensive growth and development. An individualized plan and programme, based on diagnostics, enables maximal use of a player's potential and allows for potentially achieving a successful long-term sports career.

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 Faculty of Kinesiology, University of Zagreb. 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

Conceptualization, PB and DM; methodology, DM, SŠ, and BD; software PB and SŠ; validation, MG and DM; formal analysis, SŠ, PB, and DM; investigation, BD, SŠ, DM, and MG resources, PB, DM; data curation DM and MG; writing, BD, SŠ, and PB, original draft preparation, SŠ, PB, and DM; writing—review and editing MG, BD; visualization, SŠ, PB, and DM; supervision, PB. All authors contributed to the article and approved the submitted version.

Conflict of interest

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

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A 16-week school-based intervention improves physical fitness in Slovenian children: a randomized controlled trial

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Introduction: The aim of this study was to evaluate the effects of a 16-week school-based physical activity (PA) intervention on physical fitness (PF) (speed, hand-eye coordination, flexibility) of 8– to 9-year-olds.

Methods: A total of seventy-eight boys and girls (boys: n = 45, aged 8.4 ± 4.9 years; girls: n = 42, aged 8.6 ± 0.5 years) from a school in Slovenia were randomly assigned to either a group with an after-school PA program (EXP) or a control group (CON) that participated exclusively in mandatory physical education (PE). The EXP group engaged in the extracurricular PA program for 60 min twice a week for 16 weeks, concurrent with regular PE classes. The program primarily involved elementary PE games that included elements of athletics (e.g., skipping, push- off running, hopping, crossstepping, and jumping) and gymnastics (e.g., handstand, forward roll, backward roll, hand support jumps, squat jump on a vault box, climbing on horizontal bars, incline benches and ropes, crawling, and jumping rope). Standardized tests appropriate for this age group were used to assess PF, including the sit and reach test (SAR), the 30-meter sprint, and the alternate hand wall toss test at distances of 1.0 and 2.0 m (AHWT 1.0 and 2.0).

Results: There was a significant group-time interaction for SAR test (EXP group increase: +1.6 cm, +6.3%; CON group decrease: −0.1 cm, −0.4%; $p < 0.001$, ηp^2 = 0.361), and the 30 m sprint (EXP group improvement: −0.4 s, −6.3%; CON group decrease: +0.1 s, +1.6%; $p < 0.001$, $\eta p^2 = 0.193$). Similarly, the EXP group improved by +2.1 points (+25.6%) in the 1.0 m wall throw with the alternating hand, while the CON group showed only minimal changes (−0.2 points, −2.4%; $p < 0.001$, ηp^2 = 0.545). No significant interaction was found for the 2.0 m toss (EXP and CON group both −0.1 points, −2.6%; p = 0.888, ηp^2 = 0.001). *Post-hoc* analyses with paired t-tests revealed that the EXP group showed significant improvements in SAR test ($p < 0.001$), 30 m sprint ($p < 0.001$) and AHWT 1.0 test ($p < 0.001$), while the CON group showed no significant changes in SAR test (p = 0.533), 30 m sprint (p = 0.150), AHWT 1.0 test (p = 0.186) and AHWT 2.0 test (p = 0.430).

Discussion: The results of the study showed that the extracurricular program with only two additional weekly sessions significantly improved the components of PF in 8- to 9-year olds. Significant improvements were observed in the areas of flexibility, speed and coordination, as shown in the SAR test, 30-meter sprint and

1.0-meter handwall toss tests. However, no similar improvements were observed in the 2.0-meter handwall toss, which illustrates the specific areas of impact of the program.

KEYWORDS

children, sport, physical fitness, games, athletics, gymnastics, school intervention

1 Introduction

Improving the physical fitness (PF) of school-age children is an important endeavour that lays the foundation for a healthier lifestyle and has lasting effects on their overall wellbeing (Bermejo-Cantarero et al., 2023). Among all the components of PF, speed, hand-eye coordination and flexibility are critical attributes that contribute to children's physical performance, cognitive development and activities of daily living (Liu et al., 2022). While these components appear to have a relatively small impact on health, future outcomes and disease prevention, they play an important role in the development of 8– to 9-year-olds, contributing to their physical performance, cognitive development and activities of daily living.

During the transition from early to middle childhood, 8–to 9-year-olds undergo significant physical growth and maturation (Aliriad et al., 2023). This developmental period is characterized by the acquisition of basic PF skills that serve as a foundation for more complex movements and activities (OBrien et al., 2016; Teich et al., 2023). Compared to some recent studies by various authors (Bauer et al., 2022; Kryeziu et al., 2023; Mohammadi-Nia et al., 2023; Osipov et al., 2023; Wu et al., 2023; Yuksel et al., 2020) that have examined different exercise programs in children and their different effects on PF, the importance of understanding these relationships in the context of child development is becoming increasingly clear. Speed is a central component of PF and refers to the ability to perform movements quickly and efficiently (Barbieri et al., 2022; Fernandez-Fernandez et al., 2023; Jafar et al., 2023; Volk et al., 2023). Although it may appear to make a smaller contribution to health and long-term disease prevention, the importance of speed should not be underestimated, especially in the developmental phase of 8–to 9-year-olds (Herszage et al., 2023). Promoting speed in children at this crucial developmental stage goes beyond pure physical performance. It also plays a fundamental role in cognitive processes, including decision-making and motor responsiveness (Lin et al., 2023). Refining 8–to 9-year-olds' speed-related motor skills leads to improved reaction times and more efficient movement execution. This in turn enables them to participate in activities that require quick reactions, such as team sports and games (Herszage et al., 2023). It is important to emphasise that the development of speed in 8–to 9-year-olds not only contributes to their PF, but also has a lasting effect on their cognitive development. When children engage in activities that challenge their speed-related PF, it not only boosts their physical confidence but also their overall enthusiasm for physical engagement (Yamada et al., 2021; Schirmer et al., 2023). Hand-eye coordination is another essential element of PF that requires the seamless integration of muscle groups to perform precise and controlled movements (Lima et al., 2023; Tang et al., 2023). As 8–to 9-year-olds refine their hand-eye coordination, they gain the ability to perform complex movements with greater accuracy and fluidity. This improvement is due to the continued refinement of neural pathways that facilitate communication between the brain and muscles (Demers and Levin, 2017; Urai et al., 2022; Park and Jeong, 2023). As a result, 8–to 9-year-olds can engage in activities that require intricate hand-eye and motor coordination, such as dance, team sports, and various forms of artistic expression (Ludyga et al., 2022; Pastorek Gripson et al., 2022; Tao et al., 2022). Furthermore, it is crucial to recognise that hand-eye coordination plays a critical role in the development of fine and gross motor skills that are essential for everyday tasks and school activities. Children's ability to perform these tasks with greater accuracy and coordination can have a lasting impact on their academic progress and general wellbeing (Giuriato et al., 2022; Navarra et al., 2022; Cinar et al., 2023; Kojić et al., 2023). Flexibility, even if it appears to make a lesser contribution to health, future outcomes and disease prevention, is an important facet of PF that deserves attention. Flexibility refers to the range of motion of the joints and the suppleness of the muscles and tendons (Konrad et al., 2022). During the eighth to ninth year of life, flexibility increases significantly due to progressive growth and adaptation of the musculoskeletal system (Zhang et al., 2023). This increased flexibility allows 8–to 9-year-olds to perform a wider range of movements while reducing the risk of overuse or injury (Yang et al., 2022; Behm et al., 2023; Zvetkova et al., 2023). Activities that promote flexibility, such as stretching and yoga, can help maintain healthy joints and muscles while promoting awareness of the importance of regular physical activity (PA) (Chan et al., 2023; Y; Cho et al., 2023). Developing flexibility during this stage lays the foundation for more agile and adaptable physicality, which is important for both recreational and functional movements (Tsao et al., 2022; Zinelabidine et al., 2022). Targeted interventions at this stage therefore have the potential to positively impact children's PF and promote a lifelong appreciation for PA.

This study examined the effects of a 16-week school-based PA intervention on the PF of 8–to 9-year-olds, focusing on three selected components of PF: speed, hand-eye coordination, and flexibility. Although these components have a relatively small impact on health, future outcomes, and disease prevention, we want to emphasise their importance in the context of child development. The motor skills of speed, hand-eye coordination and flexibility are not only important for physical performance, but are also closely linked to various aspects of children's daily lives. They influence participation in sports and recreational activities and overall physical wellbeing, making them an important area of study. Previous research has demonstrated the potential benefits of school-based PA interventions on PF (Barnett et al., 2009; Van Sluijs and McMinn, 2010; Lai et al., 2014; Brandes et al., 2023; Zhou et al.,

TABLE 1 General characteristics of the participants.

Variable	EXP group (n = 44)	CON group (n = 43)	p-value
BH (cm)	124.3 ± 6.6 (95% CI: 121.1–127.5)	125.5 ± 7.1 (95% CI: 122.2–128.8)	0.243
BW (kg)	24.3 ± 3.7 (95% CI: 23.1–25.6)	24.9 ± 4.1 (95% CI: 23.7–26.1)	0.312
BMI (kg/m^2)	15.6 ± 0.9 (95% CI: 15.3–15.9)	15.7 ± 0.9 (95% CI: 15.4–16.0)	0.635
Age (years)	8.5 ± 0.5 (95% CI: 8.3–8.7)	8.6 ± 0.5 (95% CI: 8.4–8.8)	0.487

Abbreviations: BH, body height; BW, body weight; BMI, body mass index; EXP, experimental; CON, control; n, number of participants. Values are defined as mean ± standard deviation.

2023), yet there remains a need for more comprehensive investigations that target specific age groups and assess multiple dimensions of motor performance. This study focuses on 8–to 9-year-olds and their development of speed, hand-eye coordination, and flexibility. Despite the relatively small impact of these components on health, our study aims to shed light on their multifaceted importance for children's development and wellbeing. The purpose is to contribute to the existing body of knowledge on the effectiveness of school-based interventions to improve children's PF.

The hypothesis of our study was that a 16-week school-based PA intervention would positively influence the PF of 8- to 9-year-olds. This study aims to shed light on the potential of such interventions to improve PA and fitness in young children and thus contribute to the formulation of evidence-based strategies to promote the general health and wellbeing of school-aged individuals.

2 Materials and methods

2.1 Subjects

The present study was a randomized experimental trial comparing an extracurricular PA program focusing on athletic and gymnastic activities with traditional PE. The study included 78 boys and girls (boys: n = 45, aged 8.4 ± 4.9 years; girls: n = 42, aged 8.6 ± 0.5 years) from the same school. Participants were excluded based on certain criteria, such as pre-existing medical conditions (heart disease, cancer, etc.). Overweight and obese individuals were included in this study. Randomization was performed using simple randomization. The participants were then divided into two groups: One group participated in an extracurricular PA program (EXP), while the other group formed the control group (CON) and participated only in mandatory PE classes. The general characteristics of the participants are shown in Table 1. Before the intervention began, all participants and their parents or guardians were familiarized with the experimental procedures and signed an informed consent form in order for the children to participate. The study procedures were conducted in accordance with the Declaration of Helsinki.

2.2 Procedures

Each test that was carried out took place in the morning and carried out by the same investigators. The tests included an examination of body composition and the developmental level of PF (speed, hand-eye coordination, and flexibility). Body height was measured to the nearest 0.5 cm using a wall-mounted stadiometer. Body weight was measured on a calibrated beam scale with an accuracy of 0.1 kg.

Both the EXP and CON groups participated in regular PE classes three times per week for 45 min each, with the EXP group engaging in additional extracurricular PA sessions twice per week. The additional sessions were based on athletic and gymnastic activities. The program was led by a PE teacher employed at the school where the intervention took place. The additional PA sessions were conducted for 16 weeks, with each session lasting 60 min. Each session began with approximately 5 min of warm-up training, which continued with running games from low to moderate to high intensity. This was followed by 10 min of stretching and strengthening exercises. The main part of the session lasted around 40 min and focused on athletic content (speed and hand-eye coordination) in one session per week and gymnastic content (hand-eye coordination and flexibility) in the other. Each session ended with 3–5 min of stretching and calming exercises. The program included several elementary PE games that included elements of athletics (skipping, push-off running, hopping, cross-stepping, and jumping, etc.) and gymnastics (handstand, forward roll, backward roll, hand support jumps, squat jump on a vault box, climbing on horizontal bars, incline benches and ropes, crawling, and jumping rope, etc.). These elements were identified as having the most positive impact on the development of speed, hand-eye coordination, and flexibility (Bade et al., 2023; Campbell-Pierre and Rhea, 2023; Moran et al., 2023). The additional PA sessions were conducted both indoors and outdoors, depending on the weather conditions. The CON group participated only in traditional PE classes or physical activities that were scheduled for all students during the academic day.

2.3 Physical fitness testing

Participants in this study underwent a series of PF tests, including the Sit and Reach Test (SAR), followed by the 30-meter sprint and subsequently the Alternate Hand Wall Toss Test (AHWT) at 1.0 and 2.0 m.

2.4 Sit and reach test (SAR)

Each participant was asked to sit on the flat floor of the gym and place their bare feet vertically against a box. In this starting position, they then had to lean forward as far as possible with their arms and knees fully extended and hold the final position for 5 s. Participants who did not fully extend their arms and knees in the final position or could not hold the position for 5 s repeated the measurement.

Participants had 30 s rest between each trial, with their best result being recorded.

In evaluating the effectiveness and reliability of the SAR test, the study by Mayorga-Vega et al. (2014) plays a crucial role. They specifically assessed the concurrent validity of the SAR test, an important aspect in determining its accuracy in measuring flexibility. Their analysis resulted in a high intraclass correlation coefficient (ICC) of 0.93, which underlines the excellent concurrent validity of the test. This high ICC value not only confirms the reliability of the SAR test, but also its strong correlation with established benchmarks for assessing flexibility, validating its use in our study.

2.5 30-m sprint

Participants completed three 30-meter sprint trials from a standing start, with an interval of at least 5 min between each trial. Time was recorded to the millisecond for the first 30 m and measured with optical timing devices (Model: T-C System; Brower Timing Systems, Salt Lake City, UT).

The reliability and accuracy of the 30-metre sprint test is also underpinned by the study conducted by Simperingham et al. (2016), who specifically investigated the criterion-related validity of this test. Their comprehensive analysis revealed a high intraclass correlation coefficient (ICC) of 0.91. This significant result not only underlines the strong criterion-related validity of the 30-metre sprint test, but also demonstrates its consistency and robustness in line with the established criteria for measuring this particular physical attribute.

2.6 Alternate hand wall toss test 1.0 and 2.0 m (AHWT 1.0 and 2.0 m)

The AHWT is a test that measures hand-eye coordination. A tennis ball is thrown from one hand in an extended motion at a specified distance from the wall and an attempt is made to catch it with the other hand. The total number of repeated actions within 30 s is recorded. In this test, the distances were set at 1.0 and 2.0 m. First the ball was thrown with the right hand and caught with the left hand, then the ball was thrown with the left hand and caught with the right hand; this was recorded as 2 repetitions.

The precision and reliability of the AHWT test as a measure of hand-eye coordination is confirmed by the research of Cho et al. (2020). In their comprehensive study, they focused on evaluating the construct validity of the AHWT test. Their results, highlighted by an intraclass correlation coefficient (ICC) of 0.85, show a high degree of construct validity for the test. This robust ICC value is an indication of the effectiveness of the test in accurately measuring the specific construct of hand-eye coordination for which it was developed. This level of validation confirms the reliability of the test and its applicability in the given context and ensures the validity of the coordination measurements obtained in our study.

The reliability of the PF tests was determined in a preliminary study conducted by our research team that focused specifically on the same age group. In these preliminary results, all tests showed good reliability, with an intraclass correlation coefficient (ICC) ranging from 0.85 to 0.93.

2.7 Statistical analysis

Data analysis was performed with SPSS, version 23 (SPSS Inc., Chicago, IL, United States). Means and standard deviations were calculated for all variables. The normality of the data was confirmed with the Kolmogorov-Smirnov test ($p > 0.05$ for all tests), and the homogeneity of variances was assessed with the Levene test. A two-way repeated measures ANOVA was used to examine main effects and interactions for time (pre-test vs. post-test) and group (EXP vs. CON) on the selected outcomes. Following ANOVA, systematic *post hoc* paired-samples t-tests were conducted to assess within-group changes over time for each variable measured.

Cohen's d was used to measure the effect size for within-group comparisons. The calculation of Cohen's d was based on the standardized mean difference between the pre- and post-test scores in each group divided by the pooled standard deviation of both time points. This provides a measure of the size of the effect of the intervention in units of standard deviation. In our study, the effect size was categorised according to the guidelines of (Hopkins et al., 2009). In particular, a Cohen's d value of less than 0.2 was interpreted as a trivial effect, 0.2–0.6 as a small effect, 0.6–1.2 as a moderate effect, 1.2–2.0 as a large effect, greater than 2.0 as a very large effect and greater than 4.0 as an extremely large effect. The partial Eta^2 values (η^2) were first calculated for the differences between the groups. These η^2 values were then converted to Cohen's d to ensure consistency in the quantification of effect sizes across the study. This conversion was particularly relevant in the context of significant interaction effects identified by the two-way repeated measures ANOVA. Once these interactions were identified, systematic *post hoc* paired-samples t-tests were conducted to assess within-group changes over time for each variable measured.

All statistical tests were two-tailed, and a *p*-value of ≤0.05 was considered statistically significant.

3 Results

The results presented in Table 2 show significant interactions between group and time for several tests. Post-hoc paired-samples t-tests within the EXP group showed a statistically significant improvement in the SAR test ($p < 0.001$), with an average increase of +1.6 cm from the pre-test (25.2 ± 3.3 cm) to the post-test (26.8 ± 3.7 cm) and an effect size (Cohen's d) of +1.28, indicating a large effect (Figure 1). In addition, the EXP group showed a significant time reduction in the 30-metre sprint by −0.4 s on average (from 6.3 ± 0.5 to 5.9 ± 0.4 s), with an effect size of +0.67, representing a moderate effect, and a *post hoc* *p*-value of <0.001 (Figure 2). Significant improvements were also observed in the AHWT 1.0 test for the EXP group (Figure 3), with an average improvement of +2.1 points (from 8.2 ± 3.7 to 10.3 ± 3.9) and an effect size of +1.78, reflecting a very large effect (*post hoc* *p*-value <0.001).

In contrast, the *post hoc* analyses within the CON group showed no statistically significant changes over time for the measures with interaction. In particular, the *p*-values for SAR test ($p = 0.533$), 30-m sprint ($p = 0.150$), AHWT 1.0 test ($p = 0.186$), and AHWT 2.0 test ($p = 0.430$) were non-significant differences, indicating a clear change over time in the CON group. The interaction between

TABLE 2 Physical fitness results and changes from pre- to post-test in EXP and CON group.

Variable	Group	Pre-test	Post-test	ES	% Change	p-value, η^2_p	Post-hoc test (paired t-test p-value)
Sit and reach test (cm)	EXP	25.2 ± 3.3	26.8 ± 3.7	+1.28	+6.3	Group: $p = 0.469$, η^2_p: 0.006 Time: $p < 0.001$, η^2_p: 0.306 Interaction: $p < 0.001$, η^2_p: 0.361	$p < 0.001$
	CON	25.5 ± 3.0	25.4 ± 3.5	−0.09	−0.4		$p = 0.533$
30 m sprint (seconds)	EXP	6.3 ± 0.5	5.9 ± 0.4	+0.67	+6.3	Group: $p < 0.177$, η^2_p: 0.021 Time: $p < 0.001$, η^2_p: 0.179 Interaction: $p < 0.001$, η^2_p: 0.193	$p < 0.001$
	CON	6.2 ± 0.6	6.3 ± 0.6	−0.22	−1.6		$p = 0.150$
Alternate hand wall toss test 1.0 m (score)	EXP	8.2 ± 3.7	10.3 ± 3.9	+1.78	+25.6	Group: $p < 0.241$, η^2_p: 0.016 Time: $p < 0.001$, η^2_p: 0.456 Interaction: $p < 0.001$, η^2_p: 0.545	$p < 0.001$
	CON	8.3 ± 4.0	8.1 ± 4.6	−0.21	−2.4		$p = 0.186$
Alternate hand wall toss test 2.0 m (score)	EXP	3.8 ± 3.6	3.7 ± 3.9	−0.13	−2.6	Group: $p = 0.949$, η^2_p: 0.001 Time: $p = 0.254$, η^2_p: 0.015 Interaction: $p = 0.888$, η^2_p: 0.001	$p = 0.400$
	CON	3.8 ± 3.6	3.7 ± 4.2	−0.12	−2.6		$p = 0.430$

Abbreviations: EXP, experimental group; CON, control group; ES, cohen d effect size; Values are defined as mean ± standard deviation.

FIGURE 1
Change in the results of the Sit and Reach over time for the EXP and CON groups.

group and time for AHWT 2.0 test was not significant ($p = 0.888$), with both groups showing a slight decrease in scores, suggesting that the intervention did not lead to significant improvements on this measure (Figure 4).

There were no dropouts in either the EXP or CON groups throughout the study period, demonstrating the feasibility and tolerability of the intervention program.

4 Discussion

Incorporating interventions that aim to improve the PF of speed, hand-eye coordination, and flexibility is particularly important during the developmental period of 8–to 9-year-olds. This is because improvements made during this period can have a positive impact on a child's lifelong physical health and wellbeing (Stanković et al., 2022). Acquiring PF not only contributes to performance in sports and physical activities, but also promotes a holistic understanding of their bodies and the value of an active lifestyle (Baena-Morales and González-Víllora, 2023). Therefore, the aim of this study was to examine the impact of a 16-week extracurricular intervention program focusing on PA and the impact it had on the PF of 8–to 9-year-olds. A key finding of this study was that the EXP group showed remarkable improvements in speed, hand-eye coordination, and flexibility following the concise program. In addition, the 16-week school-based PA intervention effectively improved PF in all studied domains except AHWT 2.0 m test, where no differences between groups were recorded.

Lack of flexibility in children aged 8–9 years can hinder their physical development by limiting their range of motion and

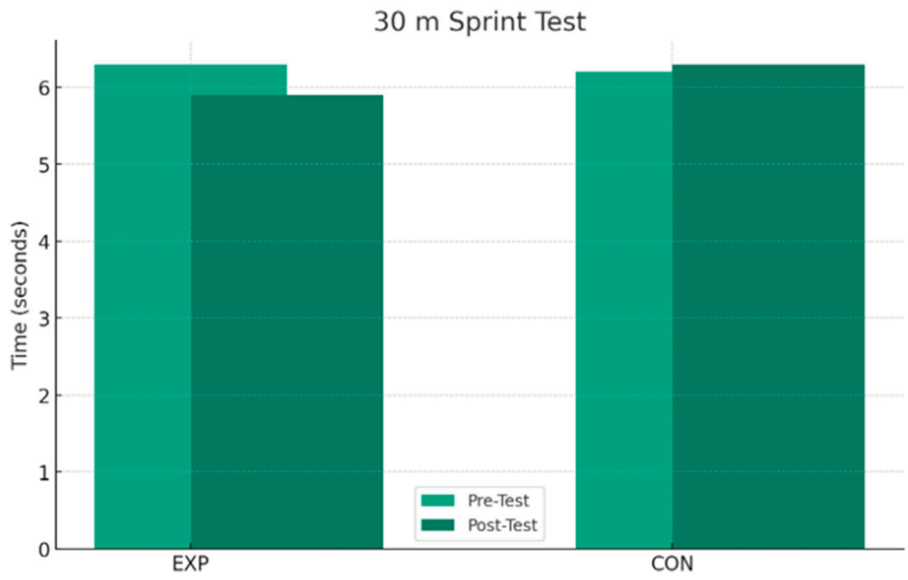

FIGURE 2
Change in 30 m sprint times over time for the EXP and CON groups.

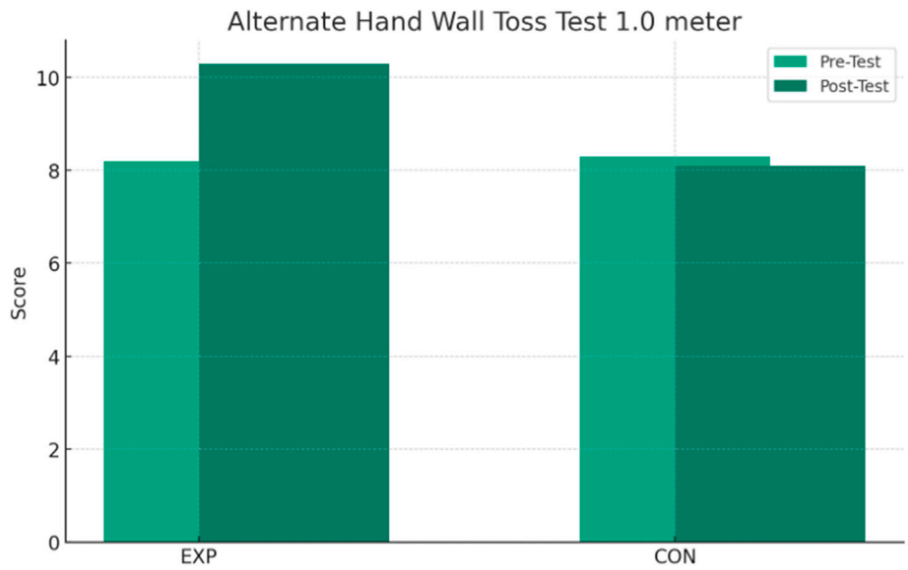

FIGURE 3
Change in results in the Alternate Hand Wall Toss Test 1.0 m over time for the EXP and CON groups.

predisposing them to musculoskeletal problems (Bauer et al., 2021; Zmyślna et al., 2021). It is important to address this issue as promoting proper flexibility at this age improves the overall efficiency of movement. Previous studies (Radulović et al., 2022; Xu et al., 2022; Kryst et al., 2023) have shown that flexibility decreases significantly between the ages of 7 and 15 (1996–2011). Subsequently, boys' scores steadily declined and reached their lowest point in the year of 2019, while the studies show that girls reached their highest observed flexibility throughout the years of 1989–2019 (Radulović et al., 2022). Studies that included flexibility-targeted interventions, such as stretching programs or specific PE curricula, have shown improvements in SAR test scores over specific time periods (Kumar and Zemková, 2022; Stamenković et al., 2022; Wang et al., 2022). The results of this study suggest that flexibility can be effectively improved through a school-based PA intervention, resulting in a notable 6.3% increase in performance SAR test. The flexibility of the children in this study increased statistically and significantly in the EXP group; however, it should be noted that the observed increase after the 16-week intervention in the supplementary program was somewhat lower than originally expected. This result can be attributed to several factors. One important factor is the role of muscle extensibility and

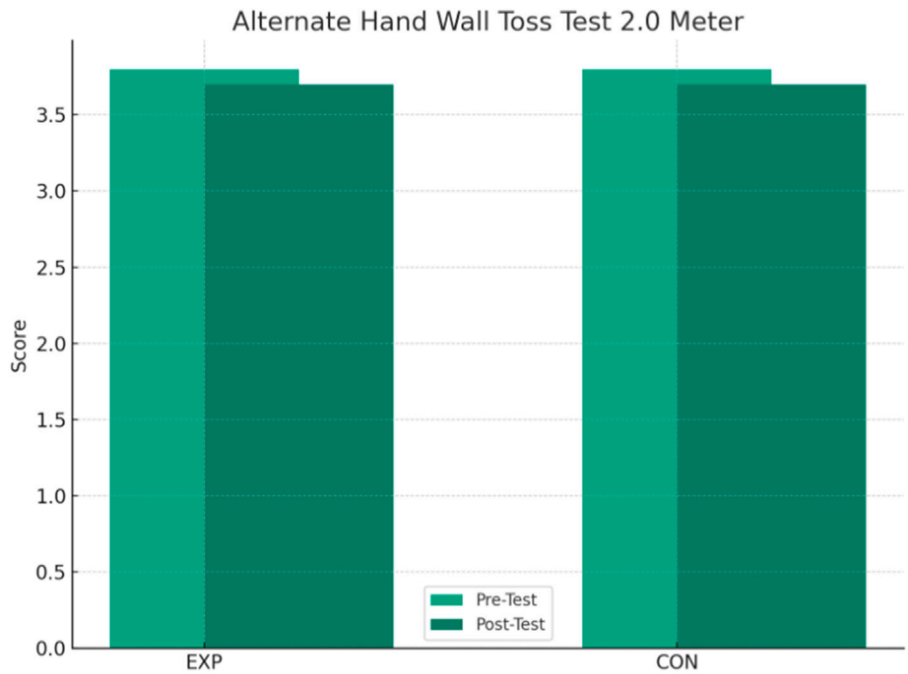

FIGURE 4
Change in results in the Alternate Hand Wall Toss Test 2.0 m over time for the EXP and CON groups.

suppleness. Both extensibility and suppleness are essential for optimal joint function and mobility. During the intervention, these muscle properties were specifically trained and improved, which contributed to improved flexibility. Advances in flexibility have been shown to reduce the risk of musculoskeletal injury by ensuring that joints can move through their full intended range without strain as proven in the study by Zvetkova et al. (2023). In addition to the two additional hours of PA in school for the EXP group, the difference in flexibility improvement between the EXP and CON group, in which the score decreased by 0.4% instead of improving, could be attributed to the nature of the program content. The program offered to the EXP group may have been more engaging and effective compared to traditional PE. As mentioned, each session was based around athletic and gymnastic exercises; however, these were conveyed through games, which could have influenced the children's motivation and consequently resulted in a higher number of repetitions.

The results of the 30-m sprint test were also similar, as the students in the EXP group improved by 6.3%, just as they did in the SAR test, while there was a slightly larger decrease in the CON group, where the students dropped in speed by 1.6%. The result was not a surprise, as a greater progress in the students who participated in the supplemental program was expected than in those who participated only in regular PE. This was predicted because improvements in speed as a PF are often influenced by the specificity of the training program, and in the EXP group, the teacher tried to adjust the activities and games in each lesson to focus on specific components of speed, such as acceleration, agility, or sprint mechanics, which led to an improvement in overall speed performance. Similar findings were obtained by Mijalković et al. (2022), who investigated school-based exercise programs to promote cardiorespiratory fitness in overweight and obese children aged 6–10 years. In their study, the implementation of structured exercise programs potentially contributed to the improvement of the participants' speed. This underscores the importance of exercise programs that are tailored to specific age groups and fitness components. Additionally, Wang et al. (2022), conducted a study that examined the effects of an 8-week neuromuscular training (NMT) method combined with regular tennis training in beginner tennis players aged 7–8 years old. In the 30-m sprint test, they recorded statistically significant differences ($p = 0.001$) in speed within the EXP group. This suggests that the combination of structured PA and potentially sensitive periods in child development may contribute to improved speed performance in this age group. However, on the other hand, Stojanović et al. (2023) compared the effects of a 16-week Teaching Games for Understanding (TGfU) volleyball intervention in students aged 13 ± 3.7 years, and also found a statistically significant improvement in speed in the 30-m sprint test ($p = 0.019$).

In this study, slightly different results were obtained when examining the effects of the intervention on hand-eye coordination development in children. The AHWT test, which was divided into two parts, AHWT 1.0 m and AHWT 2.0 m test, was used to investigate this depending on the level of difficulty. In the easier version, students stood 1 meter away from the wall during the test and statistically significant differences in hand-eye coordination development was found between the EXP and CON groups. In particular, the result of the EXP group improved by 25.6%. This result is quite high, suggesting that the participants may not have exerted much effort on the initial test, despite precise demonstration and explanation by the teacher. However, the significant gains in hand-eye coordination observed in the EXP group may indicate that the intervention program not only improved their hand-eye coordination, but also enhanced the development of their ability to handle a tennis ball with greater dexterity and precision. This multifaceted improvement underscores the potential of well-structured programs that not only target specific fitness components, but also promote related motor skills and coordination. The comprehensive impact of such interventions on the overall development of participants is a notable finding of this study. Compared to the EXP group, the CON group had poorer results, deteriorating by an average of 2.4% from the pre-test to the post-test. The more challenging version of the hand-eye coordination development test, in which all participants performed the same movements as in the first part of the test but were positioned 2 m away from the wall, resulted in significantly lower pre-test scores. Neither the EXP nor the CON group showed any improvement on the test; instead, both groups experienced a 2.6% decrease in performance. In this context, Frikha and Saad Alharbi (2023) conducted an intervention aimed at improving fine motor coordination, selective attention, and reaction time in children aged 8.29 ± 0.74 years through precision motor exercises. In the EXP group, hand-eye coordination improved significantly ($p < 0.05$). In contrast to this study, where there was no statistically significant improvement in the AHWT 2.0 test even within the EXP group after the intervention, Kahana et al. (2022) observed statistically significantly higher results ($p < 0.0001$) in children aged 10 by an intervention in which a training application was introduced (APP). Despite the potential of this study's PA intervention to improve various aspects of PFin children, the complicated nature of hand-eye coordination development might require more targeted and prolonged interventions to show remarkable improvements. In addition, individual differences in baseline hand-eye coordination skill and the complexity of the coordination process itself could contribute to the difficulty of achieving significant improvements through general PA interventions.

Although a significant improvement in PF was observed, the study acknowledges certain limitations. While the selection of participants aged 8–to 9-years ensured homogeneity within the study group, it did not consider differences in biological age that may affect physical development and performance. This is a potential limitation as biological age may differ significantly from chronological age, especially during a developmental phase. Future research could benefit from the inclusion of measures of biological maturity to better understand the effects of PA interventions. In addition, the study did not measure participants' enjoyment and satisfaction, which could influence the effectiveness of the intervention. Assessing participant engagement and enjoyment could provide valuable insights for future PA programs. Furthermore, the lack of objective accelerometer data to measure students' overall PA during the intervention period could limit the interpretation of the results. Despite these considerations, this study highlights the value of school-based PA programs, which appear to significantly improve PF in 8- to 9-year-olds compared to traditional PE, particularly in an age group where there has been a marked decline in moderate to vigorous PA.

5 Conclusion

The results of this study indicate that a 16-week school-based PA program can significantly improve speed and flexibility, or musculoskeletal fitness compared to traditional PE. In addition, hand-eye coordination was also improved as measured by the 1.0-meter AHWT test. An important finding of our research is that remarkable progress can be made in certain aspects of PF within a relatively short period of time. However, this was not true for all measures of fitness, as the 2.0-meter AHWT test showed no significant improvement. These results suggest that the development of PF in younger students can be significantly improved by introducing just two additional hours of weekly PA for some fitness components, but that this is not equally true for all aspects of PF. While the results support the integration of additional PA into the curriculum, they also highlight the need for a differentiated approach tailored to the different components of PF.

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 Faculty of Education, University of Ljubljana, Ljubljana, Slovenia. 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

TP: Conceptualization, Investigation, Methodology, Writing–original draft. DN: Conceptualization, Investigation, Writing–review and editing.

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

The reviewer NT declared a past co-authorship with the author TP to the handling editor.

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Relationships of lower extremity and trunk asymmetries in elite soccer players

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In light of previous research highlighting the prevalence of asymmetries in soccer players and possible links to injury risks, there is a crucial gap in the biomechanical understanding of complex relationships between lower extremity and trunk asymmetries in elite soccer players. The purpose of this study was to investigate the level, relationships, and differences among twelve different parameters of strength, morphological, and neuromuscular asymmetries in elite soccer players.

Methods: Elite male soccer players (n = 25, age 21.7 ± 3.9 years) were tested in the following tests: bilateral fluid distribution, hip flexor range of motion, postural stability, isokinetic strength of knee extensors and flexors, isometric lateral trunk rotation strength, eccentric strength of knee flexors, isometric bilateral strength of hip adductors, and vertical ground reaction force in counter-movement jump-free arms, counter-movement jump, squat jump, and drop jump tests. One-way ANOVA, Pearson's coefficient (r), and partial eta squared (η_p^2) were used for data analysis.

Results: Significant differences in asymmetries were found in elite soccer players ($F_{11,299}$ = 11.01, p < .01). The magnitude of asymmetry over 10% was in postural stability and drop jump parameters. The lowest magnitudes of asymmetries were in the fluid distribution of the lower limbs and the vertical ground reaction force during the take-off phase in squat jumps. The highest asymmetries between the dominant and non-dominant sides were found in postural stability and drop jump. A total of eleven significant correlations (p < 0.05, r = 0.41–0.63, R^2 = 0.17–0.40) were detected between the analyzed asymmetries in elite soccer players. The lateral trunk rotation asymmetries were significantly correlated to vertical ground reaction force asymmetries and knee extensors.

Conclusion: Long-term exposure in elite soccer leads to unilateral biomechanical loading that induces abnormal strength and morphological adaptations in favor of the dominant side while linking lower limb and trunk strength asymmetries. By unraveling these complex relationships, we strive to contribute novel methods that could inform targeted training regimens and injury prevention strategies in the elite soccer community. The data should encourage future researchers and coaches to monitor and develop trunk strength linked to lower body kinematics.

KEYWORDS

strength, power, performance, football, injury prevention, isokinetic, isometric

1 Introduction

In elite soccer, the interaction between lower limb and trunk strength is crucial for the intricate demands of kicking (Carvalho et al., 2021), running, and rapid changes in movement direction (Hodges and Richardson, 1997; Hedrick, 2000; Liebenson, 2010; Nagahara et al., 2018; Niewiadomy et al., 2021). Santana (2003) mentioned that the diagonal pre-stretch in the trunk's ventral musculature, also known as the "serape effect," optimizes force production by providing the core muscles with an optimal length-tension environment. This mechanism is an excellent way to produce force between the shoulder and the opposite hip (Santana, 2003). The majority of soccer players have a preferential or dominant lower limb to carry out repetitive unilateral movements, such as kicking a ball or changing directions (Carey et al., 2001). When unilateral load is involved in sport-specific movement, the limb becomes preferred by neural-motor patterns, resulting in different morphological and strength asymmetries (SAs) (Maly et al., 2019). Studies suggest that genetic factors, such as the LRRTM1 and protocadherin11X/Y gene pair, not only play a role in handedness but also acknowledge the influence of accidental variation, developmental instability, and early fetal development (Annett, 1978; Yeo and Gangestad, 1993; Francks et al., 2007; Crow et al., 2009). Asymmetries may result in significant changes in the myodynamic characteristics of the muscle, particularly in the dominant leg (Fousekis et al., 2010a). According to Iga et al. (2009), soccer players rarely use both limbs with the same emphasis, and this preference is related to hemispheric brain dominance. As the specific adaptation to imposed demands (SAID) principle dictates, this creates a functional asymmetry (FA) as the limbs respond to their respective roles of force generation during movement (Barbieri et al., 2015), balance (Gstottner et al., 2009; King and Wang, 2017), and morphology (Mala et al., 2023). These functional asymmetries between limbs (BLAs) fluctuate due to the demands of the environment (Maloney, 2019). They can manifest in aspects ranging from gait mechanics to the change of direction differences (Nicholson et al., 2022). However, the largest BLA in soccer has been reported in lower limb strength (Nicholson et al., 2022), with this being affected by long-standing participation in soccer (Fousekis et al., 2010b; Maloney, 2019; Maly et al., 2021). Côté et al. (2007) reported that elite players achieved more hours in specific football training during childhood and adolescence compared to those who did not achieve professional status. Long-term and highly specific physical activity (especially with more frequent use of the dominant lower limb compared to the non-dominant) may give athletes an incentive to reproduce functional and morphological asymmetries (Fousekis et al., 2010c). Hanimann et al. (2023) compared the asymmetry in knee valgus (medial knee displacement during drop jump) and core stability (displacement during dead bug bridging exercise) in high-level soccer and alpine skiers athletes. The study reported a similar magnitude of asymmetries in athletes, but the effect on the direction of laterality was different, which means differences in sport-specific demands. The most predominately measured BLA has been knee extensor and flexor muscles (Fousekis et al., 2010a; Menzel et al., 2013; Nicholson et al., 2022) and ground reaction force or heights attained during jump testing (Menzel et al., 2013; Arundale et al., 2020; Read et al., 2021). Asymmetry evaluation in elite soccer has also expanded to eccentric hamstring strength (Bishop et al., 2022a), trunk strength (Kubo et al., 2010), hip strength (Ocarino et al., 2021), and hip range of motion (Ocarino et al., 2021). The reason for this expansive search for SA in soccer players is due to its link to performance deficit (Read et al., 2021), decreased soccer-specific skills (Maly et al., 2018), or increased injury risk (Mala et al., 2020; Markovic et al., 2020; Helme et al., 2021). However, no consensus exists on these effects (Bishop et al., 2022a). This may be because asymmetries are usually analyzed in isolation despite BLA adaptations occurring throughout the lower limbs of elite soccer players in response to long-term sports participation (Fousekis et al., 2010b; Maly et al., 2021). Given the significant role that the trunk plays in energy transfer in soccer, revealing the mechanical strategies and kinematics between the lower limbs, hips, and trunk during kicking and running, the available data on trunk rotational strength in elite soccer players and its correlation with lower limb strength is incomplete. In particular, the effects of unilateral loading and asymmetry on optimal trunk performance require further investigation. However, addressing these gaps in knowledge will be critical to improving athletic performance and reducing the risk of injury. Thus, a novel approach to this problem would be to analyze the relationship between different morphological, neuromuscular, strength, and power asymmetries of lower limbs and trunk muscles. The purpose of the study was to investigate the level, relationships, and differences between twelve different parameters of strength, morphological, and neuromuscular asymmetries in elite soccer players.

2 Materials and methods

2.1 Study design

A cross-sectional design was used in this investigation. The study overview was explained before testing, and signed informed consent was collected from all players. The study was approved by the Ethical Committee of the Faculty of Physical Education and Sport, Charles University, under approval no. 107/2021. The ethical document preparation and measurement taking were completed in accordance with the ethical standards of the Declaration of Helsinki and the ethical standards in sport and exercise science research (Harriss et al., 2017).

TABLE 1 Brief overview of weekly training/match in-season period in relation to a match day.

Day	Field-based training	Gym training	Match (min)
MD + 1	Recovery[a], top-up (60 min)[b]	30 min[a,b]	
MD - 2	60 min		
MD - 1	60 min		
MD		20 min[c]	90
MD + 1	Recovery[a], top-up (60 min)[b]	30 min[a,b]	
MD - 1	60 min		
MD		20 min[c]	90

MD, match day.
[a]Recovery and gym session for players who played for more than 45 min.
[b]Field-based session includes players who either did not appear in line-up or played less than 45 min.
[c]Prime pre-match session with the aim to use the post-activation potentiation effect.

2.2 Participants

Elite male soccer players from the highest division of the Czech Republic (n = 25, age 21.7 ± 3.9 years) volunteered to participate in the study. The majority of the players were recent members of their national teams. The playing positions of the players were as follows: goalkeepers (n = 4), fullbacks/wingbacks (n = 5), central backs (n = 4), midfielders (n = 5), wingers (n = 4), and attackers (n = 3). In total, 19 players were classified as right-footed and 6 players as left-footed. The average years of football training experience of the players was 15.4 ± 3.9 years. The typical weekly training/match frequency in-season is shown in Table 1. Inclusion criteria included the following: 90% of training and competition availability for the last 2 months prior to measurement; free from any musculoskeletal injuries or medical conditions that may significantly affect physical performance. Exclusion criteria included the following: high resistance or strenuous training performance within the last 48 h that may affect the maximal physical performance and strength asymmetry manifestation; recent history of lower limb or trunk injury within the last 6 months to minimize the potential for injury-related strength asymmetries; and any knee surgery in their entire playing career that may cause increased strength asymmetry.

2.3 Data collection

Measurements were taken before the beginning of the regular season 2022/2023 in the morning from 9:00 to 11:30 a.m. The players were not exposed to any exhausting physical load 2 days before testing.

2.3.1 Anthropometric data

Body height was measured using a digital stadiometer (SECA 242, Hamburg, Germany), and body mass was measured using a digital scale (SECA 769, Hamburg, Germany).

2.3.2 Morphological asymmetries

The bilateral fluid distribution in the lower limbs (MA_FD) was assessed using a multi-frequency bio-impedance analyzer (MC-980MA; Tanita Corporation, Tokyo, Japan). MA_FD was calculated as a percentage difference between the dominant vs non-dominant limb. Dominancy was assessed by determining which limb was preferred by the participant to kick a ball (Maly et al., 2019). To ensure consistency for bio-impedance measurements (Kyle et al., 2004), the procedure was conducted in the morning from 9:00 to 11:30 when the participants had not been exposed to various foods and hydration during lunchtime. This approach accounts for the potential limitations of three-frequency analyzers, such as the presence of material in the human body and hydration level, which may influence the measurements (Cridlig, 2013).

2.3.3 Range of motion

Range of motion in hip flexion (HIPS_ROM) was performed as previously described by Cameron and Bohanon (1993). It was an active straight leg raise test. The examiner fixed the contralateral leg in place while the player raised their leg as far as possible. HIPS_ROM was measured by using a VALD DYNAMO goniometer (Vald Performance, Queensland, Australia), which was positioned and fixated on the outer femur.

2.3.4 Neuromuscular asymmetry

Neuromuscular asymmetry was tested by the multi-sensory FOOTSCAN platform (RS scan; Belgium; 0.5 m × 0.4 m; approximately 4,100 sensors; sensitivity from 0.1 of $N.cm^{-2}$; sampling frequency 500 Hz) during posturographic examination. Postural stability (PS_COP) was tested by single leg stance (flamingo stance). The total distance of the center of pressure excursion was recorded for 60 s for each leg, while the non-standing leg was in a semi-flexed knee position, as previously described (Marencakova et al., 2018).

2.3.5 Isokinetic strength of knee extensors and flexors

The isokinetic peak torque of knee extensors and flexors was measured in concentric muscle contraction at $60^{\circ}\cdot s^{-1}$ using the Cybex Humac Norm isokinetic dynamometer (Cybex NORM ®, Humac, CA, United States). There was high reliability of peak muscle torque in isokinetic testing on Cybex Humac Norm for knee extensors (ICC = 0.98, 95% CI = 0.95–0.99) and flexors (ICC = 0.95, 95% CI = 0.88–0.98) (Impellizzeri et al., 2008). The testing protocol consisted of three attempts, with the maximal effort during knee flexion and

FIGURE 1
Maximal voluntary contraction test of trunk rotational strength using the isometric mode of the Humac NORM dynamometer with trunk modular and wheel components (CSMi, Stoughton, MA, United States).

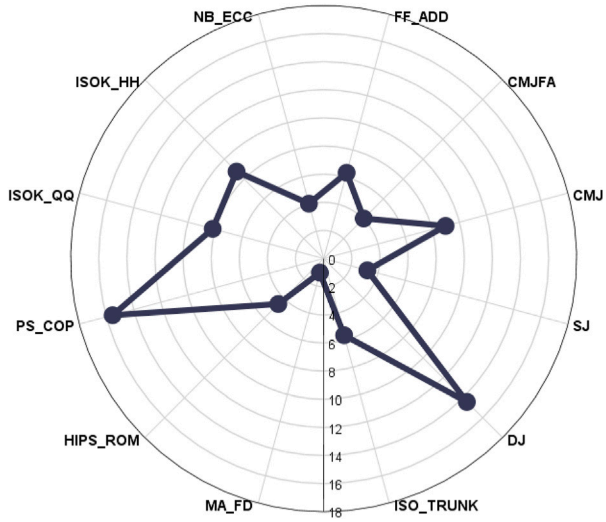

FIGURE 2
Level of asymmetries in the measured parameters. Data are expressed in relative values (%). MA_FR, morphological asymmetries; HIPS_ROM, range of motion asymmetries; PS_COP, neuromuscular asymmetry; ISOK_QQ, isokinetic strength of knee extensors; ISOK_HH, isokinetic strength of knee flexors; NB_ECC, eccentric strength of knee flexors; FD_ADD, isometric strength of hip adductors; CMJFA, vertical ground reaction force asymmetry in counter-movement jump with arms; CMJ, vertical ground reaction force asymmetry in counter-movement jump; SJ, vertical ground reaction force asymmetry in squat jump; and DJ, vertical ground reaction force asymmetry in the drop jump test.

extension. The bilateral ratio of knee extensors (ISOK_QQ) and flexors (ISOK_HH) was expressed as the percentage differences of peak torques between the legs. The torque was gravity-corrected, and dynamometer calibration was performed in accordance with the manufacturer's instructions. After five submaximal warm-up repetitions, the participants performed three repetitions with maximum effort. Visual feedback and verbal stimulation were provided during the testing.

2.3.6 Isometric lateral trunk rotation strength

The isokinetic dynamometer device was also used for the isometric lateral trunk rotation strength (ISO_TRUNK) test. The maximal voluntary contraction (MVC) of ISO_TRUNK measures was obtained with an additional Trunk Modular Component (CSMi, Stoughton, MA, United States) and the Humac NORM wheel attachment (CSMi, Stoughton, MA, United States). The peak force of MVC was represented in kilograms (kg) by the manufacturer and, consequently, in the percentage of individual body weight (%BW), which was used for further analysis. Before testing, a standardized warm-up of three sets of 10-s planks, three sets of six repetitions (each side) of the bird–dog exercise, and three sets of 5-s (each side) Pallof press with a band was performed. For testing, players were in a vertical position, standing straight, and secured above and under their knees with stabilizing pads to prevent leg movement and allow maximal efforts during rotational movement. The height of the trunk modular component was set to individual positions until the dynamometer attachment reached the celiac plexus. Both hands held the Humac NORM wheel attachment at shoulder height while the shoulders were retracted with arms straight (elbow bending during setup and testing was not allowed). Depending on the side of rotation, the hand closer to the dynamometer was always on top (Figure 1). Prior to maximal effort, players were instructed to perform two submaximal 3-s trials at a level between 50% and 70% of their individual MVC with a 10-s rest in between due to familiarization. The testing protocol consisted of four trials of 3 s of rotational full-body pulls with a 30-s rest between trials. The test was performed for the dominant and non-dominant sides. Intra-rater reliability was calculated before data analysis by intra-class correlation coefficient (ICC = 0.979) with the standard error of measurement = 3.07 (%SEM = 13.38%) and the smallest detectable change = 4.86 (SDC% = 21.17%). This reliability refers to the consistency of the data recorded by one rater over several trials and is best determined when multiple trials are administered over a short period of time (Scheel et al., 2018).

2.3.7 Eccentric strength of knee flexors

Eccentric peak force in newton of knee flexors (NB_ECC) was tested on the NordBord device (Vald Performance, Queensland, Australia) in a kneeling position at a sampling frequency of 50 Hz. High test–retest correlations of eccentric peak force (left leg: r = 0.906, CI = 0.798–0.962; right leg: r = 0.792, CI = 0.571–0.924) on NordBord devices in elite football players were reported by Rhodes et al. (2022). Per the protocol described by Drury et al. (2020), players kneeled on the board with their ankles fixed by an individual hook for each leg (uniaxial load cell), hips fully extended, and arms across the chest. Players were instructed to move forward and lower their upper body with the slowest possible speed to achieve their maximal prone position until failure. A single set of three repetitions was performed with 30-s rest between each repetition.

2.3.8 Isometric strength of hip adductors

The isometric bilateral peak force in newton of hip adductors (FF_ADD) was tested on the ForceFrame Strength Testing System device (Vald Performance, Queensland, Australia) at a sampling frequency of 400 Hz. Ryan et al. (2019) reported a high test–retest reliability of GroinBar adductor strength testing using the Vald Performance system in professional Australian footballers (ICC = 0.87–0.96, %CV = 6.3, and %SWC = 5.0). The players were in a lying supine position with knees flexed at 45°. They performed three maximal voluntary isometric contractions (5 s) when they pushed their knees into the sensors (load cells), which were placed on the medial malleoli femoral condyles, followed by a minimum of 10 s of rest between trials (Desmyttre et al., 2019). Excellent reliability and minimal detectable change were reported in previous studies (Desmyttre et al., 2019).

2.3.9 Vertical ground reaction force in jumps

Force differences in power assessment (vertical jump test) were examined by two Kistler 8611 force plates (Kistler Group, Winterthur, Switzerland) at a sampling frequency of 1,000 Hz and using software (BioWare 5.4.3.0, Winterthur, Switzerland). Hori et al. (2009) reported the following coefficient of reliability for the Kistler force plate: peak force: ICC = 0.92, peak velocity: ICC = 0.98, and peak power: ICC = 0.98. The peak vertical ground reaction forces (VGRFs) in newton exerted under each foot separately were examined during the take-off phase of four different jump tasks: counter-movement jump-free arms (CMJFA), counter-movement jump (CMJ), squat jump (SJ), and drop jump (DJ). Based on the height of each jump type, the best of three attempts was selected for data processing.

2.4 Data processing

Descriptive statistics were calculated for all variables (mean, standard deviation, 95% confidence interval, and range). The normality of the data distribution was verified using the Shapiro–Wilk test. Research data were processed using a one-way ANOVA followed by multiple comparisons of Bonferroni's *post hoc* tests. Pearson's coefficient (r) and coefficient of determination (R^2) were used to examine the relationships between the investigated variables. Statistical significance was set at $p < 0.05$. Partial eta squared (η_p^2) was also calculated, and effect sizes were estimated as follows: between ≥0.01 and <0.06—small, between ≥0.06 and <0.14—medium, and ≥0.14—large (Richardson, 2011). Statistical analysis was carried out using IBM® SPSS® v21 (Statistical Package for Social Science, Inc., Chicago, IL, 2012).

3 Results

3.1 Magnitude of asymmetries

Significant differences of asymmetries were found in elite soccer players ($F_{11,299} = 11.01$, $p < 0.01$). While the highest level of asymmetries between the dominant and non-dominant sides were found in PS_COP (15.54% ± 9.76%, CI95 = 11.51–19.57%) and DJ (14.40% ± 13.00%, CI95 = 9.04–19.77%), the lowest asymmetries were in fluid distribution of lower limbs, MA_FD (1.03% ± 1.15%, CI95 = 0.50–1.50%), and in the SJ test, where VGRF difference during the take-off phase was 3.22% ± 0.91% (CI95 = 2.02–4.42%; Figure 2). *Post hoc* analysis revealed significant differences between the variables (Table 2). The magnitudes of measured asymmetries between ISOK_QQ, ISOK_HH, NB_ECC, and FF_ADD were insignificant ($p > 0.05$). The VGRF difference between SJ and DJ was significant (3.22% ± 2.91% vs 14.41% ± 13.00%).

3.2 Correlations between asymmetries

Eleven significant correlations ($p < 0.05$, r = 0.41–0.63, R^2 = 0.17–0.40; Table 3) were detected between the examined asymmetries in elite soccer players. The highest relationships were revealed between CMJFA vs. CMJ (r = 0.63, R^2 = 0.40, d = moderate), MA_FD vs. ISOK_HH (r = 0.61, R^2 = 0.37, d = moderate), CMJ vs. DJ (r = 0.58, R^2 = 0.34, d = moderate), and ISO_TRUNK vs. DJ (r = 0.56, R^2 = 0.31, d = moderate). HIPS_ROM and PS_COP showed no relationship with any other parameter ($p > 0.05$).

4 Discussion

Eleven out of a total of sixty six analyzed relationships were significantly correlated in a group of elite players. Those most strongly related to each other were the jump tests. The counter-movement jump has been analyzed extensively in the literature, with results indicating a typical asymmetry in vertical ground reaction force of 0.9%–7.0% (Menzel et al., 2013; Yanci and Camara, 2016; Nicholson et al., 2022). Asymmetries as low as 5% in CMJ testing have been found to be associated with decreased physical performance during sports tasks (Bishop et al., 2021). Our results found 5.6%–7.1% asymmetries in our two CMJ movements. This indicates that there is still room for elite soccer players to improve this asymmetry. The drop jump has been analyzed previously but without vertical ground reaction force (Arundale et al., 2020). The results presented here show a moderate correlation between all jump tests, except between SJ and DJ. Since these jumps represent different measures of the stretch-shortening cycle, it is interesting to find that the test of the fastest reaction (slowest possible ground time-contact control in drop jump) had the largest SA of the jump tests (14.41% on average). Given that 10%–15% is often used as a cut-off for jump asymmetry assessment (Menzel, et al., 2013), elite players may still require an intervention to limit potential performance deficits and reduce injury risk. Moreover, high-level reactive jump training, with a focus on balanced load (force)

TABLE 2 Levels and differences between asymmetries (the letter in *post hoc* means a significant difference with the variable in the same row).

Variable	Mean ± SD	95% CI	Range	*Post hoc*
MA_FD[a]	1.03 ± 1.15	0.56–1.50	3.64	c, d, e, h, k
HIPS_ROM[b]	4.56 ± 3.41	3.15–5.97	11.90	c, k
PS_COP[c]	15.54 ± 9.76	11.51–19.57	37.68	a, b, d, e, f, g, h, i, j, l
ISOK_QQ[d]	8.17 ± 7.24	5.18–11.16	26.60	a, c
ISOK_HH[e]	8.76 ± 6.29	6.16–11.36	22.90	a, c
NB_ECC[f]	4.04 ± 4.89	2.03–6.07	23.88	c, k
FF_ADD[g]	6.32 ± 4.56	4.44–8.20	16.15	c, k
CMJFA[h]	4.03 ± 3.35	2.65–5.41	11.82	c, k
CMJ[i]	8.98 ± 8.83	5.33–12.63	33.20	a, c
SJ[j]	3.22 ± 2.91	2.02–4.42	13.84	c, k
DJ[k]	14.41 ± 13.00	9.04–19.77	46.20	a, b, f, g, h, j, l
ISO_TRUNK[l]	5.64 ± 3.64	4.14–7.14	14.00	c, k

MA_FD, morphological asymmetries; HIPS_ROM, range of motion asymmetries; PS_COP, neuromuscular asymmetry; ISOK_QQ, isokinetic strength of knee extensors; ISOK_HH, isokinetic strength of knee flexors; NB_ECC, eccentric strength of knee flexors; FD_ADD, isometric strength of hip adductors; CMJFA, vertical ground reaction force asymmetry in counter-movement jump with arms; CMJ, vertical ground reaction force asymmetry in counter-movement jump; SJ, vertical ground reaction force asymmetry in squat jump; DJ, vertical ground reaction force asymmetry in the drop jump test; SD, standard deviation; CI, confidence interval.

production, may be required to reduce the large asymmetry in the DJ.

Lower-limb muscle strength values were below 10% (except VGRF in DJ), which is generally accepted as a "low asymmetry." This is in line with more recent research (Lutz et al., 2022), as elite male soccer players have benefitted from the intervention programs implemented to reduce asymmetries, as indicated by previous studies (Tyler et al., 2001; Fousekis et al., 2010a). On the other hand, we need to pay attention to individual player strength and asymmetric profile instead of group mean assessment because large inter-individual values were found (Table 2). Constant loading of one side of the body over time (passing, shooting, ball dribbling, and specific movement patterns) may lead to strength asymmetry and imbalances in tissue adaptation. Among the strength asymmetry variables, it is interesting to note that the relationship between the NordBord eccentric hamstring strength and the isokinetic concentric hamstring strength was only moderate ($r = 0.407$). A similar correlation ($r = 0.35$) between eccentric strength in "Nordic hamstring curls" (NordBord device) and the isokinetic test in professional soccer players ($n = 306$) has been reported by van Dyk et al. (2018). This reinforces the point that both concentric and eccentric hamstring strength should be tested in elite soccer players as their asymmetries cannot be interchanged. Another key aspect was that eccentric strength on the NordBord device was tested bilaterally in the closed kinetic chain, while testing on isokinetic dynamometry was performed unilaterally in the open kinetic chain and concentric muscle contraction. Different lower limb muscle asymmetries were associated with different jump tests. Adductor asymmetry was significantly correlated to SJ, which may be because the reduced movement of the hips requires more adductor input into the jumping movement (Yoshioka et al., 2011). The quadriceps asymmetry was significantly correlated to DJ, with this test requiring the most elastic energy activity from the quadriceps (Peng et al., 2011). Connected to both of these variables is the isometric trunk-rotation strength, which was moderately correlated to both asymmetries. This represents an interconnection between the asymmetry of the trunk, quadriceps, and DJ. This indicates a multifaceted approach and adaptations to reactive jumping in elite soccer players (Hammami et al., 2019). This is a novel relationship that has not been identified previously. This result can be used in designing strengthening programs by practitioners, especially when ISO_TRUNK rotation strength testing was just one of the tests that were performed in the transverse plane. Strength testing of players in the transverse plane may be beneficial for players and practitioners as soccer players move their whole-body segments to produce and transfer mechanical energy in all three planes during soccer movements. It has been reported that trunk–pelvic motion in the transverse plane is related to sports performance in soccer (Fonseca et al., 2011), but research has also shown asymmetry in the trunk–pelvic stabilization in the transverse plane in soccer players regardless of limb dominancy or field position (Santos et al., 2014).

Hamstring strength asymmetry (ISOK_HH) was significantly correlated with fluid distribution in lower limbs (morphological asymmetry). This can be explained through biomechanical and physiological considerations. If one lower limb exhibits greater strength repetitively, it may affect muscle activation during movement (Mertz et al., 2019). Fluid asymmetry, often observed as interstitial fluid distribution changes, may be a consequence of altered biomechanics and load repetition (Pereira and Shefelbine, 2014). The muscles play a role in the lymphatic system's function, which helps regulate fluid balance (Muthuchamy and Zawieja, 2008). Asymmetric muscle forces may impact this system, potentially leading to fluid asymmetry in the affected limb. Moreover, hamstring strength asymmetry can influence joint mechanics and increase the risk of injuries

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TABLE 3 Relationships between morphological, strength, and neuromuscular asymmetries.

	MA_FD	HIPS_ROM	PS_COP	ISOK_QQ	ISOK_HH	NB_ECC	FF_ADD	CMJFA	CMJ	SJ	DJ	ISO_TRUNK
MA_FD	**1**											
HIPS_ROM	−.11	**1**										
PS_COP	−.18	.34	**1**									
ISOK_QQ	.08	−.17	−.26	**1**								
ISOK_HH	**.61****	−.26	−.08	−.12	**1**							
NB_ECC	.31	−.24	.04	.02	**.41***	**1**						
FF_ADD	.29	−.09	−.08	−.32	.08	−.13	**1**					
CMJFA	−.01	−.08	.06	.24	.14	.13	−.11	**1**				
CMJ	−.19	−.10	.15	.16	−.07	−.08	−.21	**.63****	**1**			
SJ	−.01	.03	.17	.30	.19	.07	**−.48***	**.45***	**.51****	**1**		
DJ	−.01	−.18	.06	**.42***	−.16	−.18	−.12	**.44***	**.58****	.20	**1**	
ISO_TRUNK	.33	−.13	−.10	**.43***	.00	.09	.11	.36	.28	.33	**.56****	**1**

MA_FD, morphological asymmetries; HIPS_ROM, range of motion asymmetries; PS_COP, neuromuscular asymmetry; ISOK_QQ, isokinetic strength of knee extensors; ISOK_HH, isokinetic strength of knee flexors; NB_ECC, eccentric strength of knee flexors; FD_ADD, isometric strength of hip adductors; CMJFA, vertical ground reaction force asymmetry in counter-movement jump with arms; CMJ, vertical ground reaction force asymmetry in counter-movement jump; SJ, vertical ground reaction force asymmetry in squat jump; DJ, vertical ground reaction force asymmetry in the drop jump test.

(Fousekis et al., 2010c; Koźlenia et al., 2022; Oleksy et al., 2023), which may further contribute to fluid asymmetry. It is crucial to consider the interconnected nature of the musculoskeletal and fluid systems, recognizing that alterations in muscle strength and function can have cascading effects on fluid dynamics within the body. Additional research is needed to provide a more comprehensive understanding of this link. Postural stability had the largest asymmetry in elite soccer players, a parameter that remains highly asymmetrical (Chaari et al., 2022). Surprisingly, it was not significantly correlated to adductor asymmetry in our results, as previous research has linked groin injury to postural stability asymmetry (Chaari et al., 2022). This may be due to the difference in testing and measures attained between the studies. Like postural stability asymmetry, HIPS_ROM asymmetry was not significantly correlated to any other parameter, even though it is important for kicking a ball (Barbieri et al., 2015). These results indicate that other aspects also play a role instead of just the muscle strength and force generation of the lower limbs, such as flexibility in ROM and visuospatial systems in balance performance (Ocarino et al., 2021; Zemková and Zapletalová, 2022). Studies suggest that integrating the action/motor preference framework can enhance the precision of tailored training programs in soccer by analyzing top players' motor skills (Castañer et al., 2017), improving various aspects of performance (Slimani et al. 2016; Lee et al., 2020), and helping coaches monitor young players' progress (Raiola and Altavilla, 2020). Examining players' motor preferences and their alignment with hemispheric brain dominance, as suggested by Serrien and Sovijärvi-Spapé (2015), may provide an understanding of the observed asymmetries. Integrating the action/motor preference framework into the analysis could enhance the precision of tailored training programs, considering individual variations in motor dominance within the context of soccer performance.

While this research highlights significant correlations between lower limb and trunk strength in elite soccer players, it is crucial to recognize that these associations do not inherently imply a causal relationship. Factors such as training methodologies, individual biomechanics, and other confounding variables may contribute to the observed correlations. Another limitation is that the results cannot be generalized to amateur, youth, or female players, all of whom present with even higher percentages of asymmetries (Arundale et al., 2020; Maly et al., 2021; Bishop et al., 2022b), as we focused only on male elite soccer players. Future research will benefit from a larger sample size ($n > 25$) to generalize the conclusions to a broader population of elite soccer players. Additionally, future research may consider, where possible, other contextual factors, such as participants' injury history, which could also influence the strength or morphological asymmetries. The influence of lower-limb asymmetry linked to trunk strength on high-level soccer training may vary based on the specific positions of the players. Different player positions demand distinct physical attributes, movement patterns, and performance requirements (Arjol-Serrano et al., 2021). We recommend analyzing player position differences in future research, as it may reveal more detailed information to tailor training interventions. In future analysis, we encourage carefully considering these complexities, acknowledging that establishing causation requires further investigation through controlled experiments or longitudinal studies. Maintaining a functional 'baseline' asymmetry and its impacts should be the focus of future research, as the statement highlights the complexity of the relationship between reducing asymmetry below a certain threshold, such as 10%, and a decrease in injury risk. Objective evaluations must be used to identify any abnormalities, as it is recognized that some degree of asymmetry may be inherent and natural for soccer players, while an increasing number may exhibit abnormalities. Reducing something may not necessarily result in injury prevention, as current scientific evidence is not in agreement with the baselines. However, the majority of research on elite soccer players suggests that strength asymmetries can impact performance, particularly in short sprints and dynamic tasks, and increase the risk of injury, especially hamstring strains and muscular imbalances (Lehance et al., 2008; Fousekis et al., 2010a; Sannicandro et al., 2011; Bishop et al., 2021; Ascenzi et al., 2022; Stella et al., 2022).

5 Conclusion

The magnitude of asymmetries in elite soccer players varied by each parameter, from lower than 5% (MA_FD, HIPS_ROM, NB_ECC, CMJFA, SJ), asymmetries from 5% to 10% (ISOK_QQ, ISOK_HH, FF_ADD, CMJ, ISO_TRUNK), and those over 10% (PS_COP, DJ). The players with long lengths of exposure to soccer practice may develop asymmetry in different body segments. Morphological asymmetries were linked with knee flexor asymmetries (ISOK_HH). The novelty of this study was that lateral trunk-rotation asymmetries (ISO_TRUNK) were significantly correlated to VGRF asymmetries in power assessment (DJ) and knee extensors in elite soccer players. The results indicate that unilateral lower-limb load and its power characteristics at the elite soccer level may influence the development of abnormal strength and morphological adaptations in favor of the dominant side and also in the strength parameters of the trunk. Higher attention should be paid to players who had higher asymmetries (>10%) and those who suffer from hamstring and adductors muscle group based on individual assessment. Clinicians and conditioning practitioners should be aware of monitoring whole-body strength throughout the season and intentionally intervene in abnormalities.

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 Ethical Committee of the Faculty of Physical Education and Sport, Charles University, Prague. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

TM: conceptualization, funding acquisition, investigation, methodology, supervision, and writing–original draft. MH: data curation, software, validation, and writing–original draft. FV: formal analysis, investigation, and writing–original draft. CC: conceptualization, data curation, investigation, supervision, and writing–original draft. KP: data curation, formal analysis, methodology, software, visualization, and writing–review and editing. FZ: funding acquisition, project administration, resources, supervision, and writing–review and editing. LM: data curation, investigation, validation, and writing–review and editing. KF: supervision and writing–review and editing.

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Conflict of interest

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

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The effect of plyometric training and moderating variables on stretch-shortening cycle function and physical qualities in female post peak height velocity volleyball players

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Purpose: Although several studies investigated the effect of plyometric training on physical performance, there is a lack of clarity regarding the effectiveness of plyometric training or its moderator variables in youth female volleyball players. The primary aim of this study was to explore the effect of horizontal plyometric training on explosive stretch-shortening cycle hops and jumps in the vertical and horizontal directions in female post peak height velocity (PHV) volleyball players. The secondary aim was to assess the influence of participant and training related moderators on horizontal plyometric training in post-PHV volleyball players.

Methods: A total of 23 post-PHV volleyball players participated in this 8-week intervention with horizontal plyometric exercises, twice a week. Pre-testing and post-testing included bilateral and unilateral vertical sub-maximal hopping, horizontal jumping and hopping, and a drop jump test. The effectiveness of the intervention was assessed using a paired *t*-test. The influence of internal moderators such as age, maturity and body mass and external moderators such as training volume were assessed using regression and correlation analysis.

Results: An 8-week plyometric training improved sub-maximal hopping at 2.5 Hz left by 4.4%, bilateral sub-maximal hopping at 2.0 Hz by 9.5% and bilateral sub-maximal hopping at 2.2 Hz by 6.8% in post-PHV female volleyball players. Horizontal jumping and hopping, reactive strength index and other sub-maximal hopping conditions did not improve significantly. Body mass had a large moderating effect on vertical unilateral sub-maximal hopping at 2.5 Hz right (p = 0.010, η^2 = 0.314), vertical unilateral hopping at 3.0 Hz right (p = 0.035, η^2 = 0.170), and vertical unilateral hopping at 3.0 Hz left (p = 0.043, η^2 = 0.203). Training volume together with generalized joint hypermobility moderated right leg triple broad hop performance, whereas maturity and age did not moderate any variables.

Conclusion: This study determined that 8 weeks of horizontal plyometric training can improve unilateral absolute leg stiffness in post-PHV female volleyball players, and this training effect can be moderated by body mass. Furthermore, the training effect on triple hopping performance on the right leg can be moderated by combined training volume with generalized joint hypermobility.

KEYWORDS

girls, stiffness, maturation, plyometric exercises, reactive strength index, youth sport

1 Introduction

The stretch-shortening cycle (SSC) involves the coupling of a stretch action and rapid shortening action, divided by a very brief pause (Pedley et al., 2020). The stretch action primarily involves an eccentric muscle action and lengthening of the tendon in series, whereas the shortening action primarily involves a concentric muscle action and a shortening of the tendon in series (Turner and Jeffreys, 2010). The SSC plays an important role in jumping ability (Kums et al., 2005; Idrizovic et al., 2018), which is a fundamental component for offensive and defensive actions in volleyball (Giustino et al., 2022). These actions require a high level of explosive ability to successfully execute these jumps within the context of a match (Lehnert et al., 2017). Jumping high and jumping quickly are relevant skills to develop in volleyball players (Fatthi and Sadeghi, 2014; Rojano-Ortega et al., 2021), both during which effective SSC function encourages more efficient yielding and propulsive phases (Idrizovic et al., 2018; Carrasco-López et al., 2019). Plyometric training can be used to improve force and power output by improving SSC function (Kums et al., 2005; Carrasco-López et al., 2019). Effective SSC function optimizes elastic energy storage and return, increases stretch-reflex contribution, and increases neuromuscular recruitment and activation (Turner and Jeffreys, 2010; Radnor et al., 2017). These potentiating mechanisms thus lead to improved control and coordination of the yielding phase, reduced metabolic cost of movement, enhanced propulsive force, and greater force at a given velocity during the propulsive phase (Flanagan and Comyns, 2008; Turner and Jeffreys, 2010).

SSC function is governed by the effective interaction between neural, muscular and muscle-tendon structural factors (Radnor et al., 2017). The development of neural factors consists of improved recruitment and activation in the agonist muscles, improved stretch reflex function, and improved intermuscular coordination (Lambertz et al., 2003; Grosset et al., 2005; Grosset et al., 2008; Markovic and Mikulic, 2010; Asadi et al., 2017), while muscular factors include increased muscle size. Additionally, muscle-tendon factors include increased tendon size, and improved Young's modulus, which is an indication of intrinsic material properties reflected by the stress-strain relationship (Waugh et al., 2012). Improvement in these factors may contribute to improved force production, increased rate of force production, improved stiffness, and overall SSC function, leading to improved jump and sprint performance (Radnor et al., 2017; Tumkur Anil Kumar, 2021).

The neuromuscular regulatory factors that govern the SSC develop as an individual grows and matures. Briefly, growth and maturation consist of the increase in size and progress towards a mature state of the body (Lloyd et al., 2014b; Radnor et al., 2021). These changes lead to a non-linear natural development of the SSC throughout childhood and adolescence (Radnor et al., 2017). To make improvements over and above the natural development of physical qualities, a developmentally appropriate training stimulus is required (Lloyd et al., 2016). More specifically, a training stimulus like plyometric training, targets the SSC and matches the natural adaptive processes, thus resulting in a synergistic relationship that leads to more effective adaptation (Lloyd et al., 2015; Moran et al., 2018). In youth, plyometric training enhances the ability to use the SSC, improving jump height, jump distance, reactive strength index (RSI) (Turner and Jeffreys, 2010; Johnson et al., 2011; Behm et al., 2017; Moran et al., 2018), stiffness (Lloyd et al., 2012a; Hammami et al., 2016), and power (Johnson et al., 2011; Lloyd et al., 2012a; Asadi et al., 2017).

The effectiveness of a plyometric training program is dependent on the training content and the external and internal moderator variables. External moderator variables include program variables like intensity, volume, program duration, total training sessions, and training frequency (Johnson et al., 2011; Asadi et al., 2017; Moran et al., 2018). For outcomes like countermovement jumping, longer duration interventions with higher frequency have led to a greater adaptive response (Moran et al., 2018), whereas for outcomes like stiffness, shorter durations of training have proven effective in boys, but are largely unknown in girls (Lloyd et al., 2012a; Ramirez-Campillo et al., 2023a). These findings suggest that plyometric training effectiveness may differ between girls and boys due to maturational related adaptations (Lloyd et al., 2015; Moran et al., 2018; Ramirez-Campillo et al., 2023a). The findings also suggest that other internal moderator variables such as age, maturity, body size and generalized joint hypermobility (GJH) are also important to consider (Radnor et al., 2017; Simmonds, 2022). However, there are fewer studies in girls that evaluate the effect of plyometric training only on leg stiffness, standing long jumps, broad hops (Myer et al., 2005), triple broad hops (Noyes and Barber-Westin, 2015), or RSI compared to boys (Moran et al., 2018; Bogdanis et al., 2019; Ramirez-Campillo et al., 2023b). Second, there are fewer studies in girls that evaluate the influence of external moderators like training volume, or internal moderators like chronological age and maturity timing, body size, body composition, and total GJH score (Moran et al., 2018; Ramirez-Campillo et al., 2023a). There is a limited understanding of plyometric training effectiveness in girls during both childhood and adolescence (Ford et al., 2011; Moran et al., 2018; Pichardo et al., 2018; Ramirez-Campillo et al., 2023a) and a limited understanding on how well the training stimulus elicits an appropriate adaptation while assessing the influence of external and internal moderating variables (Moran et al., 2018; Ramirez-Campillo et al., 2023a). Therefore, the aims of this study are to explore the effect of horizontal plyometric training on SSC jumping and hopping and to assess the influence of training, age, body size and tissue related moderators on plyometric training in post-PHV girls. The first hypothesis of the study was that an 8-week plyometric training program with horizontal exercises would improve variables associated with stretch-shortening cycle function. The second hypothesis was that changes in variables associated with the stretch-shortening cycle would be moderated by anthropometric, functional, and training related variables such as body mass, total GJH, and training volume respectively.

2 Materials and methods

2.1 Participants

A total of 23 post-PHV female volleyball players between the ages of 11.8 and 15.8 years were selected to participate in this study. Local volleyball clubs in Olomouc, Czechia, were approached to ascertain their interest in participating in the research study, of which the volleyball academy VAM Olomouc agreed to participate. Afterwards the coaches approached the parents and their children to gauge their interest in participating. Ultimately most of the children and parents of VAM Olomouc agreed to participate. Inclusion criteria for initial participation included: a) participation in highest national youth level competition in the competitive age categories U13–U16; b) being free from major orthopedic injuries (e.g., sprains, fractures, and tears) for at least 3 months prior to the start of the study; c) being free from any pain which would limit safe participation. Only participants who completed both the pre-test and post-test component of a given assessment were taken forward for analysis. These participants were also required to attend at least 75% of all training sessions (Lloyd et al., 2012a). These criteria for analysis resulted in 28 participants being excluded. All participants and parents/guardians were informed of the benefits and risks of being a part of this study. Written parental consent and written participant assent were obtained prior to commencing all data collection procedures. All data collection procedures were reviewed and approved by the Auckland University of Technology Ethics Committee (reference number: 19/434) and the Ethics Committee of the Faculty of Physical Culture, Palacký University Olomouc (reference number: 15/2023). This study was conducted according to the Declaration of Helsinki regarding the use of human participants.

2.2 Study procedures

The current study, which used a quasi-experimental design, consisted of pre-testing and post-testing, separated by an 8-week intervention, with two sessions per week. Participants attended a testing familiarization session 1-week prior to the pre-testing sessions. Pre-testing consisted of two consecutive testing days. Day one consisted of a GJH test, a vertical bilateral sub-maximal hopping test, and a drop jump test, whereas day two consisted of a series of single and triple horizontal jumps and hops tests and vertical unilateral sub-maximal hopping tests. Pre-testing was conducted 1-week prior to the start of the intervention. For the post-testing, all tests were completed on 1 day, 3 days after the end of the intervention. During both pre-testing and post-testing, anthropometric measurements were taken. Participants were asked to refrain from any vigorous activity for 24 h prior to the testing sessions to limit the effects of fatigue (Turner et al., 2015). Each testing session began with a standardized warm-up which progressed from low intensity to high intensity, simple to complex and general to specific. The warm-up started with fundamental movement skills such as skipping, jogging, shuffling and dynamic stretching that targeted the calves, quadriceps, hamstrings and adductors. Following the fundamental movement skills and dynamic stretching, vertical bilateral and unilateral sub-maximal hopping, a series of single and triple horizontal jumps and hops of progressive intensity and three sprints of progressive intensity (60%, 90%, and 100% of maximal effort) were performed. Consistent verbal encouragement was used during all trials and sessions for each participant. All tests were performed inside the university sport facility. Tests were performed in the afternoon at the same time of the day by researchers qualified to deliver the testing and instruction.

2.3 Testing protocols

2.3.1 Anthropometric and maturity measures

Standing height, seated height, body mass, body fat percentage, and hip width (bitrochanteric and biiliac) were measured. Stature measurements were completed using a portable stadiometer (Seca 213, Seca, Hamburg, Germany), after which leg length was determined by subtracting seated height from standing height. Bioelectric impedance analysis using the Tanita SC-240 (Tanita Corporation, Tokyo, Japan) was used for body mass and body fat percentage. Lastly, hip width at the level of the iliac crest and the level of the greater trochanter were measured using large bone calipers (Model 01293, Lafayette Instrument, Lafayette, IN, United States). Maturity timing was determined with a non-invasive method based on anthropometric variables, calendar age, date of birth, and testing date. This data was used in a regression equation to estimate maturity offset and age at PHV which indicate maturity timing (Mirwald et al., 2002). All maturity calculations were completed using the spreadsheets by Towlson et al. (2020).

2.3.2 Sub-maximal hopping

Sub-maximal hopping data was collected instantaneously through a mobile contact mat with attached electronic hub (SmartJump. Fusion Sport, Brisbane, Australia). The calculation of leg stiffness using the method described by Dalleau et al. (2004) is valid and reliable in youth hopping on a contact mat (Lloyd et al., 2009). Absolute leg stiffness was determined by vertical bilateral hopping at a frequency of 2.0 Hz and 2.2 Hz. Conversely, leg stiffness was determined by vertical unilateral sub-maximal hopping at two different frequencies 2.5 Hz on the right leg, 2.5 Hz on the left leg, 3.0 Hz on the right leg, and 3.0 Hz on the left leg (Lloyd et al., 2009; Beerse and Wu, 2016). Hopping at 2.5 Hz has been referred to as the hopping frequency during which stiffness is best expressed (Beerse and Wu, 2016). Each participant completed one trial of 20 consecutive hops in which they attempted to match a frequency set by a digital metronome (Eiling et al., 2007; Lloyd et al., 2009; Lloyd et al., 2011b). To minimize fatigue, 3-min of passive rest were given between each hop type. Participants were instructed to keep their hands on hips, jump and land on the same spot, land with legs extended and maintain their gaze forwards to minimize the additive effect of the arms and trunk (Lloyd et al., 2009). The average stiffness of all contacts was used for analysis. Contacts in which the participant jumped off the mat then back or where participants misheard instructions and stopped for too long or lost rhythm (i.e., contacts exceeded 300 ms) were excluded.

2.3.3 Horizontal jump and hop tests

A series of single and triple horizontal jump and hop tests were measured to the nearest 0.2 cm using a standard fiberglass tape measure. Hopping tests are typically executed by taking off and landing on the same leg, whereas jumping tests are typically executed by taking off and landing on two legs (McGann et al., 2020). The hopping tests of the present study used a novel technique, where they used a one leg take-off but a final landing on two feet.

Overall, maximum jump distance was measured over two trials each with a 1-min rest between attempts and 2-min rest between jump or hop type. The average of the two trials was used for analysis (Myers et al., 2014). Jumps were considered a fault if the participant moved their foot upon landing, or if the participant put their hands on the ground to stabilize themselves upon the final landing. Hops used the same criteria in addition to being a fault if the free leg touched the ground prior to the final landing. All jumps and hops were completed with the final landing on two feet.

2.3.3.1 Broad jumps

For the single and triple broad jump tests, participants started in a standing position with the toes of both feet behind the start line. Both the single and triple broad jump required the participant to start with a countermovement and jump horizontally as far as possible either once or three consecutive times without pause respectively (Ramirez-Campillo et al., 2015a; Delextrat et al., 2015).

2.3.3.2 Broad hops

For the single and triple broad hop tests, participants started in a standing position with the toes of one foot behind the start line. During the single broad hop test, participants performed a maximal hop for distance, completing the landing on two feet. The triple broad hop test required participants to perform three maximal consecutive hops for distance without pausing between hops and landing from the last hop on two feet (Turner and Jeffreys, 2010; Hammami et al., 2016).

2.3.4 Drop jump

Drop jump testing using a height of 30 cm was used to measure RSI with an Opto-jump Next system (Microgate, Bolzano, Italy) with 0.001 s accuracy. The rest interval between attempts was 30 s. Participants were instructed to place their hands on their hips, maintain their gaze forwards and step off the box towards the ground and rebound upwards. They were instructed to complete this action while getting off the ground as quickly as possible and jump as high as possible (Dalleau et al., 2004). Participants were also instructed to keep their legs extended during the flight phase of the jump and refrain from tucking their legs upwards or outwards. Trials in which the participants noticeably stepped down or noticeably jumped up from the box were not included and were asked to be repeated. Three trials were performed and the average of the two best results were used for further analysis (Sole et al., 2007). RSI was calculated as the ratio between jump height and contact time (Flanagan and Comyns, 2008; Lloyd et al., 2009). This method has been shown to be valid and reliable in youth athletes (Lloyd et al., 2009).

2.3.5 Generalized joint hypermobility

The GJH was tested using the Beighton score which is a valid and reliable criterion used in diagnosing this condition (Remvig et al., 2007). The score consists of five components: passive dorsiflexion and hyperextension of the fifth metacarpal joints, passive apposition of the thumbs to the forearms, passive hyperextension of the elbows and knees, and active forward trunk flexion with knees fully extended. Note that the first four elements can be given a maximum score of two points because these are performed bilaterally (i.e., one point for each hypermobile joint), whereas the last element has a maximum score of 1 point. Thus, the total score ranges from 0 to 9 points, a higher score indicating the greater extent of joint hypermobility. The assessment was performed by an experienced physiotherapist and followed standard protocols employing a hand-held goniometer (Smits-Engelsman et al., 2011).

2.4 Training program

The training program consisted of various horizontal oriented plyometric exercises. These exercises were reactive in nature and involved an SSC action, meaning they required the participants to rebound off the ground and project their bodies in the horizontal direction (Lloyd et al., 2011b). The intervention ran twice a week for a period of 8 weeks. Each session commenced with a warm-up consisting of 5–7 min of problem-based movement activities, progressing from low to high intensity. The duration of each session was 35–45 min and session volume were tracked by distance (Ramirez-Campillo et al., 2023b). Intensity was determined based on the magnitude of eccentric loading of each exercise (Lloyd et al., 2011c; Meylan et al., 2012). Each exercise had three to six sets which required the participant to traverse 10–25 m. Rest between sets was one to 2 min. Exercises were progressed over the course of the 8-week intervention by exercise technique complexity (Talukdar et al., 2022), intensity, and volume (Ramirez-Campillo et al., 2023a). The training intervention was implemented by an experienced strength and conditioning coach certified by the National Strength and Conditioning Association. Exercise quality was carefully observed to ensure proper execution and limit the risk of injury. Researchers routinely confirmed with the participants whether or not an exercise produced any pain. There were no injuries that occurred as a result of the intervention. Specific intervention details are in Table 1.

2.5 Statistical analysis

Statistical analyses were performed in MATLAB R2020a with Statistics Toolbox (MathWorks, Natick, MA, United States). Data were presented using arithmetic mean and standard deviation. Total GJH score was also presented using median and interquartile range. For all statistical tests, $p < 0.05$ was considered statistically significant. The normality of the data was evaluated using a Shapiro-Wilk test. Data were also plotted on a quantile-quantile plot and visually examined by a statistician. Change in the

TABLE 1 Training program details.

Category	Sets	Distance (m)	Intensity (Eccentric load)	Technique progressions	Reference
MDJLC	3–4	10–20	2–Low	Bilateral jump jump stick, Unilateral hop hop stick	Hewett et al. (1996)
MDAH	3–4	10–20	3–Moderate	Travelling forwards, backwards and laterally (Emphasize ankle dorsi-flexion)	Kong (2018); Lephart et al. (2005)
Power skipping	3–4	10–20	3–Moderate	Skipping with rhythm—Skipping for height—Skipping for distance	Faigenbaum et al. (2009)
Galloping	3–4	10–20	3–Moderate	Galloping with rhythm- Galloping for height-Galloping for distance	Konukman et al. (2008)
Broad jumping	4–6	10–15	2–Low	Broad jump with reset—Two "pump" broad jump with reset—Repeat broad jump	McCormick et al. (2016); Delextrat et al. (2015); Cochrane and Booker (2014)
Horizontal hopping	5–6/leg	10–20	4/5–Mod/High	Rhythm hops (100 bpm)—Hop over cones—Hop for distance	Witzke and Snow (2000); Lephart et al. (2005)
Bounding	4–6	15–20	5–Mod/High	Diagonal bounding—Straight bounding (short)—Straight bounding (long)	Witzke and Snow (2000); Kong (2018); Hewett et al. (1996)

MDJLC, multi-directional jump landing combination; MDAH, multi-directional ankle hops; Mod, moderate.

dependent variable during the training program was calculated as post-test minus pre-test (Δ = post–pre). A specialized spreadsheet (Hopkins, 2015) was used to obtain changes expressed as percentages. The statistical significance of the change was evaluated using a one-sample two-tailed *t*-test. In addition to statistical significance, effect size was also calculated. Cohen's *d* was calculated as $d = M_\Delta/SD_{pre}$, where M_Δ was the mean value of delta scores and SD_{pre} was calculated from the pre-test values (baseline). The following thresholds were used to interpret the magnitude of *d*: trivial 0.00–0.19, small 0.20–0.49, moderate 0.50–0.79, and large ≥0.80 (Cohen, 1988).

Multiple regression analysis was used to determine whether individual changes in the dependent variable could be moderated by calendar age, maturity offset, body height, body mass, total GJH score, and training volume. Only linear moderators without interactions were considered. In Wilkinson notation, the regression model can be written as follows: Δy ~ 1 + calendar age + maturity offset + body height + body mass + total GJH score + training volume, where Δy is the change during the training program in the selected dependent variable. Effect size for each moderator was calculated using the eta squared statistic $\eta^2 = SS_{effect}/SS_{total}$, where SSeffect is the sum of squares associated with the moderator and SStotal is the total sum of squares (Fritz et al., 2012). The following thresholds were used to interpret η^2: trivial 0.000–0.009, small 0.010–0.059, moderate 0.060–0.139, and large ≥0.140 (Cohen, 1988). To evaluate the relationship between changes in the dependent variable and one selected moderator, Pearson's correlation coefficient (*r*) was calculated. The following thresholds were used to interpret the magnitude of *r*: trivial 0.00–0.09, small 0.10–0.29, medium 0.30–0.49, and large ≥0.50 (Cohen, 1988).

Power analysis was performed using G*Power version 3.1.9.7 (Faul et al., 2007). The level for statistical significance was set at α = 0.05 and the power was set at 1-β = 0.80. Under the first hypothesis, a large effect size ($d = 0.8$) was considered for the paired two-tailed *t*-test. The required sample size resulted in 15 participants. Under the second hypothesis, a large correlation ($r = 0.5$) was considered for the Pearson's correlation coefficient. The required sample size resulted in 26 participants. Thus, 26 participants were required to test both hypotheses.

3 Results

3.1 Data normality

The characteristics of the participants are shown in Table 2. The median total GJH score was 3 and the interquartile range was 3. Although the total GJH score was an ordinal scale ranging from 0 to 8, the Shapiro-Wilk test did not reject normality ($p = 0.20$, Table 2). Therefore, total GJH score was considered quasi-normal and used as a moderator in the regression analysis without any transformation. Normality was rejected for standing height ($p = 0.013$, Table 2). Upon examination of the quantile-quantile plot, it was found that the non-normality was due to one player whose standing height was 187.4 cm. This value was not considered as outlier and this player was retained in further statistical analysis. The remaining variables used as moderators in the regression analysis had normal distributions (all $p \geq 0.15$, Table 2).

The results of testing the normality of the differences between pre-values and post-values are provided in Table 3. The quantile-quantile plot was visually inspected for 3 out of the total 18 variables for which normality was rejected according to the Shapiro-Wilk test ($p < 0.05$). Upon examination, the deviation from normality was assessed as acceptable and parametric statistical methods were used as they are considered robust for such deviations from normality (Ghasemi and Zahediasl, 2012).

3.2 Training effect

The effect of the plyometric training program on the examined dependent variables is shown in Table 3. After plyometric training, there was a statistically significant increase in standing height

TABLE 2 Characteristics of the participants (n = 23).

Variable	Mean ± SD	p
Chronological age (years)	13.8 ± 1.2	0.40
Maturity offset (years)	1.7 ± 0.8	0.15
Mirwald APHV (years)	12.1 ± 0.6	0.27
Standing height (cm)	165.4 ± 6.8	0.013
Seated height (cm)	84.5 ± 3.3	0.22
Leg length (cm)	81.0 ± 4.8	0.36
Body mass (kg)	58.1 ± 9.6	0.20
Body fat (%)	24.3 ± 5.8	0.56
Total GJH score	3.5 ± 2.1	0.20
Attended sessions	13.8 ± 1.2	0.014
Training volume (km)	6.20 ± 1.00	0.16

SD, standard deviation; p, statistical significance of Shapiro-Wilk normality test; APHV, age at peak height velocity; GJH, generalized joint hypermobility.

TABLE 3 The effect of the plyometric training program on the dependent variables.

Variable	Pre-test	Post-test	Δ = post-pre	p_{sw}	p_{tt}	d
	Mean ± SD	Mean ± SD	Absolute (%)			
Standing height (cm)	165.4 ± 6.8	165.9 ± 7.0	0.5 (0.3%)	0.34	0.001	0.07
Seated height (cm)	84.5 ± 3.3	84.7 ± 3.3	0.2 (0.3%)	0.96	0.31	0.07
Leg length (cm)	81.0 ± 4.8	81.2 ± 5.0	0.2 (0.3%)	0.34	0.31	0.05
Body mass (kg)	58.1 ± 9.6	59.0 ± 10.1	1.0 (1.6%)	0.13	0.001	0.10
Body fat (%)	24.3 ± 5.8	24.2 ± 5.9	−0.1 (−0.4%)	0.40	0.68	−0.02
Sub-max hop 2.0 Hz (kN/m)	19.4 ± 4.0	21.4 ± 4.9	2.0 (9.5%)	0.67	0.021	0.50
Sub-max hop 2.2 Hz (kN/m)	23.2 ± 4.4	24.9 ± 4.8	1.6 (6.8%)	0.85	0.049	0.37
Sub-max hop 2.5 Hz right (kN/m)	19.0 ± 2.4	19.5 ± 2.7	0.5 (2.3%)	0.032	0.28	0.19
Sub-max hop 2.5 Hz left (kN/m)	18.9 ± 2.7	19.7 ± 3.0	0.9 (4.4%)	0.049	0.032	0.32
Sub-max hop 3.0 Hz right (kN/m)	23.7 ± 4.0	25.4 ± 4.7	1.6 (6.8%)	0.35	0.056	0.40
Sub-max hop 3.0 Hz left (kN/m)	24.1 ± 3.4	24.9 ± 4.0	0.8 (3.0%)	0.51	0.11	0.23
Broad jump (cm)	192 ± 21	187 ± 18	−5 (−2.4%)	0.84	0.012	−0.23
Broad hop right (cm)	164 ± 16	166 ± 13	2 (1.6%)	0.80	0.28	0.15
Broad hop left (cm)	168 ± 17	170 ± 14	3 (1.7%)	0.024	0.22	0.15
Triple broad jump (cm)	579 ± 58	569 ± 53	−10 (−1.6%)	0.34	0.13	−0.17
Triple broad hop right (cm)	493 ± 59	496 ± 50	3 (0.7%)	0.90	0.75	0.04
Triple broad hop left (cm)	491 ± 55	501 ± 60	10 (2.0%)	>0.99	0.18	0.18
Reactive strength index (m/s)	1.03 ± 0.31	1.04 ± 0.27	0.01 (2.0%)	0.84	0.66	0.04

SD, standard deviation; p_{sw}, statistical significance of Shapiro-Wilk normality test; p_{tt}, statistical significance of paired t-test; d, Cohen's effect size; Sub-max, sub-maximal; Hz, Hertz.

(pre: 165.4 ± 6.8, post: 165.9 ± 7.0 cm, p = 0.001, d = 0.07, trivial effect) and body mass (pre: 58.1 ± 9.6, post: 59.0 ± 10.1 kg, p = 0.001, d = 0.10, trivial effect), which was the expected growth effect. Importantly, the effect of training on body fat (pre: 24.3 ± 5.8, post: 24.2% ± 5.9%, p = 0.68, d = −0.02, trivial effect) was not significant. Among the vertical sub-maximal hopping variables, significant increases were found for vertical bilateral hopping at 2.0 Hz (pre: 19.4 ± 4.0, post: 21.4 ± 4.9 kN/m, p = 0.021, d = 0.50, medium effect), vertical bilateral hopping at 2.2 Hz (pre: 23.2 ± 4.4, post: 24.9 ± 4.8 kN/m, p = 0.049, d = 0.37, small effect), and vertical

TABLE 4 Values of regression coefficients.

Variable	Calendar age	Maturity offset	Body height	Body mass	Total GJH score	Training volume
	[(y)/year]	[(y)/year]	[(y)/cm]	[(y)/kg]	[(y)/point]	[(y)/km]
Body mass (kg)	1.610	−3.153	0.184	0.054	0.220	−0.220
Body fat (%)	2.218	−4.338	0.204	0.046	0.197	0.376
Sub-max hop 2.0 Hz (kN/m)	−1.932	3.629	−0.333	0.060	−0.260	−1.719
Sub-max hop 2.2 Hz (kN/m)	1.142	−3.131	−0.060	0.176	−0.092	−1.337
Sub-max hop 2.5 Hz right (kN/m)	1.216	−2.661	0.061	0.171	−0.031	0.065
Sub-max hop 2.5 Hz left (kN/m)	−0.636	0.710	−0.112	0.122	−0.086	−0.006
Sub-max hop 3.0 Hz right (kN/m)	5.877	−10.151	0.648	0.245	0.211	−0.045
Sub-max hop 3.0 Hz left (kN/m)	0.135	−0.114	−0.051	0.162	−0.083	−0.025
Broad jump (cm)	−1.839	3.973	0.027	−0.064	−1.167	3.253
Broad hop right (cm)	−9.497	17.881	−0.597	−0.300	−2.337	3.673
Broad hop left (cm)	1.324	−5.075	0.869	−0.305	−1.966	3.067
Triple broad jump (cm)	−13.983	21.429	−1.146	0.249	−4.893	4.579
Triple broad hop right (cm)	−34.424	44.255	0.213	−0.464	−8.951	17.375
Triple broad hop left (cm)	−15.683	24.076	0.211	−0.494	−8.531	11.097
Reactive strength index (m/s)	−0.151	0.238	−0.010	−0.003	−0.022	0.010

GJH, generalized joint hypermobility; (y), unit of the dependent variable; Sub-max, sub-maximal; Hz, Hertz.

unilateral hopping at 2.5 Hz left (pre: 18.9 ± 2.7, post: 19.7 ± 3.0 kN/m, $p = 0.032$, $d = 0.32$, small effect). Examination of the broad jump variable revealed a significant decrease in broad jump distance (pre: 192 ± 21, post: 187 ± 18 cm, $p = 0.012$, $d = -0.23$, small effect).

3.3 Effect of moderators

The results of the regression analysis are presented in Tables 4–6. Table 4 contains the values of each regression coefficient, Table 5 contains the statistical significance for each regression coefficient, and Table 6 contains the eta-squared for each regression coefficient. Body mass moderated the following three dependent variables: vertical unilateral hopping at 2.5 Hz right ($p = 0.010$, $\eta^2 = 0.314$, large effect), vertical unilateral hopping at 3.0 Hz right ($p = 0.035$, $\eta^2 = 0.170$, large effect), and vertical unilateral hopping at 3.0 Hz left ($p = 0.043$, $\eta^2 = 0.203$, large effect). Additionally, total GJH score moderated both the triple broad hop right ($p = 0.012$, $\eta^2 = 0.210$, large effect) and the triple broad hop left ($p = 0.034$, $\eta^2 = 0.226$, large effect). Training volume significantly moderated only triple broad hop right ($p = 0.024$, $\eta^2 = 0.160$, large effect). Calendar age (all $p \geq 0.11$), maturity offset (all $p \geq 0.12$), and body height (all $p \geq 0.077$) did not significantly moderate any dependent variable.

Interestingly, two simultaneous significant moderators were found for triple broad hop on the right leg, whereas the other dependent variables had at most one significant moderator. Therefore, a correlation analysis was performed to assess the association between changes in the dependent variable before and after the training program and one variable with pre-test values. Body mass alone was significantly correlated with the same three variables for which the regression analysis yielded a significant result mentioned above: vertical unilateral hopping at 2.5 Hz right ($r = 0.56$, $p = 0.006$, large effect, Figure 1A), vertical unilateral hopping at 3.0 Hz right ($r = 0.60$, $p = 0.002$, large effect, Figure 1B), and vertical unilateral hopping at 3.0 Hz left ($r = 0.56$, $p = 0.006$, large effect, Figure 1C). Total GJH score was significantly correlated only with triple broad hop left ($r = -0.43$, $p = 0.042$, medium effect, Figure 1E). Triple broad hop right was not significantly correlated with either total GJH score ($r = -0.33$, $p = 0.13$, Figure 1D) or training volume ($r = 0.39$, $p = 0.063$, Figure 1F). Thus, total GJH score and training volume together significantly influenced triple broad hop right, as shown in the regression analysis, but when these moderators were taken separately, no significant correlation was found.

4 Discussion

The primary aim of this study was to explore the effect of an 8-week horizontal plyometric training program on SSC jumping and hopping in post-PHV female volleyball players. The main findings of the current study demonstrated that an 8-week plyometric training program improved absolute leg stiffness at the preferred frequency (2.5 Hz, left leg) in post-PHV female volleyball players. To our knowledge this is the first intervention study to explore the effect of horizontal plyometric training on leg stiffness during vertical

TABLE 5 Statistical significances of regression coefficients.

Variable	Calendar age	Maturity offset	Body height	Body mass	Total GJH score	Training volume
Body mass (kg)	0.18	0.15	0.12	0.14	0.078	0.41
Body fat (%)	0.16	0.13	0.19	0.33	0.21	0.28
Sub-max hop 2.0 Hz (kN/m)	0.65	0.63	0.42	0.64	0.54	0.082
Sub-max hop 2.2 Hz (kN/m)	0.79	0.68	0.89	0.19	0.83	0.18
Sub-max hop 2.5 Hz right (kN/m)	0.54	0.45	0.75	0.010	0.88	0.88
Sub-max hop 2.5 Hz left (kN/m)	0.74	0.84	0.56	0.050	0.66	0.99
Sub-max hop 3.0 Hz right (kN/m)	0.11	0.12	0.077	0.035	0.56	0.96
Sub-max hop 3.0 Hz left (kN/m)	0.96	0.98	0.83	0.043	0.74	0.96
Broad jump (cm)	0.85	0.82	0.98	0.83	0.25	0.15
Broad hop right (cm)	0.41	0.39	0.60	0.39	0.057	0.17
Broad hop left (cm)	0.89	0.77	0.36	0.30	0.056	0.17
Triple broad jump (cm)	0.70	0.74	0.74	0.82	0.19	0.57
Triple broad hop right (cm)	0.28	0.44	0.94	0.63	0.012	0.024
Triple broad hop left (cm)	0.67	0.72	0.95	0.66	0.034	0.19
Reactive strength index (m/s)	0.31	0.37	0.49	0.52	0.14	0.76

GJH, generalized joint hypermobility; Sub-max, sub-maximal; Hz, Hertz.

TABLE 6 Eta-squared of regression coefficients.

Variable	Calendar age	Maturity offset	Body height	Body mass	Total GJH score	Training volume
Body mass (kg)	0.075	0.090	0.102	0.091	0.136	0.028
Body fat (%)	0.093	0.111	0.082	0.044	0.072	0.053
Sub-max hop 2.0 Hz (kN/m)	0.010	0.011	0.031	0.010	0.017	0.154
Sub-max hop 2.2 Hz (kN/m)	0.003	0.008	0.001	0.091	0.002	0.095
Sub-max hop 2.5 Hz right (kN/m)	0.015	0.022	0.004	0.314	0.001	0.001
Sub-max hop 2.5 Hz left (kN/m)	0.005	0.002	0.016	0.193	0.009	0.000
Sub-max hop 3.0 Hz right (kN/m)	0.090	0.084	0.114	0.170	0.011	0.000
Sub-max hop 3.0 Hz left (kN/m)	0.000	0.000	0.002	0.203	0.005	0.000
Broad jump (cm)	0.002	0.003	0.000	0.002	0.073	0.114
Broad hop right (cm)	0.031	0.035	0.013	0.034	0.187	0.093
Broad hop left (cm)	0.001	0.003	0.032	0.042	0.156	0.077
Triple broad jump (cm)	0.009	0.006	0.006	0.003	0.104	0.018
Triple broad hop right (cm)	0.032	0.016	0.000	0.006	0.210	0.160
Triple broad hop left (cm)	0.008	0.006	0.000	0.008	0.226	0.077
Reactive strength index (m/s)	0.058	0.044	0.025	0.022	0.122	0.005

GJH, generalized joint hypermobility; Sub-max, sub-maximal; Hz, Hertz.

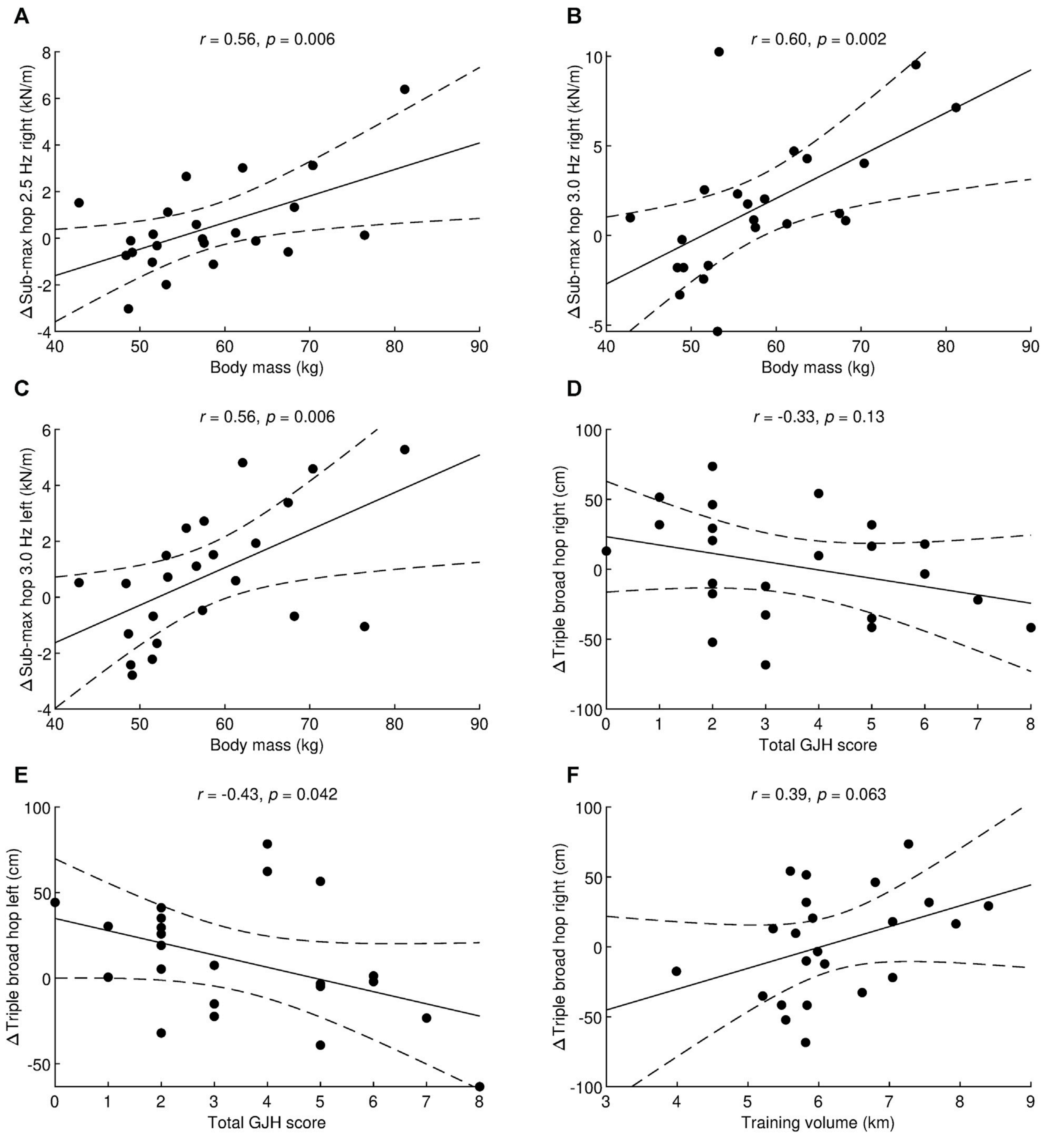

FIGURE 1
Correlation analysis between change in unilateral sub-maximal hopping at 2.5 Hz right and body mass **(A)**, change in unilateral sub-maximal hopping at 3.0 Hz right and body mass **(B)**, change in unilateral sub-maximal hopping at 3.0 Hz left and body mass **(C)**, change in triple broad hop right and total generalized joint hypermobility score **(D)**, change in triple broad hop left and total generalized joint hypermobility score **(E)**, and change in triple broad hop right and training volume **(F)**. *r*, Pearson's correlation coefficient; *p*, statistical significance of the correlation coefficient; Δ, difference between post-test versus pre-test; Sub-max, sub-maximal; Hz, Hertz. Dashed lines denote a 95% confidence interval.

unilateral sub-maximal hopping and on explosive horizontal jumping and hopping ability using a novel protocol in post-PHV female volleyball players. The second aim was to assess the influence of training, age, body size, and tissue related (GJH) moderating variables on plyometric training. Regarding the interaction of plyometric responses and moderating variables, body mass moderated the effect of plyometric training on the largest number of parameters, specifically, vertical sub-maximal hopping at 2.5 Hz on the right leg, and at 3.0 Hz on the left and right leg. This is the first study to assess the influence training, age, body size, and tissue related (GJH) variables on such plyometric training in post-PHV female volleyball players. The results of the present study indicate that a sufficient training stimulus was provided to improve leg stiffness at the preferred hopping frequency in youth, but not for horizontal jumping and hopping ability or RSI. Lastly, body mass and not age, maturity, training volume or GJH served as the best moderator of horizontal plyometric training.

4.1 Training effect

The intervention in the current study consisted of horizontally oriented plyometric exercises that involved an SSC and were reactive in nature. The ability to rebound off the ground can be aided by leg stiffness, a component of effective SSC function (Radnor et al., 2017). Leg stiffness describes the ability to attenuate an applied force during deformation of the leg, where an optimal level of stiffness allows a large force to be attenuated over a shorter range of motion (McMahon and George, 1990). This training intervention led to a significant increase in absolute leg stiffness during vertical bilateral hopping at 2.0 Hz, 2.2 Hz, and vertical unilateral hopping at 2.5 Hz on the left leg. The medium intervention effect for sub-maximal hopping at 2.0 Hz (9.5%) and 2.5 Hz (4.4%) on the left leg exceeds the within subject error (2.0 Hz: 8.23%, 2.5 Hz: 3.89%) of a unpublished PhD thesis reliability study, and can thus be considered clinically significant (Sylvester, 2024). Furthermore, the small degree of intervention effect for sub-maximal hopping at 2.2 Hz (6.8%) did not exceed the within subject error (7.25%) of a unpublished PhD thesis reliability study and are not considered clinically significant (Sylvester, 2024). Furthermore, the significant improvement in leg stiffness during vertical unilateral hopping at 2.5 Hz on the left and not the right leg agrees with the unpublished PhD thesis reliability study (Sylvester, 2024), during which the left leg represented the non-dominant leg for most participants, as determined by the kicking leg. The increased reliability of left leg vertical hopping might have influenced why significant results were demonstrated on that leg in the current investigation.

Changes larger than the within subject error indicate that plyometric training can induce changes in leg stiffness over and above what would be expected by natural development (Radnor et al., 2017). The findings of the present study are relevant in demonstrating that a horizontal plyometric stimulus can also lead to improvement in vertical outcomes other than vertical countermovement jumps in post-PHV female athletes (Talukdar et al., 2022), in this case, absolute leg stiffness during unilateral vertical sub-maximal hopping. In addition to body mass and maturity, muscle pre-activation and the stretch-reflex response of the leg extensors, are the major predictors of absolute leg stiffness in youth, explaining approximately 97% of the variance in leg stiffness (Oliver and Smith, 2010). In the present study, where maturity did not moderate change in leg stiffness and body mass did, increased leg stiffness observed in youth female volleyball players after the plyometric training program could also presumably be explained by muscle activity (Oliver and Smith, 2010).

The current study suggests that post-PHV female volleyball players can improve leg stiffness after a plyometric training program. However, the effect of plyometric training on leg stiffness in post-PHV female athletes overall still requires further investigation. Moreover, the effect of plyometric training on leg stiffness in pre-PHV or circa-PHV girls also remains unclear due to a paucity of studies. It is for this reason studies in boys are used to help elucidate these effects. For example, improvement in absolute and relative leg stiffness in 12- and 15-year-old male physical education students have been demonstrated during vertical bilateral hopping at 2.5 Hz after a 4-week plyometric training program. The same study revealed that 9-year-old physical education students did not demonstrate improvements in leg stiffness (Lloyd et al., 2012a). Similar investigations have not been conducted in girls, therefore, further studies in youth female athletes are needed to affirm the effect of plyometric training on leg stiffness in general. Moreover, it is desirable to ascertain the effect of plyometric training on leg stiffness in youth female athletes across maturation in comparison to a control group to further discern the training effect from the natural development effect.

The present study did not reveal significant increases in RSI after a plyometric training intervention. This finding indicates that while potential benefits for SSC behavior could be expected due to increased leg stiffness, other aspects of SSC performance were not improved. More specifically, the RSI parameter in our study derived from the drop jump test, is used to assess an athlete's ability to produce force rapidly. Higher values of the RSI are associated with the effective use of muscle elasticity and neuromuscular control of working muscles (Flanagan and Comyns, 2008; Jarvis et al., 2022). Observation of the discrepancy between training induced effects in absolute leg stiffness and RSI indirectly supports a previous suggestion, that RSI has only a limited amount of variance with leg stiffness (Lloyd et al., 2011a). Absence of benefit in the case of RSI agrees with previous studies in 8-year-old female gymnasts after an 8-week plyometric training intervention (Bogdanis et al., 2019), and in 8-year-old female gymnasts after a combined 8-week plyometric, muscular strength, muscular endurance, movement competency and dynamic stabilization training program (Moeskops et al., 2018). However, our finding regarding RSI is not commensurate with findings of a recent systematic review with meta-analysis by Ramirez-Campillo et al. (2023a), which revealed significant gains in RSI after plyometric training programs in males and females under 18 years old. This systematic review with meta-analysis by Ramirez-Campillo et al. (2023a) also did not find sex or maturational status to be a significant moderator of plyometric training effect on RSI. Moreover, another recent systematic review with meta-analysis on healthy individuals across the lifespan revealed that plyometric jump training was effective (ES = 0.54, small effect) at improving leg stiffness (Ramirez-Campillo et al., 2023b). We assume that one of the reasons why positive changes of the RSI were not observed in our study were the differences between movement content of the current investigation's horizontal plyometric program exercises, and the vertical nature of the drop jump test. As it is generally accepted that RSI is an important measure of SSC capability in youth athletes related to both athletic performance (Flanagan and Comyns, 2008; Ramirez-Campillo et al., 2018; Jarvis et al., 2022) and injury prevention (Toumi et al., 2006; Raschner et al., 2012) and considering that the natural development of RSI differs in boys and girls (Laffaye et al., 2016; De Ste Croix et al., 2021; Lehnert et al., 2022), existing ambiguities concerning potential benefits of plyometric training on RSI in youth female athletes should be clarified. Therefore, more investigations into different lengths and types of plyometric training interventions in girls are required to elucidate this theory. It must also be considered that the sport and training experience level and sex of participants are important, given that improvements may be more difficult to induce in girls or more athletically experienced individuals (Faigenbaum et al., 2002; Asadi et al., 2017; Moran et al., 2018; Moeskops et al., 2022b; Lehnert et al., 2022) and that in youth (age <18 years) smaller training induced changes can be expected compared to adults (Ramirez-Campillo et al., 2023b).

Horizontal plyometric training did not induce a significant improvement in any of the horizontal jumps or hops. Despite the 2.4% decrease in the broad jump, this decrease was not considered significant, given that it did not exceed the previously stated within subject error of 2.82% from a unpublished PhD thesis (Sylvester, 2024). It is difficult to explain with certainty as to why there was no significant improvement in horizontal jump and hop movements. One explanation is that horizontally directed plyometric exercises require the body to be projected into the air and across the ground, which may require a higher level of coordination to execute (Ramirez-Campillo et al., 2015b). This might be especially true when considering the reality of teaching exercises to young athletes. Horizontally directed plyometric exercises require a higher level of coordination compared to vertically oriented plyometric exercises (Fukashiro et al., 2005; Ramirez-Campillo et al., 2023a). Given that intensity is a vital consideration for plyometric training effectiveness (Brauner et al., 2014; Maloney et al., 2015; Ramirez-Campillo et al., 2023a), it is possible that while learning to coordinate these movements, the ability to perform these exercises maximally was affected.

Significant improvements in standing long jump (broad jump) have been demonstrated in girls from various sports and similar age range as players in the current study (age 13–16). For example, after a 7-week horizontal jump training intervention (Talukdar et al., 2022), after both 8-week bilateral and unilateral plyometric interventions (Kong, 2018), after both sagittal plane and frontal plane 6-week plyometric interventions (McCormick et al., 2016), after a 10-month combined movement competency, strength, ballistic, plyometric and speed training program (Moeskops et al., 2022a), and after an 8-week plyometric, speed and strength training intervention (Marta et al., 2014). The disagreement with the literature also applies to horizontal single and triple hopping where 15-year-old soccer, basketball and volleyball players were able to significantly improve their single leg hop distance after a 6-week neuromuscular training program (Myer et al., 2005). Similarly, 13–18-year-old athletic girls from various sports significantly improved in single leg triple hop distance, after a 6-week combined, jumping, plyometric, speed, endurance, agility training program (Noyes and Barber–Westin, 2015). However, differences between the current study and those in the literature are noted for movement orientation, analysis method (McCormick et al., 2016; Kong, 2018), intervention length (McCormick et al., 2016; Moeskops et al., 2022a), training content (Marta et al., 2014; Moeskops et al., 2022a), and sport background (Marta et al., 2014; McCormick et al., 2016; Moeskops et al., 2022b). These methodological differences revealed throughout the literature make clarifying the effect of plyometric training on the broad jump test difficult. The existence of the external moderators noted does not allow for clarity as to the effect of plyometric training on horizontal jumping and hopping in youth female athletes. This uncertainty is confirmed due to the findings of a recent systematic review and meta-analysis, where small significant effect sizes (d = 0.42–0.56) were found for the effect of plyometric training on horizontal jump distance (Ramirez-Campillo et al., 2023a).

4.2 Effect of moderators

The adaptive response to plyometric training may be influenced by various moderators (Moran et al., 2018; Ramirez-Campillo et al., 2023a). The present study sought to determine the influence of several moderators on plyometric training. However, the present study discovered that only body mass and total GJH combined with training volume had a moderating effect on plyometric training in post-PHV female volleyball players. Therefore, there remains uncertainty regarding the effect of moderators on plyometric training in girls.

The present study discovered that in a sample of post-PHV volleyball girls, there were no moderating effects of age, height or maturity offset. These findings agree with a meta-analysis by Moran et al. (2018) who demonstrated that older, taller and heavier girls adapted to plyometric training to a lesser extent compared to younger, lighter and shorter girls. In the study by Moran et al. (2018), which used a median split analysis, girls above age 15 were considered older. The girls in the present study were 13.8 years old, initially suggesting they should share similar characteristics (similar moderating effect of age on plyometric training) to the girls below the median in the study by Moran et al. (2018). However, this was not the case. Furthermore, when compared to girls in Moran et al. (2018), the girls of the present study were taller than the median height of the participants in Moran et al. (2018). This would suggest they resemble the older girls of Moran et al. (2018) and thus the reason for the lack of moderating effect of height or age in the present study.

Chronological age can be misleading as a moderator variable, given that many changes during adolescence occur due to increased biological age (Lloyd et al., 2016). However, in the study by Moran et al. (2018), there was no analysis completed regarding the moderating effect of maturation on plyometric training (Moran et al., 2018). This is not surprising given the scarcity of studies in girls where researchers have assessed maturation during plyometric training interventions. Currently there is no consensus regarding how girls of different maturity status adapt to plyometric training. For instance, in a recent systematic review with meta-analysis, it was shown that there is a paucity of studies in young girls where the moderating effect of maturation has been assessed during plyometric training interventions (Ramirez-Campillo et al., 2023a). Additional studies are required in youth female athletes where researchers assess maturation so a consensus can be generated regarding the moderating effect of maturation on plyometric training. It is also suggested that additional moderator analysis, other than anthropometric variables, be investigated by researchers which assess the functional qualities of the neuromuscular and musculoskeletal systems (Beerse and Wu, 2022).

4.2.1 Effect of training volume

The present study revealed that training volume moderated one dependent variable but only when combined with the moderating effect of total GJH score. Specifically, a higher training volume and a lower total GJH score led to a higher value of triple broad hop on the right leg. The absence of significant effect of training volume may be attributed to the attendance criteria of 75% or more. This criterion limited the variability in the training volume across the participants (Lloyd et al., 2012a).

In the present study, training volume did not significantly moderate the effect of plyometric training on RSI. This finding is in line with findings of a previous systematic review with meta-analysis demonstrating that training volume in the form of number of weeks, total jumps, and total training sessions did not significantly moderate the effect of plyometric training on RSI (Ramirez-Campillo et al., 2023a) and vertical countermovement jumps in youth under 18 years old (Ramirez-Campillo et al., 2023a). However, in another recent systematic review with meta-analysis, the authors noted that three sessions per week, more than 7 weeks and more than 14 sessions, was a more effective dose to improve RSI in healthy people across the lifespan than under three weekly sessions, under 14 total sessions and under 14-week of training (Ramirez-Campillo et al., 2023b). Therefore, there may be differences between how youth under 18 years old respond to plyometric training compared to individuals across the lifespan.

Despite the significant increase in absolute leg stiffness during bilateral hopping at 2.0 Hz and left leg hopping at 2.5 Hz, training volume did not significantly moderate the effect of plyometric training on absolute leg stiffness. Stiffness in healthy individuals across the lifespan was shown to increase due to lower plyometric training volume, specifically, under 16 sessions, under three sets, and equal to or under 2 sessions per week (Moran et al., 2023). This relationship between training and stiffness differs from that of training volume and RSI for healthy individuals across the lifespan. It is likely that different expressions of the SSC like stiffness and RSI, have dissimilar dose-adaptation relationships. More studies investigating the effects of training volume with different numbers of jumps, weekly frequency, total sessions, and number of training weeks in the context of growth and maturation are required to clarify this idea.

4.2.2 Effect of body mass

Correlation analysis was used to unveil the relationship between changes in each dependent variable and body mass at pre-test. Change in absolute leg stiffness during right leg vertical sub-maximal hopping at 2.5 Hz ($r = 0.56$) and 3.0 Hz ($r = 0.60$) and left leg vertical hopping at 3.0 Hz ($r = 0.56$) were correlated to body mass at pre-test. These findings indicate that when evaluating the effect of plyometric training on leg stiffness at preferred vertical hopping frequencies (2.5 Hz) and faster hopping frequencies (3.0 Hz), increased body mass at pre-test moderates plyometric training to produce higher leg stiffness. During the reactive hops, the entire body mass must be projected into the air against gravity after rebounding off the ground. This rebounding process is aided by increased amounts of leg stiffness, which helps attenuate large ground reaction forces without a large deformation (Lloyd et al., 2009; Pedley et al., 2020). Specifically, if leg stiffness does not increase with a larger mass, then the body will display a diminished ability to consistently control the landing forces and maintain an appropriate level of deformation to meet athletic task demands (Lloyd et al., 2009; Meyers et al., 2016; Pedley et al., 2020).

Athletic tasks executed in sport impose mechanical loading which leads to stiffness changes in youth (Waugh et al., 2012). This training and sport related loading can also be accompanied by chronic mechanical loading from growth and maturation related body mass increases, which also lead to increased stiffness in young people (Waugh et al., 2012; Chalatzoglidis et al., 2021). This notion is supported by literature demonstrating that body mass is a primary contributor to absolute leg stiffness in 11–12-year-old boys, explaining from 61.7% to 75.8% of the variation during vertical hopping at preferred frequencies (Oliver and Smith, 2010; Lloyd et al., 2011a). Other significant contributors include extensor muscle activity upon ground contact (Oliver and Smith, 2010), which can be improved from training and sport related loading (Waugh et al., 2012). However, it is also known that girls increase their body fat mass to a higher degree compared to boys throughout childhood and adolescence (Naughton et al., 2000). This body composition change can negatively affect relative force production and impulse during reactive movements like jumping (Emmonds et al., 2017). This previous finding has been demonstrated in a meta-analysis in which heavier girls that were taller and older, adapted to plyometric training to a lesser degree compared to lighter, younger and shorter girls (Moran et al., 2018). Thus, to offset the negative effects of maturity related increases in fat mass, appropriate training, and sport related loading, like plyometric training and strength training, may help increase extensor muscle activity and thus stiffness (Ramirez-Campillo et al., 2023a; Moran et al., 2023). Previous studies in girls have not investigated the moderating effect of body mass on the change in performance due to a plyometric training program. There remains much variation unexplained in girls concerning SSC performance (Ramirez-Campillo et al., 2023a). Therefore, SSC jump and hop performance is not solely affected by body mass but is affected by maturation related neuromuscular factors that aid in controlling landing forces to help produce a forceful subsequent propulsive phase (Meylan et al., 2014).

4.2.3 Effect of age and maturity

Correlation analysis did not reveal a significant relationship between the change in any of the performance variables and maturity offset or age. Nevertheless, it must be considered that the present study did not evaluate girls across maturation, and instead evaluated post-PHV girls only. The present study's results thus indicate that for girls between 11.8 and 15.8, maturity timing and age did not significantly influence the effect of plyometric training on jumping and hopping ability. There is a previous meta-analysis that discovered that the effect of plyometric training on jumping performance was smaller among older (above 15 years), taller (above 163 cm) and heavier girls (above 54 kg) compared to younger, shorter and lighter girls (Moran et al., 2018). Moreover, in a systematic review with meta-analysis in healthy individuals across the lifespan, it was discovered that RSI improvements were better in adults compared to youth after plyometric training (Ramirez-Campillo et al., 2023b). However, the populations investigated in Moran et al. (2018) were girls of a similar and older age to the present study, whereas Ramirez-Campillo et al. (2023b) investigated healthy individuals across the lifespan. Direct comparisons between these previous studies and the present study are difficult. It has been suggested that the SSC develops non-linearly with age (Radnor et al., 2017), a finding which has been discovered for RSI in 8–13-year-old figure skating girls (Lehnert et al., 2022), 11–20-year-old girls (Laffaye et al., 2016), and 7–16-year-old boys (Lloyd et al., 2011b). Furthermore, leg stiffness in girls has also been shown to develop non-linearly with age although, the significant increases occurred within age ranges not commensurate with those of the present study (Laffaye et al., 2016). Given the lack of moderating effects of age and maturation, it could be that the majority of participants in the present study were of an age in which plyometric training is not moderated by age or maturation. Overall, this study suggests that plyometric training may be an effective method for improving leg stiffness in post-PHV female athletes, regardless of their age and maturity status. Further research is needed to confirm age and maturity ranges which influence jumping and hopping ability in girls. These studies should include pre-PHV participants and girls under 11 years old.

4.2.4 Effect of hypermobility

The present study revealed that total GJH score moderated the triple broad hop right and the triple broad hop left. Subsequent correlation analysis was performed to determine the relationship between changes in the triple broad hops after the plyometric training program. The correlation analysis revealed that total GJH score only moderated the plyometric training effect on left leg triple broad hop performance, whereas total GJH score and training volume together significantly moderated the plyometric training effect on right leg triple broad hop performance. Given the negative correlations, this finding indicates that a lower total GJH score is associated with a higher ability to perform repetitive horizontal hops. Increased GJH may negatively affect force transmission and tissue elasticity, potentially leading to excessive tissue strain and joint excursions, thus causing a decreased ability to control landing forces through an appropriate deformation (Simmonds, 2022). Under these conditions, the ability to rebound effectively off the ground is diminished (Getchell and Roberton, 1989; Tveter and Holm, 2010). Comparisons to previous literature for this parameter are not possible since there are no studies that have investigated the moderating effect of total GJH score on plyometric training in girls. Thus, further investigations are required to clarify this moderating effect of total GJH score on plyometric training in girls, and the effect of total GJH score overall on physical qualities like speed, power, strength, and stiffness in girls.

4.2.5 Limitations

The results of the present study must be interpreted with caution due to a few limitations. The first limitation was that many participants were excluded due to low attendance rates, or missing data. This removal resulted in a final sample size of 23, which was less than the required sample size of 26 obtained from the power analysis, reducing the statistical power to observe a true effect (Turner et al., 2015). The second limitation is that only post-PHV girls were evaluated. This resulted in unequal representation of participants of different chronological and biological ages. Therefore, we recommend replicating this study using pre-PHV participants and comparing them to post-PHV participants. Lastly, considering the high level of coordination required for horizontal movements and the practicality of teaching exercises to youth, it is our recommendation to give a longer familiarization period for horizontally directed plyometric exercises. The present investigation used a minimal dose of intervention exercises during the 1-week familiarization. Upon reflection, this period and dose is deemed insufficient to properly familiarize participants to horizontal plyometric exercises. Thus, 2 weeks of familiarization before executing an 8-week training period would presumably give a more appropriate plyometric training dose to elicit improvement in horizontal plyometric exercises and potentially RSI.

5 Conclusion

The present study concludes that 8 weeks of horizontal plyometric training can improve unilateral absolute leg stiffness in post-PHV female volleyball players, and this training effect can be moderated by body mass. Furthermore, the training effect on triple broad hopping performance on the right leg can be moderated by combined training volume with total generalized joint hypermobility. This finding suggests leg stiffness, reactive strength index, single and triple horizontal jumping and hopping may require different training dosages in post-PHV female volleyball players. Future recommendations include utilizing a longer familiarization period, a longer intervention period, and investigations that include pre-PHV participants.

6 Practical implications

It seems that an 8-week horizontal plyometric training intervention increases absolute leg stiffness in post-PHV female volleyball players and that out of the observed moderators, only initial body mass of the players may influence the training effect. Concerning training induced changes, it seems that increases in leg stiffness indicate positive changes from both a performance related and an injury-prevention related point of view. However, no other observed parameter was improved after the intervention. For practitioners, it must be stressed that the results of the present study should be used with caution as specific programming parameters (horizontal plyometric exercises and their progression, etc.), program duration and volume, were applied to a specific group of post-PHV female volleyball players. Moreover, results of the study, in some cases, contradict the findings regarding studies with girls of similar characteristics. Therefore, further investigation is needed in this field to provide practitioners with valid plyometric training recommendations.

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 Auckland University of Technology Ethics Committee and Ethics Committee of the Faculty of Physical Culture, Palacký University Olomouc. 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

RS: Conceptualization, Data curation, Investigation, Methodology, Project administration, Writing–original draft. ML: Methodology, Resources, Supervision, Writing–review and editing. IH: Data curation, Investigation, Project administration, Writing–review and editing. JK: Formal Analysis, Methodology, 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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The importance of core strength for change of direction speed

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Change of direction speed (CODS) is determined by several physical aspects, such as linear sprint speed, reactive strength and power of leg muscles. It appears that core strength may also play a role in CODS, however, its relationship to CODS remains unclear. The aim of this narrative review was to analyze the literature addressing a) the relationship between core strength and CODS and b) the effect of core strength training on CODS. This analysis revealed a significant relationship between the parameters of core strength and stability (the pressure of the activated core muscles during lower limb movement and the greatest mean force output of maximum volunteered contraction) and the time in the Agility T-Test. However, this parameter was not significantly related to the strength endurance of core muscles (total time in the plank test). Core training provides a sufficient stimulus for the development of CODS in less-skilled middle-adolescent athletes, while its effectiveness decreases in higher-skilled adult athletes. These findings indicate that core muscle strength contributes significantly to the change of direction speed. Core training is therefore useful for improving CODS.

KEYWORDS

athletes, core muscles, core stability, core training, running speed

1 Introduction

Running is the most dominant type of locomotion in various sports such as court (tennis, squash, badminton, *etc.*) and team sports (soccer, handball, basketball, *etc.*). In this environment, there are many external stimuli (ball movements, movements of teammates and opponents, *etc.*) on the limited size of the playing field, forcing the player to change direction of running very frequently. These types of runs can be pre-planned, also known as change of direction speed, or non-planned as a response to external stimuli known as agility (Young et al., 2015). It can be assumed that these changes of direction sprints with multiple accelerations and decelerations are potentially one of the most important physical factors of athletes' performance in these sports (Bloomfield et al., 2007; Brughelli et al., 2008). It is known that the change of direction speed is determined by factors such as straight sprinting speed, and leg muscle qualities (strength, power, and reactive strength) (Young et al., 2002).

In recent years, the importance of core strength in change of direction sprints has also been discussed (Young et al., 2015). Some researchers consider the core strength as a determinant of CODS (Young et al., 2015) because they assume that an increase in core strength leads to higher athletic performance (Imai and Kaneoka, 2014; Ingebrigtsen et al., 2014). The question arises as to how many studies have investigated this issue in the last 8 years. Apparently, they assumed that core strength refers to the muscle control of the lumbo-pelvic region to maintain functional stability and ensure optimal energy transfer from the trunk to the distal segments (Akuthota and Nadler, 2004). The results of several studies showed that core strength correlated significantly with CODS (Nesser et al., 2008; Imai and Kaneoka, 2016; de Bruin et al., 2021; Ahmed et al., 2022), however, some of them revealed only a weak or poor correlation (Imai and Kaneoka, 2016; de Bruin et al., 2021). On the other hand, Cengizhan et al. (2019) did not find a significant correlation between core endurance and CODS in football players and recreationally active men. Therefore, the question remains whether and to what extent the core strength contributes to CODS in athletes. The aim of this narrative review was to analyze the literature that deals with a) the relationship between core strength and CODS and b) the effect of core strength training on CODS.

2 Association between core strength and CODS

A literature search was conducted with Semantic Scholar, ResearchGate and Academia. The search strategy included a combination of these terms: "relationship" AND "core strength" AND "change of direction speed" AND "athletes". The main inclusion criterion was that studies investigated correlations between core strength and CODS in young athletes (up to 30 years old) of different sports (cross-sectional studies only), regardless of gender and level of performance. Studies published before the year 2008 were excluded. A total of five studies investigated the relationship between core muscle strength and CODS (Nesser et al., 2008; Imai and Kaneoka, 2016; Cengizhan et al., 2019; de Bruin et al., 2021; Ahmed et al., 2022). Ahmed et al. (2022) found a significant negative correlation between the pressure of the activated core muscles during lower limb movement and time in change of direction speed test in young professional badminton players. Significant negative correlations were also revealed between total core endurance score in plank tests and time in the change of direction speed test in National Collegiate Athletic Association Division I football players, but not with right and left flexion endurance times (Nesser et al., 2018). In another study using this field-based setting, CODS was also only associated with total score in the core endurance tests but not with the side plank tests in male adolescent soccer players (Imai and Kaneoka, 2016). In the study by Cengizhan et al. (2019), no significant association was found between the CODS test and core endurance times in plank in young male professional basketball players.

A more complex study by de Bruin et al. (2021) investigated the relationship between core strength, muscular endurance and CODS in female athletes of different sports. Different results were obtained depending on the type of core strength assessment. CODS correlated significantly with the core strength measured by Biering-Sørensen tests where the outcome was the greatest mean force output of maximum volunteered contraction, but core endurance expressed by the time of holding the same position during maximum isometric contraction did not correlate significantly with CODS. No significant correlation was found between CODS and core neuromuscular control.

An overview of the studies that investigated the relationship between core strength and CODS is presented in Table 1.

3 Effect of core strength training on CODS

The search strategy included terms such as "effect" AND "core training" AND "change of direction speed" AND "athletes" as well as combinations of their synonyms. The main inclusion criterion was that the studies were experimental in nature, in which core exercises were the main content of the training programs and were applied to young athletes (up to 30 years old) of different sports at a frequency of at least twice a week. Studies were selected independently of gender and level of performance. The studies published before the year 2008 were excluded.

Theoretically, a strong core would transfer forces from the lower to the upper body with minimal dissipation of energy in the torso (Bompa, 1999; McGill, 2009). If power is generated but not transferred, this has a negative effect on performance (i.e., running, jumping, throwing, *etc.*).

In almost all of the studies examined, core strength training lasting six to 9 weeks (one study 12 weeks) was carried out in addition to the usual soccer training. With the exception of three studies (Imai et al., 2014; Prieske et al., 2016; Brull-Maria and Beltran-Garrido, 2021), all consisted of a control group, which only participated in normal soccer training, and one or two experimental groups. During the core strength training programs, almost similar core exercises and training load (frequency per week, core training load, and type of exercises) were performed. There was one study in which core exercises were performed on stable and unstable surfaces (Prieske et al., 2016).

Different results were observed after the application of core strength training on CODS in athletes of different ages and performance levels. For example, a significant improvement in CODS was observed after the application of core strength exercises in middle- and late-adolescent soccer players (Yapici, 2016; Bayrakdar et al., 2020; Brull-Maria and Beltran-Garrido, 2021; Aslan and Kahraman, 2023). In contrast, stabilization and conventional trunk exercises did not contribute to better CODS after 12 weeks of core strength training in 16-year-old soccer players (Imai et al., 2014). A significant improvement in CODS after the application of core strength exercises was also revealed in young, less-skilled soccer players (Afyon et al., 2017; Atli, 2021), while no improvement was observed in higher-skilled players (Prieske et al., 2016; Sever and Zorba, 2018).

An overview of studies that investigated the effect of core strength training on CODS is presented in Table 2.

4 Discussion

In most cross-sectional studies, a significant association between core strength and COD performance was observed (Nesser et al., 2008; Imai and Kaneoka, 2016; de Bruin et al., 2021; Ahmed et al., 2022). However, the results indicate that this association is highly influenced by the core strength parameter, which is related to CODS. For example, the findings by de Bruin et al. (2021) revealed significant correlations between CODS and the greatest mean force output of the maximum volunteered contraction in the McGill´s core strength tests, but not with total time in their endurance versions. These authors acknowledge that athletic

TABLE 1 Studies investigating correlations between core strength and CODS in athletes.

Authors	Participants	Core strength test	CODS test	Result
Ahmed et al. (2022)	Male professional badminton players (21.19 ± 1.95 years, n = 36)	Core stability–the pressure of activating core muscles during lower limb movement in mmHg)	Agility *t*-test	Core stability and Agility *t*-test ($r = -0.579$, $p < 0.001$)
de Bruin et al. (2021)	Female university athletes (n = 83)	Core strength - Biering-Sørensen test–IBE, LF, AF-explosive power output of maximum volunteered contraction in Newtons	Agility *t*-test	Core strength and Agility *t*-test
		Core endurance - Biering-Sørensen test–IBE, LF, AF–duration in seconds		IBE ($r = -0.44$, $p < 0.01$)
		Core neuromuscular control (NMC)–the changes in pressure of activating core muscles during low-load limb movement		LF ($r = -0.39$, $p < 0.01$)
				AF ($r = -0.44$, $p < 0.01$
				Core endurance and Agility *t*-test
				IBE ($r = 0.10$, $p = 0.37$)
				LF ($r = -0.06$, $p = 0.59$)
				AF ($r = -0.18$, $p = 0.10$)
				NMC and Agility *t*-test ($r = -0.12$, $p = 0.27$)
Cengizhan et al. (2019)	Male professional basketball players (17.0 ± 0.63 years, n = 21)	Core endurance–McGill tests (trunk flexor test, trunk extensor test, side bridge test in seconds)	Hexagonal Obstacle Test (HOT)	Core endurance and HOT
				Trunk flexor ($r = 0.288$, $p = 0.320$)
				Trunk extensor ($r = -0.166$, $p = 0.472$)
				Side bridge ($r = -0.265$, $p = 0.245$)
Imai and Kaneoka (2016)	High school soccer players (16.3 ± 0.5 years, n = 55)	Core endurance–prone and side plunk tests in seconds	The Step 50 agility test	Core endurance and the Step 50 Agility test
				Prone plank ($r = -0.436$, $p < 0.01$)
				Right side plank ($r = -0.222$, n.s.)
				Left side plank ($r = -0.088$, n.s.)
				Combined score ($r = -0.365$, $p < 001$)
Nesser et al. (2008)	Male National Collegiate Athletic Association Division I football players (n = 29)	Core endurance tests–McGill (trunk flexor test, trunk extensor test, left and right lateral musculature test in seconds)	Pro-Agility Shuttle Run	Core endurance and Pro-Agility Shuttle Run
				Trunk flexion ($r = -0.443$, $p < 0.05$)
				Trunk extensor ($r = -0.356$, n.s.)
				Right flexion ($r = -0.354$, n.s.)
				Left flexion ($r = -0.374$, $p < 0.05$)
				Total score ($r = -0.551$, $p < 0.01$)

IBE, isometric back extension; LF, lateral flexion; AF, abdominal flexion.

TABLE 2 Studies investigating the effect of core strength training on CODS in athletes.

Authors	Participants	Duration of core strength program	CODS tests	Frequency of trainings and type of core exercises	Result
Afyon et al. (2017)	Amateur soccer players	8 weeks	Illinois Agility Test	EG: 2 × 30 min/week	Significant improvement in both CODS tests performance in, EG (t = 0.172, $p < 0.001$, and t = 0.136, $p < 0.001$)
	Experimental group (EG) (23.17 ± 1.86 years; n = 20)		T-Drill Agility Test	Exercises: jump squat, alternate leg jump, squat, crunch, lying twist trunk, lunge, side plank, burpee, mountain climber, twist with medicine ball + normal soccer training	
	Control group (CG) (22.03 ± 0.50, n = 20)			CG–normal soccer training	
Aslan and Kahraman (2023)	Young male soccer players	6 weeks	Illinois Agility Test	EG: 3x/week, 30–45s application time vs. 45–60s rest, 2 series	Significant improvement in CODS in, EG (t = 8.520, $p < 0.001$)
	Experimental group (EG) - 12.16 ± 0.83 years, n = 12			Exercises: prone plank, side bridge, scissor flutter kick, sit up, superman, bird dog, bicycle crunch, leg lower + soccer team training	
	Control group (CG) (12.25 ± 0.62 years, n = 12)			CG: soccer team training	
Atli (2021)	18–24 years old amateur football players	6 weeks	Illinois Agility Test	EG: 3 × 15 min/week; Exercises: 10 - one side plank, elbow plank, hip extension, mountain climbers, scissors kicks, *etc.*) in 2 series with 20–35s duration + ongoing football training	Significant improvement in CODS in, EG (t = −3.86, $p = 0.01$)
	Experimental (EG) and control group (CG) (n = 20 in each group)			CG: ongoing football training	
Bayrakdar et al. (2020)	12–14-years football players	9 weeks	505 Agility	SEG + DEG: 2x/week; 6 exercises	Significant improvement in both CODS testsperformance in both experimental groups (SEG by 1.05% and 0.46%, respectively, $p < 0.05$, DEG by 2.84%, and 1.62%, respectively, $p < 0.05$)
	Static (SEG) and Dynamic (DEG) exercise group and control group (CG)		Test	SEG: side plank, shoulder bridge, plank, static crunch, leg lift, back extension + normal football training	
	(n = 10 in each group)		Arrowhead	DEG: balance ball with pocket knife, reverse crunch, russian return, shuttle, leg	
			Agility Test	lift, back extension + normal football training	
				CG: normal football training	
Brull-Maria and Beltran-Garrido. (2021)	16–18 years old soccer players	8 weeks	V-cut	SCG + GCS: 2 × 20 min/week; 10 rep. of a 10-s duration with interval of rest 10s	Significant improvement in CODS in both experimental groups ($d = 1.24$, $p < 0.001$, 3.80%).No superiority of any type of core training
	Specific core stability group (SCS) and general core stability group (GCS)			SCC: unilateral skater squat with elastic band, unilateral linear sprint with elastic band, turn and 90° pivot shift with elastic band, lateral lunge with elastic band and their progressions + usual soccer training	
	(n = 7 in each group)			GCG: frontal bridge, dorsal bridge, bird-dog, lateral bridge and their progressions + usual soccer training	
Imai et al. (2014)	16 years old soccer players	12 weeks	Step 50	SE: 3x/week; 40–60s, 2–4 sets	Nonsignificant improvements in CODS in

(Continued on following page)

TABLE 2 (*Continued*) Studies investigating the effect of core strength training on CODS in athletes.

Authors	Participants	Duration of core strength program	CODS tests	Frequency of trainings and type of core exercises	Result
	Stabilization exercises (SE) (n = 10), conventional trunk exercises (CE) (n = 9)			SE–planks, bridges, quadrupet exercises	both groups (SE–*p* = 0.212, −1.3%, ES = 0.55, CE–*p* = 0.309, −0.9%, ES = 0.38)
				CE–sit-ups, back extension	
Prieske et al. (2016)	Elite soccer players (n = 39)	9 weeks	T - Agility Test	CSTS + CSTU: 2–3x30 min s/week	Nonsignificant improvement in CODS in both groups (CSTS - −0.2%, CSTU–0.6%)
	Core-strengthening exercises under stable (CSTS) and unstable surface (CSTU)			5 exercises were changed every 2 weeks; 15–20s (isometric conditions) or 15–20 rep. (dynamic condition) in 2–3 sets; exercises: prone plank, shoulder bridge, crunches, back extension, side bridges*etc.*	
				CSTS–all exercises on stable surface (floor, bench)	
				CSTU–all exercises on unstable surfaces + regular in-season soccer strength training in both groups	
Sever and Zorba (2018)	Semiprofessional soccer players	8 weeks	505 Agility Test	SG + DG: 3 × 30 min s/week; 25–60s in 2 series; 25–45 rep. in 2 sets	Nonsignificant improvements in CODS in both experimental groups (SG - −1.11%, and −0.7%, respectively, DG - −1.70%, and −0.73%, respectively)
	Static group (SG) - 18.2 ± 1.8 years (n = 14)		Arrowhead Agility Test	SG–side plank, shoulder bridge, crunch, leg raise, back extension + normal soccer training	
	Dynamic group (DG) −17.3 ± 0.6 years (n = 13)			DG–swiss ball jackknife, reverse crunch, Russian twist, leg raise, back extension + normal soccer training	
	Control group (CG) - 17.7 ± 1.3 years (n = 11)			CG–normal soccer training	
Yapici (2016)	Amateur soccer players	6 weeks	Zig-Zag Agility Test	EG: 3x/week; 15 s with rest interval of 60s in 2–3 sets	Significant improvement in CODS in both groups (EG–Z = −2.38, *p* = 0.02, CG–Z = −2.52, *p* = 0.01)
	Experimental group (EG) - 13.75 ± 0.46 years; (n = 16)			Exercises: plank, side plank, crunch, bird dog, shoulder bridge, ball abductor crunch, squat, lunge + football training	
	Control group (CG) - 13.71 ± 0.34 years (n = 16)			CG–football training	

performance in different sports is associated with different components of core stability. Although performance in terms of total score in isometric core endurance tests (planks) was significantly correlated with CODS (Nesser et al., 2008; Imai and Kaneoka, 2016), nonsignificant correlation was revealed with the time in lateral planks (Nesser et al., 2008; Imai and Kaneoka, 2016). Cengizhan et al. (2019) did not confirm the relationship between CODS and endurance of core muscles when the plank tests were used. On the other hand, CODS was associated with core strength when the parameter was the pressure gauge during lower limb movement (Ahmed et al., 2022) and core strength was measured by the maximum volunteered contraction in plank tests (de Bruin et al., 2021). It seems that the assessment of core strength should not include isometric core endurance tests such as planks, back extensions, *etc.*, which do not reflect the dynamic movements specific to many sports. Core strength endurance tests require subjects to maintain a static muscle contraction over a prolonged period of time in trunk flexion, extension and lateral flexion. Athletic performance is primarily dynamic and intermittent, whereas static tests are performed in a non-functional static position, and they do not reflect the actual demands of sport-related activities (Shinkle et al., 2012). It seems that gender, age, and level of performance has not a significant effect on the relationship between core strength and CODS.

Based on the results of cross-sectional studies, this narrative review also analysed studies that investigated the effect of core training on the CODS. The core muscles provide the body's stability in connection with the skeletal system of the trunk area and has a positive effect on athletic performance (Behm et al., 2010). It plays a pivotal role in effective biomechanical function to generate force and reduce joint loading (Kibler et al., 2006). Six out of nine experimental studies confirmed the positive effect of core strength training on CODS (Yapici, 2016; Afyon et al., 2017; Bayrakdar et al., 2020; Atli, 2021; Brull-Maria and Beltran-Garrido, 2021; Aslan and Kahraman, 2023), while three of them did not observe any significant improvement in CODS after core strength training (Imai et al., 2014; Prieske et al., 2016; Sever and Zorba, 2018). The results suggest that core strength training improves COD performance mainly in middle and late-adolescent athletes (Yapici, 2016; Bayrakdar et al., 2020; Brull-Maria and Beltran-Garrido, 2021; Aslan and Kahraman, 2023) or less-skilled athletes (Yapici, 2016; Afyon et al., 2017), while the effect was not significant in semiprofessional and elite athletes (Prieske et al., 2016; Sever and Zorba, 2018). This can be attributed to their higher CODS level, so that the additional core training does not provide sufficient stimulus for its improvement. There was only one study that did not meet these criteria (Imai et al., 2014), which may be attributed to the absence of a control group and the more coordinatively demanding CODS test. It is more likely that other factors played a role in the Step 50 test than in the usual, less coordination-demanding CODS tests.

To sum up, it seems that core muscle strength plays an important role in the change of direction speed. However, the ability to generate the highest possible activation force of the core muscles in a short period of time is more important for an effective speed of change of direction rather than the endurance strength of core muscles. Core strength training is effective for improving CODS when applied to adolescent or less-skilled athletes. Core programs of semi-professional and professional athletes' should include more functional and sport-specific core exercises with closed kinematic chains to improve CODS.

There is a need to provide further insight into the relationship between core strength and CODS identify the most appropriate core test variables that more closely reflect athletic performance. The correlation between maximal core strength and performance in CODS tests is also necessary to determine to what extent the core muscle strength contributes to better CODS.

Author contributions

HH: Conceptualization, Data curation, Formal Analysis, Methodology, Writing–original draft, Writing–review and editing. EZ: Conceptualization, Formal Analysis, Supervision, Writing–review and editing.

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Conflict of interest

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

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Hydrogen-rich water supplementation promotes muscle recovery after two strenuous training sessions performed on the same day in elite fin swimmers: randomized, double-blind, placebo-controlled, crossover trial

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Purpose: Molecular hydrogen has been shown to possess antioxidant, anti-inflammatory, ergogenic, and recovery-enhancing effects. This study aimed to assess the effect of molecular hydrogen administration on muscle performance, damage, and perception of soreness up to 24 h of recovery after two strenuous training sessions performed on the same day in elite fin swimmers.

Methods: Eight females (mean ± SD; age 21.5 ± 5.0 years, maximal oxygen consumption 45.0 ± 2.5 mL.kg^{-1}.min^{-1}) and four males (age 18.9 ± 1.3 years, maximal oxygen consumption 52.2 ± 1.7 mL.kg^{-1}.min^{-1}) performed 12 × 50 m sprints in the morning session and a 400 m competitive performance in the afternoon session. Participants consumed hydrogen-rich water (HRW) or placebo 3 days before the sessions (1,260 mL/day) and 2,520 mL on the experimental day. Muscle performance (countermovement jump), muscle damage (creatine kinase), and muscle soreness (100 mm visual analogue scale) were measured during the experimental day and at 12 and 24 h after the afternoon session.

Results: HRW compared to placebo reduced blood activity of creatine kinase (156 ± 63 vs. 190 ± 64 U.L^{-1}, p = 0.043), muscle soreness perception (34 ± 12 vs. 42 ± 12 mm, p = 0.045), and improved countermovement jump height (30.7 ± 5.5 cm vs. 29.8 ± 5.8 cm, p = 0.014) at 12 h after the afternoon session.

Conclusion: Four days of HRW supplementation is a promising hydration strategy for promoting muscle recovery after two strenuous training sessions performed on the same day in elite fin swimmers.

Clinical Trial Registration: clinicaltrials.gov, identifier NCT05799911

KEYWORDS

molecular hydrogen, creatine kinase, exercise-induced muscle damage, exercise, muscle pain, peripheral fatigue

1 Introduction

Participation in fin swimming has increased worldwide. Fin swimming is metabolically demanding and this is particularly due to using a specialized fin(s) that propels the swimmer at great speeds (Wang et al., 2012). Well-trained fin swimmers, similarly to non-fin swimmers, perform two water-training sessions a day (Stavrou et al., 2019), including high-intensity interval training (HIIT) (Aspenes and Karlsen, 2012; Budnik-Przybylska et al., 2018), which typically involves repeated high-intensity short intervals interspersed with active or passive recovery (Buchheit and Laursen, 2013). HIIT is a very popular training method, however it is associated with exercise-induced muscle damage (EIMD), evidenced by increased protein such as creatine kinase (CK), myoglobin, and lactate dehydrogenase in the bloodstream together with elevated muscle pain manifesting immediately post-exercise to several days after HIIT (Leite et al., 2023). Moreover, during high-intensity exercise such as repeated sprinting, formation of excessive reactive oxygen and nitrogen species may cause exercise-induced oxidative damage to cellular structures and mitochondrial fatigue (Calbet et al., 2020). The origin of EIMD is linked with metabolic and/or mechanical stress, including oxidative stress and inflammation (Pyne, 1994; Peake et al., 2017). The severity of the EIMD depends on the type, intensity, and duration of the exercise (Tee et al., 2007), as well as on individual training status (Brancaccio et al., 2010). Further, EIMD has been associated with the transient loss of muscle strength and power, swelling, and delayed onset muscle soreness (DOMS) (Peake et al., 2017), which typically peaks 24–48 h after strenuous or unaccustomed exercise (Cheung et al., 2003). Traditionally, impairment in lower limb muscle function due to EIMD has been assessed via the measurement of countermovement jump (CMJ) height (Markovic et al., 2004).

Exercise-induced muscle pain can be noninvasively evaluated using psychometric tools such as the visual analogue scale (VAS) (Heller et al., 2016), while the activity of blood CK is widely accepted as an indirect biomarker of both EIMD and changes in membrane permeability (Brancaccio et al., 2010) that involves both connective tissue and muscle cells (Mougios, 2007; Baird et al., 2012; Peake et al., 2017). The VAS is the most frequently used and reliable, non-invasive method for the evaluation of pain severity and relief (Price et al., 1983; Boonstra et al., 2008). Furthermore (Kawamura et al., 2018), found a significant correlation at 24 and 48 h after exercise between VAS, CK, and plasma pro-inflammatory interleukin-6 concentration. However, correlations between VAS and blood CK activity are not consistent (Hartmann and Mester, 2000). In contrast to other sports, swimming generally involves mainly non-weight-bearing activities and concentric contractions of the upper and lower limb muscles that result in minor muscle damage and only a small increase in the activity of blood CK (Mougios, 2007). Despite this fact, some studies have reported a significant increase in blood CK activity immediately after (Deminice et al., 2010), at 1 h (Tauler et al., 2008), and at 24 h after strenuous swimming (Rahmanian et al., 2022).

Molecular hydrogen (H_2) is suggested as a healthy and safe gas (Nicolson et al., 2016; Cole et al., 2022; Salomez-Ihl et al., 2024) with a potent antioxidant effect (Ohsawa et al., 2007). In addition to its antioxidant properties, H_2 has been found to have anti-inflammatory properties (Gharib et al., 2001), antiapoptotic properties (Nicolson et al., 2016), and properties that modulate signal transduction and gene expression (Ohta, 2014; Slezak et al., 2021). Due to its health benefits (Ohta, 2014; Ichihara et al., 2015; Botek et al., 2022b; Johnsen et al., 2023), supplementation with H_2 has become popular among athletes to enhance performance and reduce fatigue (LeBaron et al., 2019; Botek et al., 2020; Kawamura et al., 2020; Shibayama et al., 2020; Botek et al., 2021; Timón et al., 2021; Botek et al., 2022a; Jebabli et al., 2023; Zhou et al., 2023). Several recent studies demonstrated that H_2 reduces exercise-induced pro-inflammatory response and oxidative stress (Ara et al., 2018; Nogueira and Branco, 2021), blood lactate concentrations and improves muscle function (Aoki et al., 2012; Botek et al., 2021). In addition to its physiological benefits, H_2 may also reduce perception of muscle soreness after a single-strength training session (Todorovic et al., 2020; Botek et al., 2021; Yoshimura et al., 2023) and after down-hill running (Kawamura et al., 2016). However, there is still limited research examining the effects of hydrogen-rich water (HRW) supplementation on muscle damage and perception of muscle soreness within and after two physically highly demanding exercise sessions performed on the same day during routine training periodization in elite fin swimmers.

Therefore, the primary objective of this study was to evaluate the effect of HRW ingestion on muscle function, damage, and soreness perception up to 24 h of recovery after two strenuous training sessions performed on the same day in elite fin swimmers.

2 Materials and methods

2.1 Participants

Fourteen national and international elite Czech fin swimmers participated in the study. Two swimmers did not complete the protocol due to injury (one participant) and illness (one participant), with the final population consisting of 12 participants (eight females and four males, Figure 1). The characteristics of the participants are shown in Table 1. The study was carried out according to the Declaration of Helsinki and was approved by the Ethics Committee

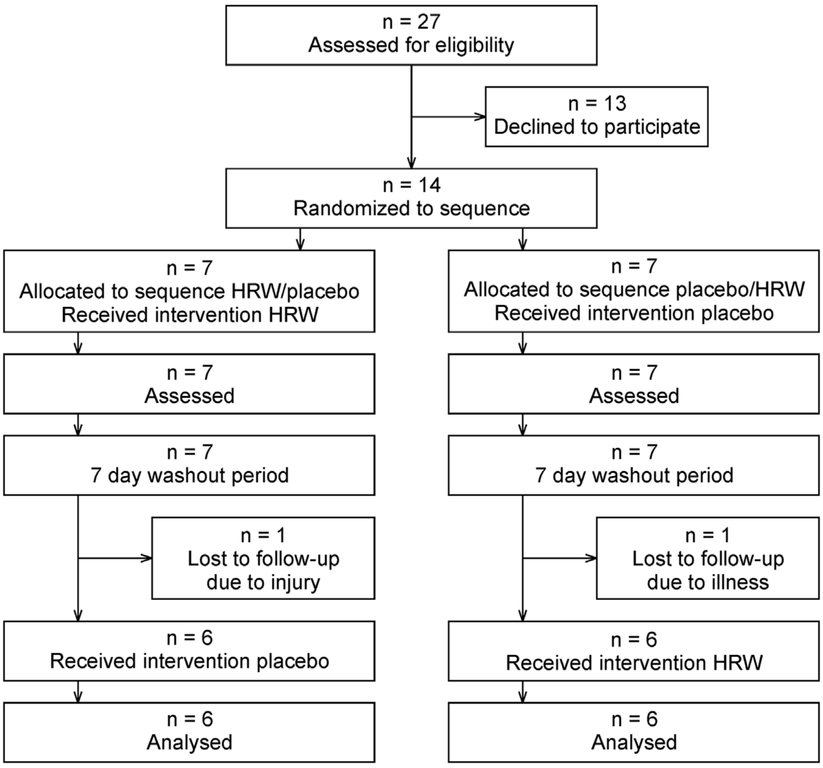

FIGURE 1
CONSORT flow diagram. HRW, hydrogen-rich water.

TABLE 1 Characteristics of the fin swimmers.

Variable	Female	Male	*p*
	Mean ± SD	Mean ± SD	
Sample size	8	4	
Age (years)	21.5 ± 5.0	18.9 ± 1.3	0.72
Body height (cm)	164 ± 6	184 ± 9	0.004
Body mass (kg)	62 ± 7	78 ± 10	0.012
BMI (kg.m^{-2})	22.8 ± 1.2	23.1 ± 1.9	0.81
Body fat (%)	22.0 ± 1.5	12.1 ± 4.6	0.004
VO_2max (mL.kg^{-1}.min^{-1})	45.0 ± 2.5	52.2 ± 1.7	0.004

SD, standard deviation; *p*, statistical significance of the comparison between males and females (Mann-Whitney U test); BMI, body mass index; VO_2max, maximal oxygen consumption.

of the Faculty of Physical Culture, Palacký University Olomouc (reference number 11/2023). Participation in the study was voluntary and written informed consent was provided after detailed verbal explanation of the objectives and protocol. Participants were requested to not take any supplements at least 2 weeks before the experiment and to avoid strenuous exercise in the 24 h before the first morning session. In addition to HRW/placebo supplementation, a dose of 0.5–1.0 L of tap water was recommended during the simulated racing day. During the recovery on the following day, participants were requested to keep hydrated, drinking between 1.5 and 2.5 L of tap water.

2.2 Experimental protocol

The study had a randomized, double-blind, placebo-controlled, crossover design and was performed in a swimming pool and laboratories of the Faculty of Physical Culture, Palacký University Olomouc, Olomouc, Czech Republic. The protocol of this study was registered on ClinicalTrials.gov (NCT05799911). The experimental protocol (Figure 2) consisted of two swimming testing days, with each testing day including two swimming pool training sessions in a 25 m long indoor swimming pool and monitoring of recovery for 24 h after the second session. The initial assessment (IA) began at 7 a.m. The

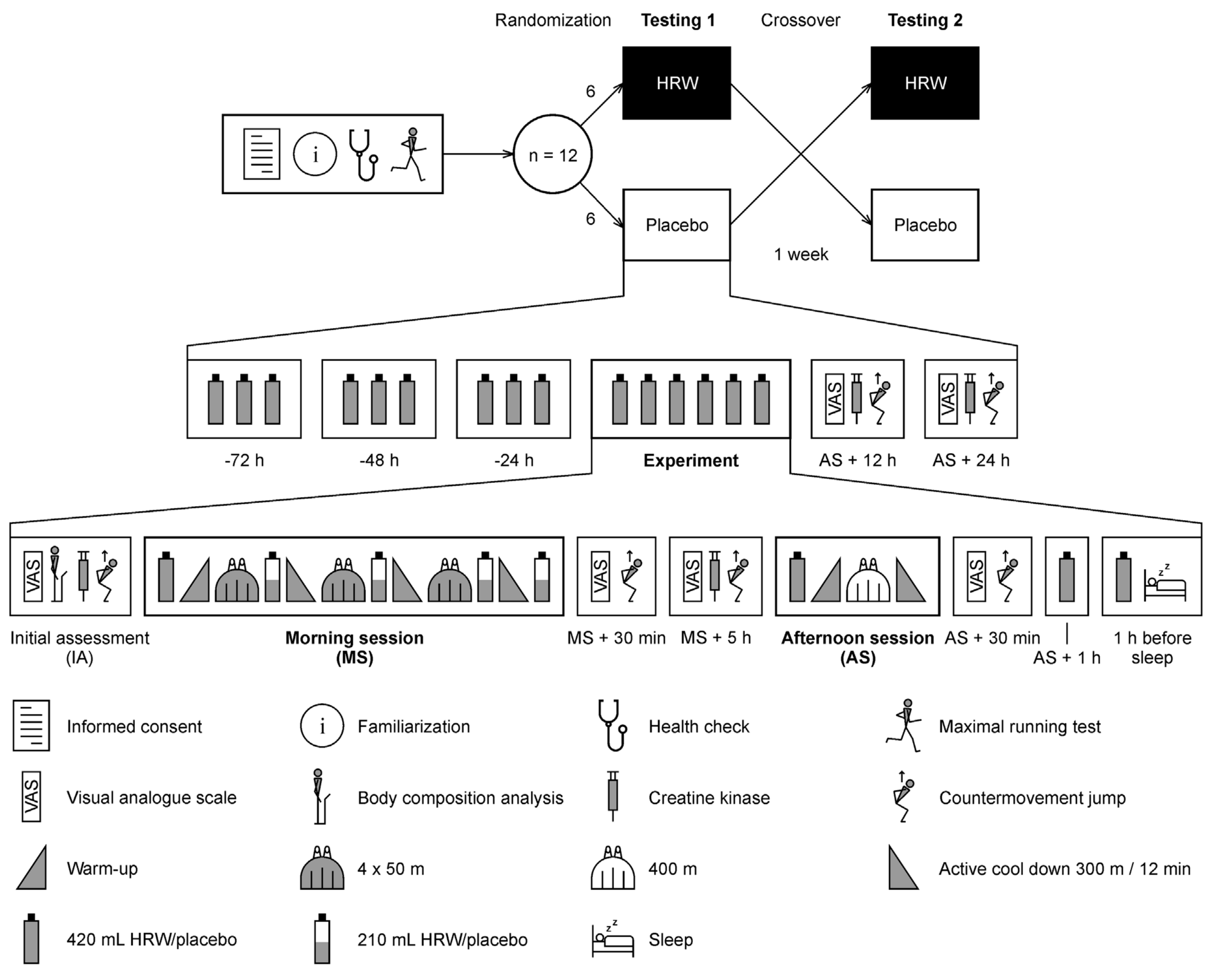

FIGURE 2
Overview of the study protocol. HRW, hydrogen-rich water.

morning fin swimming session (MS) took place between 9 and 11 a.m. and included three high-intensity interval sets consisting of maximum 4 × 50 m swims. The time interval to complete the swim and rest was always 1 min (participants completed 50 m and rested for the remaining time up to 1 min). Between each set and after the last one, there were 300 m and 12 min of active cool down. The afternoon fin swimming session (AS) took place between 5 and 6 p.m. and included 400 m of continuous competitive performance and 300 m of active cool down. A 1,400 m warm-up was performed prior to each training unit. The washout between the tests was 1 week as was used in previous studies (Botek et al., 2021; 2022a; Valenta et al., 2022).

2.3 HRW and placebo characteristics and administration

The HRW (Aquastamina-R, Nutristamina, Ostrava, Czech Republic) and placebo (Aquastamina-H_2 free, Nutristamina, Ostrava, Czech Republic) were contained within 420 mL plastic aluminum packages with a gas-tight cap. HRW/placebo characteristics were as follows: pH 7.9/7.7, oxidation-reduction potential −652/+170 mV, temperature 20/20°C (pH/ORP/Temperature-meter AD14, Adwa Instruments, Szeged, Hungary), and dissolved H_2 concentration 0.9/0.0 ppm (H2Blue reagent, H2 Sciences, Henderson, NV, USA). Because H_2 is colorless, odorless, and tasteless (Nicolson et al., 2016), it was not possible to distinguish HRW from placebo. The type of water (HRW/placebo) was indicated on the pack using different batch numbers. The details of the batch numbers were kept confidential by the manufacturer until the experiment was completed. Three days before testing, the participants were provided with 1,260 mL of HRW/placebo (divided into three 420 mL doses). On the day of the test, the supplementation strategy was as follows: 420 mL HRW/placebo just before MS, 210 mL after each set of swimming (morning), and after the final cool down (total 1,260 mL). Another 420 mL immediately before AS and 1 hour after AS. The last pack (420 mL) was administrated 1 hour before going to sleep. The order of HRW/placebo or placebo/HRW was determined for each participant based on a randomization table created at the beginning of the study by a technical staff member not involved in the experimental part using a random number generator (MATLAB R2020a, MathWorks, Natick, USA).

2.4 Visual analogue scale

The VAS was used to assess lower limb muscle pain before the exercise protocol, 30 min and 5 h after MS, and 30 min, 12 and 24 h after AS. The VAS was a horizontal 100 mm length line, marked with 0, indicating "no pain" and 100 indicating the "worst imaginable pain" (Crichton, 2001). Participants were asked to assume the position of an unweighted squat at approximately 90° of knee flexion and mark perceived pain on the 100 mm VAS (Twist and Eston, 2005; Jakeman et al., 2010).

2.5 Creatine kinase

CK was determined in a capillary blood sampled from the fingertip. An alcohol wipe was used to clean the fingertip and the skin was punctured with a lancet (Accu-Chek, Roche Diagnostics, Rotkreuz, Switzerland). The first drop was wiped away and the second drop was used. A Reflotron applicator with a 32 µL disposable pipette tip was used to extract a 32 µL sample of blood and place it on a CK assay strip (Reflotron CK strips, Roche Diagnostics, Rotkreuz, Switzerland). The blood sample was analyzed using a spectrophotometer (Reflotron Plus, Roche Diagnostics, Rotkreuz, Switzerland) to determine the whole blood CK activity. CK was monitored before the exercise protocol, 5 h after MS, and 12 and 24 h after AS.

2.6 Countermovement jump

Each participant completed an individual warm-up procedure consisting of running at an intensity of 50% of their perceived maximum speed for 3 min, ten squats, and one submaximal CMJ. After 1 minute of rest, each participant performed three single maximum effort CMJs with 30 s of rest between jumps. The starting position for the CMJ was an upright posture with the hands placed on the hips. Vertical ground reaction force was measured on two parallel force platforms (AMTI OR6-7-1,000, Advanced Mechanical Technology, Watertown, MA, USA) with a sampling frequency of 1,000 Hz. A quiet standing period of 2 s was recorded prior to the initiation of each CMJ to ensure an initial velocity of zero and to calculate the body mass. The jump height was calculated from the force-time curve using the formula published by (Vaverka et al., 2013). The average jump height calculated from three CMJs was used for statistical analysis. CMJ was measured before the exercise protocol, 30 min and 5 h after MS, and 30 min, 12 h, and 24 h after AS.

2.7 Statistical analysis

Power analysis was performed using G*Power version 3.1.9.7 (Faul et al., 2007). The level of statistical significance was set at α = 0.05 and power was set at 1-β = 0.80. Based on previous studies with a crossover design (Kawamura et al., 2016; Botek et al., 2021), the effect of HRW in this research was estimated to be d_z = 0.8, expressed as Cohen's d of the difference scores (Lakens, 2013). Assuming a paired one-tailed *t*-test, the result for the required sample size was 12 participants.

Statistical analyses were performed using MATLAB R2020a with Statistics Toolbox (MathWorks, Natick, MA, USA). Data are presented as an arithmetic mean ± standard deviation. Characteristics between females and males were compared using the Mann-Whitney U test due to the small sample size of the male group. The assumption of normality for CK, VAS and CMJ was assessed using the Shapiro-Wilk test. The sphericity was assessed using the Mauchly test. The effect of HRW compared to placebo was evaluated using a paired two-tailed *t*-test for each time point. Therefore, a set of 4, 6 and 6 tests for CK, VAS, and CMJ, respectively, were used. The significance level was set at α = 0.05. The Holm-Bonferroni method (Holm, 1979) was used to control the family-wise error rate. The statistical level for the set of t-tests was adaptive and the actual level was calculated in an iterative procedure based on the number of rejected null hypotheses. The difference score between HRW and placebo (Δ = HRW - placebo) was expressed using a 95% confidence interval (CI). The effect size was evaluated using Cohen's *d*, where the standard deviation was calculated as the pooled value of the standard deviations for males and females on a placebo. The following thresholds recommended for athletes (Hopkins et al., 2009) were used to interpret the magnitude of Cohen's *d*: trivial 0.00–0.19, small 0.20–0.59, moderate 0.60–1.19, and large ≥1.20.

To examine the individual responses, the minimum clinically important difference (MCID) was established and the frequencies of positive responders ($\Delta \geq$ MCID), non-responders (MCID $> \Delta >$ −MCID), and negative responders ($\Delta \leq$ −MCID) were calculated. The significance of the odds ratio of positive/negative responders was evaluated using a chi-square test. No clinical or physiological criteria have been established to determine the MCID for CK (Machado and Willardson, 2010). Therefore, a value of 37 U.L^{-1} previously determined in the study (de Sousa Neto et al., 2022) was reused for the MCID. A systematic review by (Olsen et al., 2017) included 37 studies and reported a range of 8–40 mm for MCID in acute pain. Thresholds for differences should be lower in highly trained athletes than in recreationally trained or untrained individuals (Rhea, 2004). Therefore, in this study, we adopted the lower limit of 8 mm as the MCID for VAS. The MCID for CMJ height was recommended to be 0.2 between-subject standard deviation (Turner et al., 2015; Warr et al., 2020). The CMJ was measured three times for each occasion, therefore, it was possible to calculate the technical error according to (Hopkins, 2015). The relationship between the two difference scores was assessed using Pearson's correlation coefficient.

3 Results

Raw data are available in the Supplementary Material. The characteristics of participants are presented in Table 1. As expected, there were significant differences in body height, body mass, body fat, and maximal oxygen consumption between females and males. Each participant received 2.8 mmol of H_2 dissolved in a total of 6,300 mL of HRW during the experimental protocol. The dose relative to body mass was 46.6 ± 6.1 µmol kg^{-1} for females and 36.6 ± 4.5 µmol kg^{-1} for males. The difference in relative dose was statistically significant (p = 0.012), which was caused by the statistically significant difference in body mass (p = 0.012, Table 1).

TABLE 2 Effect of hydrogen-rich water on creatine kinase, visual analogue scale, and countermovement jump.

Variable	HRW	Placebo	Effect of HRW	p	d
	Mean ± SD	Mean ± SD	Δ (95% CI)		
CK ($U.L^{-1}$)					
IA	155 ± 49	156 ± 73	−1 (−33 to 31)	0.92	−0.02
MS + 5 h	201 ± 65	210 ± 64	−9 (−55 to 38)	0.69	−0.14
AS + 12 h	156 ± 63	190 ± 64	−34 (−66 to −1)	0.043	−0.53
AS + 24 h	155 ± 54	175 ± 66	−21 (−43 to 1)	0.064	−0.30
VAS (mm)					
IA	23 ± 10	27 ± 8	−4 (−9 to 1)	0.13	−0.47
MS + 30 min	56 ± 18	54 ± 17	2 (−7 to 11)	0.57	0.14
MS + 5 h	45 ± 12	47 ± 16	−3 (−8 to 3)	0.33	−0.17
AS + 30 min	48 ± 19	46 ± 17	2 (−5 to 10)	0.54	0.14
AS + 12 h	34 ± 12	42 ± 12	−7 (−15 to 0)	0.045	−0.74
AS + 24 h	29 ± 10	29 ± 9	0 (−3 to 4)	0.78	0.05
CMJ (cm)					
IA	30.3 ± 5.4	30.4 ± 5.6	0.0 (−0.9 to 0.8)	0.94	−0.01
MS + 30 min	28.8 ± 5.6	29.1 ± 5.9	−0.3 (−1.0 to 0.4)	0.40	−0.06
MS + 5 h	30.9 ± 5.6	30.4 ± 5.7	0.5 (−0.5 to 1.4)	0.29	0.12
AS + 30 min	30.7 ± 5.7	29.7 ± 5.6	1.0 (0.0 to 2.0)	0.041	0.23
AS + 12 h	30.7 ± 5.5	29.8 ± 5.8	0.9 (0.2 to 1.7)	0.014	0.21
AS + 24 h	31.2 ± 5.2	30.3 ± 5.9	0.9 (0.0 to 1.8)	0.053	0.21

HRW, hydrogen-rich water; SD, standard deviation; Δ, difference between hydrogen-rich water and placebo; CI, confidence interval; p, statistical significance of paired t-test; d, Cohen's d effect size; CK, creatine kinase; VAS, visual analog scale used to assess muscle soreness; CMJ, countermovement jump height; IA, initial assessment; MS, the morning session; AS, the afternoon session.

The effects of HRW on CK, VAS, and CMJ are given in Table 2; Figure 3. However, since the sphericity was rejected for CK ($p <$ 0.001), VAS (p = 0.002), and CMJ (p = 0.001), individual paired t-tests were used to evaluate the effects of HRW compared to placebo instead of repeated measures analysis of variance. HRW decreased CK at all times compared to placebo, but a statistically significant decrease was found only 12 h after AS (HRW: 156 ± 63 $U.L^{-1}$, placebo: 190 ± 64 $U.L^{-1}$, p = 0.043, d = −0.53, small effect). In the remaining times, the decreases were not statistically significant (all $p \geq 0.064$, Table 2). HRW also statistically significantly reduced VAS 12 h after AS (HRW: 34 ± 12 mm, placebo: 42 ± 12 mm, p = 0.045, d = −0.74, moderate effect). However, in the remaining times, the changes were not statistically significant (all $p \geq 0.13$, Table 2). HRW significantly improved CMJ 12 h after AS (HRW: 30.7 ± 5.5 cm, placebo: 29.8 ± 5.8 cm, p = 0.014, d = 0.21, small effect). In the remaining times, the changes were not statistically significant ($p \geq 0.041$, Table 2). Note that p = 0.041 30 min after AS was not considered significant because, according to the Holm-Bonferroni method, in the case of two concurrent significant outcomes, both p-values must be less than 0.025.

The analysis of individual responses is shown in Figure 4. For CK 12 h after AS, four participants (3 males, 1 female) responded positively to HRW (decrease in CK greater than MCID), eight participants (1 male, seven females) did not respond, and no participants responded negatively. The odds ratio of positive/negative responders (4/0) was statistically significant (p = 0.046, chi-square test). For VAS 12 h after AS, four participants (1 male, three females) responded positively to HRW (decrease in VAS greater than MCID), eight participants (3 males, 5 females) did not respond, and no participants responded negatively. The odds ratio of positive/negative responders (4/0) was statistically significant (p = 0.046, chi-square test). Between-subject standard deviation for CMJ height 12 h after AS on placebo was 5.2 and 4.2 cm for males and females, respectively. Consequently, the pooled standard deviation was 4.5 cm and the MCID was 0.2 × 4.5 = 0.9 cm. Based on the data from this study, the technical error for CMJ height came out to be 0.5 cm. The analysis of individual responses in CMJ height 12 h after AS, showed that four participants (1 male, three females) responded positively to HRW (increase in height greater than MCID), eight participants (3 males, 5 females) did not respond, and no participants responded negatively. The odds ratio of positive/negative responders (4/0) was statistically significant (p = 0.046, chi-square test). The correlation analysis did not reveal a statistically significant relationship between changes in CK, VAS, and CMJ 12 h after AS (Figure 5).

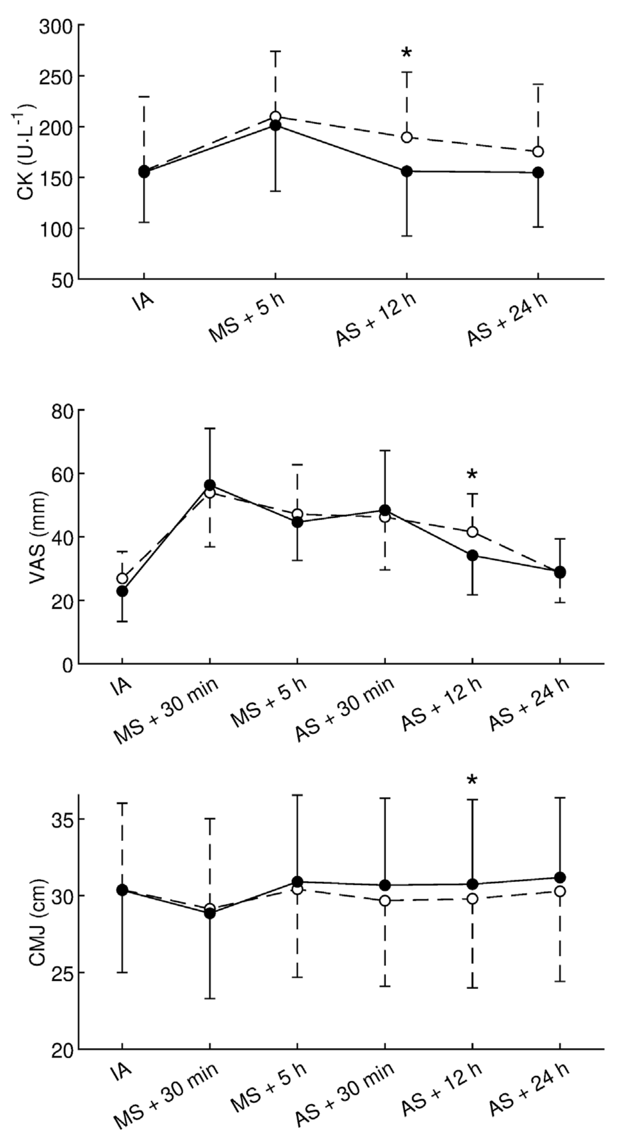

FIGURE 3
Effect of hydrogen-rich water on creatine kinase, visual analogue scale, and countermovement jump. CK, creatine kinase; VAS, visual analog scale used to assess muscle soreness; CMJ, countermovement jump height; IA, initial assessment; MS, the morning session; AS, the afternoon session; ●, hydrogen-rich water; ○, placebo; ★, statistically significant (p < 0.05, paired t-test) difference between hydrogen-rich water and placebo. Values are presented as the mean and standard deviation.

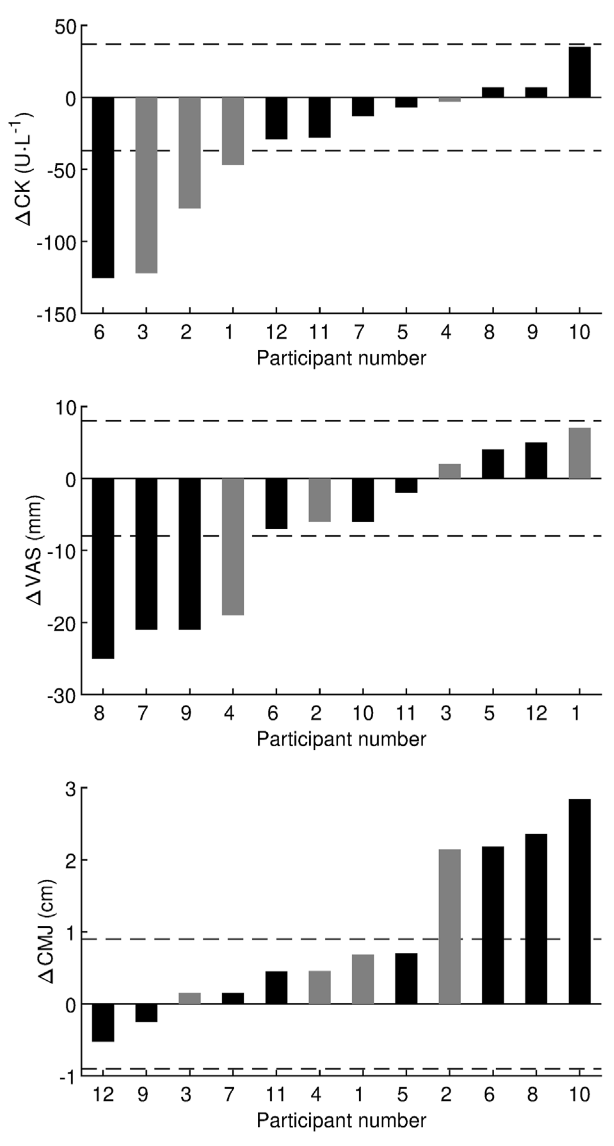

FIGURE 4
Individual responses in effect of hydrogen-rich water on creatine kinase, visual analogue scale, and countermovement jump. Δ, difference between hydrogen-rich water and placebo values obtained 12 h after the afternoon session; CK, creatine kinase; VAS, visual analog scale used to assess muscle soreness; CMJ, countermovement jump height. Black bar denotes female and gray bar denotes male. The horizontal dashed lines represent the minimum clinically important difference.

4 Discussion

To the best of our knowledge, this is the first study to show that 4 days of HRW supplementation had a beneficial effect on post-exercise muscle recovery within 24 h, after two strenuous training sessions performed on the same day in elite fin swimmers. Specifically, the primary findings were that HRW intake compared to placebo significantly a) alleviated an indirect marker of muscle damage (reduction in capillary blood CK activity), b) reduced DOMS perception, and c) improved lower limb muscle performance at the 19 and 12 h recovery time points, after the morning HIIT and afternoon fin swimming sessions, respectively.

This study shows that CK peaked at 5 h after the morning high-intensity interval fin swimming training. The minimal rise in the mean values of CK blood activity was about 40% greater than the baseline. This finding contrasts with the usual increase in CK after exercise, which is typically ~4-fold (Brancaccio et al., 2010). We assume that the specific type of physical task along with the water environment could explain the small increase in CK after exercise. This rise in CK may be because of the metabolic response to the physiological load of swimming rather than specific muscle damage (Lombard et al., 2012). To this situation (Mougios, 2007), previously reported that swimming involves mainly non-weight-bearing activities along with mostly concentric contractions that likely

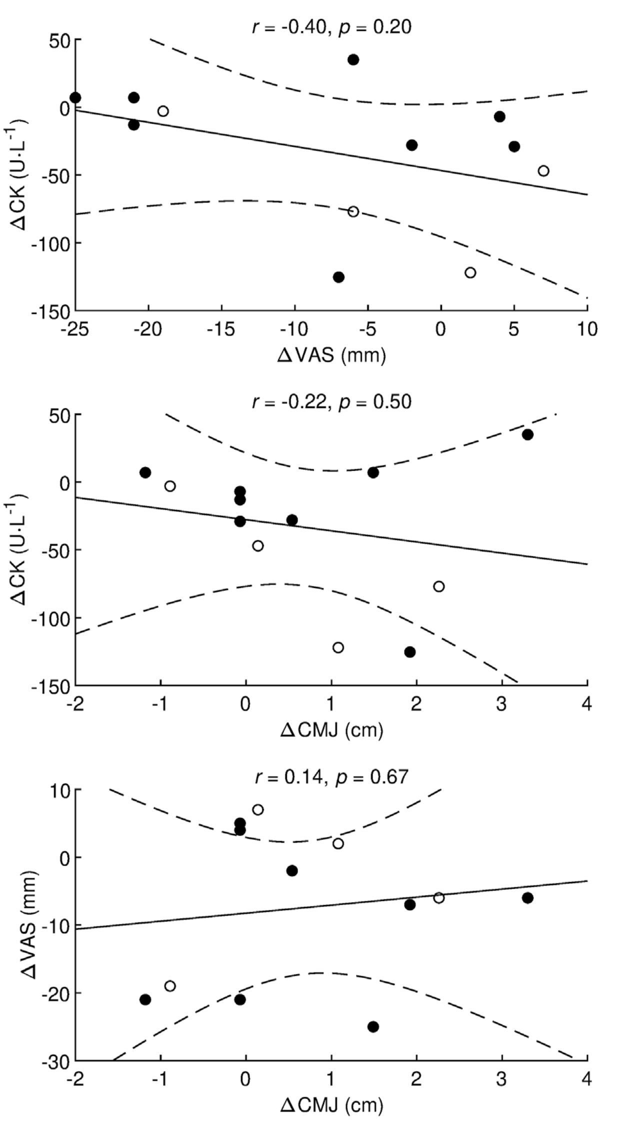

FIGURE 5
Correlation analysis between the effects of hydrogen-rich water on creatine kinase, visual analogue scale, and countermovement jump *r*, Pearson's correlation coefficient; *p*, statistical significance of the correlation coefficient; Δ, difference between hydrogen-rich water and placebo values obtained 12 h after the afternoon session; CK, creatine kinase; VAS, visual analog scale used to assess muscle soreness; CMJ, countermovement jump height; ●, females; ○, males. Dashed lines denote a 95% confidence interval.

resulted in only minor EIMD, and consequently, only a small increase in the activity of blood CK could be detected. Nevertheless, a peak in CK may be because of the presence of a mild EIMD. During recovery period, blood samples exhibited a significantly lower concentration in CK with HRW compared to placebo, particularly at 19 h after morning HIIT and 12 h after (the next morning) the second fin swimming session performed in the afternoon. It has been well documented that a progressive efflux of cytosolic CK into the blood after HIIT occurs immediately and up to several days after exercise (Leite et al., 2023). This CK efflux could result from both mechanical muscle damage and indirectly through increased permeability of muscle cell membranes (Pyne, 1994; Brancaccio et al., 2010; Peake et al., 2017). Relating to the increase in blood CK activity, a few theoretical models have been formulated explaining changes in cell membrane permeability such as an overproduction of reactive oxygen and nitrogen species during intensive exercise (Pyne, 1994; Calbet et al., 2020), or phagocyte migration into damaged muscle tissue after exercise producing both reactive oxygen and nitrogen species and pro-inflammatory cytokines (Baird et al., 2012). The increased free radical oxygen species then cause oxidative damage to cellular components such as proteins, nucleic acids, and lipids present in the cell membrane (Blake et al., 1987; Calbet et al., 2020). From an oxidative stress perspective, H_2 has been recognized as a selective antioxidant with the capability to reduce solely the most cytotoxic oxidants–hydroxyl radical (•OH) and peroxynitrite ($ONOO^-$) (Ohsawa et al., 2007; Jin et al., 2023). In this regard (Nogueira et al., 2018), previously showed, in an animal model, that 30 min of H_2 inhalation before exercise (30 min run at 80% of maximal running velocity) significantly reduced oxidative stress based on the measurement of plasma concentration of thiobarbituric acid reactive species during 3 h of recovery. Therefore, it is tenable that 4 days of extensive H_2 supplementation (6,300 mL of HRW) may alleviate muscle damage by altering the permeability of the muscle cell membrane by both reducing oxidative stress and balancing cellular redox in the muscle tissue. A lower blood CK immediately and at 24 h after recovery from HIIT was recently reported by (Todorovic et al., 2020) who showed that 30 min of whole-body bathing in supersaturated HRW (8 mg of H_2 per L) is a safe procedure that attenuates muscle damage. On the other hand, some studies did not show any significant decrease in post-exercise CK (Aoki et al., 2012; Shibayama et al., 2020; Botek et al., 2021) after H_2 administration. Although the most effective way to administer H_2, as well as what the optimal dose is, has been discussed in sports medicine for a long time (Kawamura et al., 2020), repetitive HRW consumption, particularly before, immediately after exercise, and in later phases of the post-exercise recovery may be considered a promising approach for alleviating muscle damage after physically demanding exercise.

Our study further revealed that HRW intake compared with placebo caused a significant decrease of 8 mm in muscle soreness perception on the 100 mm VAS either at 19 h after morning HIIT and at 12 h after the second fin swimming session, respectively. In this regard (Olsen et al., 2017), reported that the minimum clinically important difference of 8–40 mm on a standardized scale of 100 mm, has been established in the literature. In the current study, if we take into consideration that our elite fin swimmers carried out well-planned and highly specific drills, then even a small difference in muscle pain perception the next day, may represent practically important information about the time course of recovery or readiness to perform subsequent exercise. Similarly, to these results (Botek et al., 2021), recently observed "an analgesic effect" of HRW on DOMS perception 24 h after strenuous strength training, when 1,260 mL of HRW was applied. Furthermore (Todorovic et al., 2020), reported a significant decrease in VAS compared to placebo immediately, as well as 24 h after, high-intensity eccentric exercise indicating a beneficial effect of bathing in HRW on the progression of DOMS. A reduction in VAS perception was also reported by (Kawamura et al., 2016) who demonstrated that 1-week of H_2 bathing for 20 min, significantly reduced DOMS sensation at

24 and 48 h after a 30 min down-hill running bout at an intensity of 75% maximal oxygen consumption and a −8% slope. Though the origin of DOMS is still unclear (Armstrong, 1984; Cheung et al., 2003; Peake et al., 2017), it has been suggested that EIMD followed by cytosolic enzyme efflux, and a local inflammation response, plays an essential part in DOMS development (Peake et al., 2017; Hotfiel et al., 2018). Recently, in an animal model (Nogueira et al., 2018), found an anti-inflammatory effect of a 2% H_2 inhaled dose, 30 min before and then 30 min during exercise at 80% of maximum running velocity. Specifically, there was a significant reduction in exercise-induced pro-inflammatory plasma cytokines, particularly tumor necrosis factor alpha, interleukin-1, and interleukin-6.

Regarding DOMS, which is associated with EIMD, a significant transient reduction in muscle strength and power (Cheung et al., 2003; Brentano and Martins Kruel, 2011) up to 48 h after exercise has been reported (Peake et al., 2017). Our results show that HRW consumption, compared with placebo, enhanced the recovery of lower limb muscle performance (vertical jump height) at 19 h after the morning HIIT and at 12 h after the second fin swimming exercise. In this study, the MCID for CMJ height was determined to be 0.9 cm. The CMJ was measured three times, and the technical error was calculated to be 0.5 cm. Therefore, the technical error was less than the MCID, which is an important requirement for detecting clinically significant change (Hopkins, 2000). The improvement in CMJ height with HRW compared to placebo was 0.9 cm which is equal to MCID. Therefore, we suggest that the recovery-enhancing effect of HRW consumption, manifested through improved CMJ height, may be considered clinically significant. Recently (Shibayama et al., 2020), assessed the effect of 60 min of hydrogen-rich gas inhalation (4% of H_2) immediately after completion of a 30 min treadmill run at an intensity corresponding to 75% of maximal oxygen consumption followed by CMJ (5 sets × 10 repetitions). They found a correlation ($r = -0.78$, $p < 0.01$) between urinary 8-hydroxydeoxyguanosine and CMJ performance. These findings led the authors to suggest that hydrogen-rich gas inhalation during the post-exercise recovery period might improve neuromuscular performance via reducing systemic oxidative damage. A significant attenuation in the reduction (3.7%) of peak torque after 20 maximal isokinetic knee extensions, after HRW ingestion (1.5 L of HRW, H_2 = 0.9–1.0 ppm, within 8 h before exercise), despite no changes in serum CK and markers of oxidative stress, was also reported by (Aoki et al., 2012). Although no statistically significant correlation was found between CMJ, VAS and CK in the present study, we feel that the positive effect of HRW consumption on muscle recovery and performance could be related to the combination of the antioxidant and anti-inflammatory properties of H_2. In addition to our main findings, four positive responders were found for all variables examined, although the group of positive responders varied for each variable. No group of participants was identified that responded positively to all variables simultaneously. A more detailed analysis of positive responders is precluded by the low sample of four participants. The question of whether and how to predict positive responders to HRW supplementation remains unresolved, although some association between HRW effect and subject characteristic was found (Botek et al., 2020). Importantly, in the current study, HRW did not have a substantially negative effect as defined by MCID in any participant for CK, VAS, and CMJ. Currently, H_2 has no known adverse effect (Cole et al., 2022; Salomez-Ihl et al., 2024) and is no on the Prohibited List (World Anti-Doping Agency, 2024), therefore HRW can be recommended as a supplement to accelerate the muscle recovery in professional athletes. However, more studies are needed to clarify on the exact mechanism of H_2 action on the muscle recovery process after exercise.

There are some limitations in this study. Firstly, the dose of H_2 was constant per subject for logistical reasons and was not adjusted for body mass. Secondly, molecular (e.g., immune, reactive oxygen and nitrogen species) mechanisms were not evaluated. Knowledge of molecular responses may enhance the understanding of the H_2 mechanisms for altering DOMS perception and improvement in muscle performance during post-exercise recovery. From practical standpoint, the limited ability to control the adherence of elite athletes to follow all instructions regarding the daily regimen (dietary regimen, sleeping habits, and prescribed amount of tap water) within the study could be seen as a limitation. In addition, not controlling for the potential effect of the menstrual cycle phase during experiment on the primary outcomes could be also considered a limitation.

5 Conclusion

Four days of HRW supplementation represents a promising hydration strategy for enhancing recovery after two strenuous swimming training sessions performed on the same day in elite fin swimmers. Lower limb muscle power performance and markers of EIMD, including capillary blood CK activity and DOMS were all enhanced by HRW supplementation compared with placebo.

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 Ethics Committee of the Faculty of Physical Culture, Palacký University Olomouc. 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

BS: Conceptualization, Data curation, Investigation, Methodology, Writing–original draft, Funding acquisition, Project administration, Resources, Visualization. MB: Conceptualization, Investigation, Methodology, Supervision, Writing–original draft, Writing–review and editing, Resources. JK: Data curation, Investigation, Methodology, Writing–original draft, Formal Analysis, Visualization. MV: Investigation, Writing–review and editing. AM: Writing–review and editing. FN: Investigation, Writing–review and editing. IK: Investigation, Writing–review and editing.

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Conflict of interest

MB is the external research consultant of H2 Global Group (Ostrava, Czech Republic).

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.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2024.1321160/full#supplementary-material

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Exploring the interplay of trunk and shoulder rotation strength: a cross-sport analysis

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Introduction: Trunk and shoulder strength are consistently shown to be involved in performance limitations, as well as contributing to stability, power output, and reducing the risk of injury. Although their biomechanical interaction is a critical aspect for athletes, there is limited research on the relationship between trunk and shoulder strength in sports where upper body mechanics are critical for optimal performance.

Purpose: This study examined the differences and relationships between trunk rotational strength and shoulder rotational strength among athletes participating in mixed martial arts (MMA), tennis, swimming, and baseball.

Methods: Maximal voluntary contraction tests were performed to evaluate strength of 39 professional adult male athletes from disciplines of MMA (n = 6), tennis (n = 11), swimming (n = 11) and baseball (n = 11). Peak force data were used in sports comparison and relationship analysis between trunk and shoulder rotation strength parameters.

Results: The findings revealed a complex and significant relationship between trunk and shoulder strength, with unique patterns for each athletic discipline. Tennis players exhibited a strong correlation between trunk bilateral differences and internal shoulder rotation, while other disciplines demonstrated a more balanced use of trunk asymmetry. Swimmers displayed the best interactions between trunk and shoulder overall, emphasizing the aquatic environment's biomechanical demands. In MMA, the strongest correlation was between shoulder internal and external rotation with the trunk, mainly due to the number of defensive movements in addition to offensive ones. Baseball pitchers showed a significant correlation between internal/external shoulder rotation strength ratio and trunk asymmetry.

Conclusion: While no differences in peak force variables were found, unique relationships between trunk and shoulder rotational performance were discovered. The results suggest a long-term sport-specific adaptation of the trunk-shoulder interaction in sports that require upper limb power movements. It seems, that the relationship between the various parameters of trunk and shoulder was influenced by the movement stereotype of each sport. Therefore, recognition of sport-specific interactions is critical to the development of effective training programs that enhance performance and potentially reduce injury risk in different sports. Researchers and practitioners should focus on longitudinally monitoring fluctuations in TRS and SRS relationships throughout each sport season and examining potential associations with injury incidence.

KEYWORDS

isometrics, muscular strength, performance, optimization, injury prevention, adaptation, professional athletes

1 Introduction

The interaction between trunk rotational strength (TRS) and shoulder rotational strength (SRS) is a critical aspect of athletic performance in various sports, where pelvis and upper body mechanics are critical for optimal performance during locomotion or ballistic throwing (Eckenrode et al., 2012; Weber et al., 2014; Zenovia et al., 2016; Kaurkin et al., 2020; Sioutis et al., 2022). The biomechanical underpinnings of athletic movements also have implications for training strategies (Prieske et al., 2016), injury prevention (Peate et al., 2007; Wright et al., 2021), and performance optimisation (Hibbs et al., 2008) in sports. The trunk acts as a kinetic chain linking the lower and upper extremities, facilitating power transmission and rotational power during complex movements such as mixed martial arts (MMA), tennis, swimming, or baseball (Liebenson, 2010; Çetinkaya, 2015; Zemková et al., 2020; Mornieux et al., 2021). Additionally, trunk strength was correlated with performance limitations and contributes to stability, high performance, and reduced injury risk (Roth, 2019). In tennis, the ability to execute powerful serves and rapid rotational movements directly correlates with TRS (Baiget et al., 2016). Similarly, in MMA, effective striking and grappling manoeuvres rely on the athlete's ability to generate force through rapid trunk rotations (Tong-lam et al., 2017; Dunn et al., 2022). Swimmers, who participate in a sport predominantly characterised by upper body movements, require robust trunk rotation to optimise their strokes and maintain streamlined body positions (Lawsirirat and Chaisumrej, 2017). Baseball athletes, specifically during pitching, rely on the synchronisation of trunk and shoulder rotations to unlock the full potential of throwing motions (Bullock et al., 2018). Meanwhile, the role of SRS in these sports should not be overlooked. Research continues to highlight the role of SRS in improving performance and preventing overuse and imbalance related injuries (Payton et al., 2002; Liebenson, 2010; Lawsirirat and Chaisumrej, 2017). The shoulder complex is intimately involved in various sport-specific movements, such as the execution of powerful strikes in MMA (Zhou et al., 2023), the rapid rotational movements of overhead serve in tennis (Gordon and Dapena, 2006), the propulsive arm strokes in swimming (Collado-Mateo et al., 2018), and the high-speed throws in baseball (Cross et al., 2023). Despite the apparent commonality in the need for TRS, the specific demands of each sport may result in unique musculoskeletal stressors and adaptations (Stefan et al., 2015), requiring a harmonious interplay between the rotational forces generated by the trunk and shoulders (Zenovia et al., 2016; Kaurkin et al., 2020; Sioutis et al., 2022). Although individual studies have focused on either TRS or SRS measurements in specific sports, there is a research gap in comprehensively examining their interrelationship across multiple sport disciplines. Therefore, this study investigated the trunk and shoulder rotational strength differences and relationships between trunk and shoulder variables in athletes from various sports, including MMA, tennis, swimming, and baseball. The goal was to gain a better understanding of how these strengths interacted and influenced athletic performance. We hypothesized significantly different strength performance of trunk and shoulder between sports. Additionally, we expected significant correlations between trunk and shoulder strength variables. A deeper explanation of the relationships between these factors can provide valuable and novel insights in the fields of sports science and performance enhancement. Additionally, the development of new tailored training regimes can help athletes optimize their performance and reduce the risk of overuse injuries and musculoskeletal imbalances associated with the repetitive rotational movements and high-impact nature of their sports.

2 Materials and methods

2.1 Study design

This was a cross-sectional study. All participants were fully informed of the research procedures and agreed to the experimental design by signing an informed consent form. This research was approved by the ethic committee of Faculty of Physical Education and Sport at Charles University, and was in accordance with the Declaration of Helsinki guidance.

2.2 Participants

A total of 39 adult male professional athletes were included: 6 MMA athletes at the highest national competitive level, 11 tennis players at the international and national competitive level, 11 swimmers at the highest international and national competitive level, and 11 baseball pitchers at the Czech Republic national team level. Descriptive group characteristics are presented in Table 1. Dominant upper limb categorisation was based on verbal questioning. To be included in this study, athletes had to be free from any musculoskeletal injuries or medical conditions that would exclude them from competition and training; no high resistance and exhausting physical activity in the last 48 h prior testing.

2.3 Data collection

2.3.1 Isometric trunk rotational strength

Maximal voluntary contraction (MVC) of the TRS was assessed using the Humac NORM dynamometer (CSMi, Stoughton, MA) in isometric mode. A standardised warm-up of 3 × 6 repetitions (each

TABLE 1 Descriptive research group characteristics.

		Mean	Std. Deviation	Std. Error	95% CI for mean	
					Lower bound	Upper bound
Age (years)	Baseball	28.27[a, b]	5.55	1.67	24.54	32.00
	MMA	26.83	8.54	3.49	17.87	35.80
	Swimming	21.46[a]	2.54	0.77	19.75	23.16
	Tennis	22.18[b]	3.60	1.09	19.76	24.60
BH (cm)	Baseball	184.45	6.89	2.08	179.83	189.08
	MMA	183.17	4.36	1.78	178.60	187.74
	Swimming	185.03	4.00	1.21	182.34	187.71
	Tennis	185.55	6.86	2.07	180.94	190.15
BW (kg)	Baseball	84.82	10.25	3.09	77.93	91.71
	MMA	80.55	7.11	2.90	73.09	88.01
	Swimming	81.25	3.67	1.11	78.79	83.72
	Tennis	81.83	7.48	2.25	76.80	86.85

Note: BH, body height; BW, body weight.
[a, b]–Bonferroni *post hoc* test (same letter means that both groups are significantly different each other.

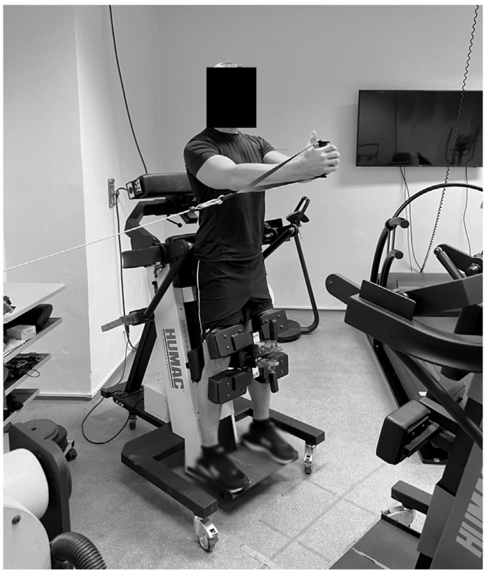

FIGURE 1
Maximal voluntary contraction test of trunk rotational strength using isometric mode of Humac NORM dynamometer with Trunk Modular and Wheel Components (CSMi, Stoughton, MA).

side) of Bird Dog; 3 × 5 seconds (each side) of Pallof Press with elastic band and 3 × 6 roll-up crunch was performed prior to TRS testing. The study utilized a variant of the anti-rotation pallof press (Mullane et al., 2021) in a vertical position with as many degrees of freedom as possible. This was done because the force of trunk rotation in the serape effect is closely linked to the movement of the entire body, including the lower limbs and pelvic region. To execute maximal force without shearing the feet, fixation was chosen in the knee region. Pilot measurements with fixation in the ankle region caused too much stress and discomfort when achieving sub-maximal to maximal forces. The closest possible point was at the knee area, which proved to be ideal and stable. For testing, participants stood upright in the Trunk Modular Component (CSMi, Stoughton, MA) with their knees fixed to prevent lower limb movement and allow for maximal effort trials (Figure 1). The Trunk Modular Component was adjusted to individual height until the dynamometer attachment reached the celiac plexus. Both hands held the Humac NORM Wheel (CSMi, Stoughton, MA) at shoulder height with the arms straight (no elbow flexion was allowed during the test). Starting testing side was decided by freeware online random number generator (1-right; 2-left) to prevent the order effect. Depending on testing side, the hand closer to the dynamometer was always on top. For familiarisation, participants performed 2 submaximal trials of 3 s separated by 30-s rest. The MVC protocol consisted of 4 maximal 3-s trials separated by a 60-s rest. The test was performed on the dominant and non-dominant side. Evaluated variables were absolute TRS for dominant (TRD) and non-dominant side (TRN), TRS normalized according to body weight in percentages for dominant (TRDrel) and non-dominant side (TRNrel), and TRS asymmetry in percentages (TRdiff).

2.3.2 Isometric shoulder rotational strength

MVC of internal and external rotational SRS was assessed using the ForceFrame isometric dynamometer (Vald Performance, Albion, Australia). Besides individual shoulder mobilization before SRS testing, a standardised warm-up of 3 × 10 repetitions (each side) of internal and external shoulder rotation with a medium resistance elastic band was performed. For testing, the body was positioned in the supine position with 90° of shoulder abduction and 90° of elbow flexion, while bending the knees at 90° (Figure 2). For familiarisation, participants performed 3 submaximal trials of 3 s

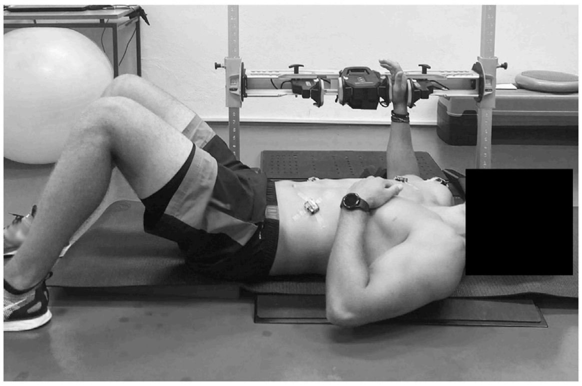

FIGURE 2
Maximal voluntary contraction test of shoulder internal and external rotational strength using isometric dynamometer ForceFrame (Vald, United States) in supine body at 90° shoulder abduction and 90° elbow flexion.

separated by 30 s rest. The MVC protocol consisted of 3 maximal 3-s trials of internal and external rotation in the dominant upper limb separated by a 60-s rest. Evaluated variables were absolute internal and external SRS for dominant upper limb (IRD; ERD), SRS normalized according to body weight in percentages for dominant upper limb (IRDrel; ERD_{rel}), and SRS ratio between external and internal rotation (IRD:ERD).

2.4 Data processing

Statistical analysis was performed using IBM SPSS v24 (Statistical Package for Social Sciences, Inc., Chicago, IL, United States). Basic descriptive statistics (Mean and Std. Deviation) were calculated for all dependent variables. Normal data distribution was evaluated and confirmed using the Shapiro-Wilk test, while homogeneity of variance was tested with Levene's test. Pairwise comparison was calculated by independent T-Test with 95% CI, while multiple comparison was calculated by One-way Between-groups ANOVA with 95% CI. Statistical significance was set at $p < 0.05$. Relationships between the dependent variables were calculated by Pearson's correlation. Explanation of the proportion of factor variance (effect size) was evaluated by the Partial Eta Squared ($\eta_p{}^2$) as small 0.01, medium 0.06 and large 0.14 (Richardson, 2011).

3 Results

3.1 Isometric trunk rotational strength

Intra-class correlation coefficient in TRS (ICC = 0.979) with standard error of measurement = 3.07 (%SEM = 13.38%) and minimum detectable change = 4.86 (SDC% = 21.17%) was calculated prior to analysis. There were no statistically significant differences between groups in TRS parameters ($p > 0.05$, Table 2). Higher, but non-significant differences were found in TRdiff between MMA (9.83% ± 8.33%), tennis players (9.73% ± 7.75%) compared to swimmers (5.12% ± 3.09%) and baseball pitchers (6.36% ± 3.75%).

3.2 Isometric shoulder rotational strength

SRS parameters were not statistically different between groups ($p > 0.05$, Table 3). While MMA athletes were able to generate similar strength in IRDrel (2.14 ± 0.43 %BW) and ERDrel rotation (2.12 ± 0.40 %BW), tennis players had up to 11.32% stronger IRDrel (2.12 ± 0.37 %BW) compare to ERDrel (1.88 ± 0.30 %BW). The highest value of IRDrel was 2.85 %BW in swimmer and lowest values (1.18 %BW) has been detected in baseball pitcher.

3.3 Relationship between isometric trunk and isometric shoulder rotational strength

Isometric trunk rotational strength significantly correlated between dominant and non-dominant side in each group of athletes (baseball: $r = 0.94$, $R^2 = 0.88$, MMA: $r = 0.87$, $R^2 = 0.76$, swimming: $r = 0.88$, $R^2 = 0.77$, tennis: $r = 0.74$, $R^2 = 0.55$). We found significant correlation between internal and external SRS in MMA athletes ($r = 0.91$, $R^2 = 0.83$) (Table 4).

Interestingly in Table 5, significant relationship has been detected between TRdiff and isometric IRD in tennis players ($r = 0.63$, $R^2 = 0.40$), while in another athletes this association was insignificant ($p > 0.05$).

Results revealed, that the stronger isometric TRS, the stronger isometric SRS in swimmers (Table 6), MMA and baseball pitchers. But these relationships were not confirmed in tennis athletes. This relationship was insignificant for rest groups (baseball: $r = 0.52$, $R^2 = 0.27$, swimming: $r = 0.51$, $R^2 = 0.26$, tennis: $r = 0.35$, $R^2 = 0.12$).

Conversely, TRdiff were significantly associated with IR:ER ratio just in baseball players, as seen in Table 7 ($r = 0.67$, $R^2 = 0.45$).

4 Discussion

Positive correlations were observed between TRS parameters and SRS performance across all sports, suggesting that strong and coordinated trunk rotation is a common denominator among successful athletes in MMA, tennis, swimming and baseball pitchers. However, the strength of this correlation varied between disciplines. This highlights the complex interaction between these two factors of rotational strength and the need for sport-specific training approaches.

When analysing each sport discipline, tennis players exhibited a strong correlation between TRS asymmetry and internal SRS. This finding aligns with the long-term unilateral demands of the sport, where a forceful rotation of the torso is imperative for delivering powerful serves and groundstrokes in overhead arm extension. Thus, tennis players are exposed to one-sided maladaptation (Patel et al., 2020), leading to higher interconnected shoulder and trunk rotational muscular imbalance, and consequently to potential shoulder or lower back injury (Dines et al., 2015; Zemkova, 2018). The results found in this study corroborated this, and therefore, there is a necessity to integrate training programs that address imbalances of the trunk and shoulder strength while continuing to maximize

TABLE 2 Differences in isometric trunk rotational strength.

		Mean	Std. Deviation	Std. Error	95% CI for mean		F	p
					Lower bound	Upper bound		
TRD (kg)	Baseball	23.64	4.80	1.45	20.41	26.86	0.46	0.71
	MMA	24.17	6.59	2.69	17.26	31.08		
	Swimming	22.09	2.70	0.81	20.28	23.90		
	Tennis	22.36	3.70	1.11	19.88	24.85		
TRN (kg)	Baseball	24.73	4.96	1.50	21.39	28.06	1.44	0.25
	MMA	22.67	4.23	1.73	18.23	27.10		
	Swimming	21.55	2.25	0.68	20.03	23.06		
	Tennis	24.27	4.13	1.24	21.50	27.04		
TRdiff (%)	Baseball	6.36	3.75	1.13	3.85	8.88	1.62	0.20
	MMA	9.83	8.33	3.40	1.09	18.57		
	Swimming	5.12	3.09	0.93	3.04	7.20		
	Tennis	9.73	7.75	2.34	4.52	14.93		
TRDrel (%BW)	Baseball	28.06	4.33	1.31	25.15	30.97	0.22	0.89
	MMA	29.00	6.60	2.70	22.07	35.93		
	Swimming	27.15	2.92	0.88	25.19	29.11		
	Tennis	27.64	5.30	1.60	24.08	31.19		
TRNrel (%BW)	Baseball	28.61	3.18	0.96	26.47	30.74	1.55	0.22
	MMA	29.00	4.24	1.73	24.55	33.45		
	Swimming	26.54	2.60	0.78	24.79	28.29		
	Tennis	30.09	5.30	1.60	26.53	33.65		

Note: TRD, trunk rotational strength for dominant side; TRN, trunk rotational strength for non-dominant side; TRD_{rel}, trunk rotational strength to body weight for dominant side; TRN_{rel}, trunk rotational strength normalized to body weight for non-dominant side; TRdiff, trunk rotational strength asymmetry between dominant and non-dominant side.

performance (Zemkova et al., 2018). The results found a very balanced trunk and shoulder strength for MMA fighters, particularly in shoulder strength, with stronger TRS associated with stronger SRS. Strength is a key factor for MMA fighters, as Folhes et al. (2022) found an association between competition level and strength performance. However, different fighting styles can have different demands, and MMA is multifaceted, where athletes engage in a combination of punches and grappling techniques from judo, jujitsu, and wrestling (Pujszo and Adam, 2016). Additionally, certain combat styles require different movement patterns and fitness demands (Iwai et al., 2008; Ambroży et al., 2021). The varying demands of these techniques may contribute to a more diversified pattern of strength development in the trunk and shoulders. Thus, these athletes had the least imbalance between shoulder IRD and ERD. Furthermore, they reached the highest relationships between TRS in non-dominant side and external SRS among all other sports. This may indicate the importance of defensive movements to prevent opponents' dangerous actions, when MMA fighters not only exert upper limb motion in forward directions like punching, where internal shoulder rotation of dominant arm finds its support in dominant side trunk rotation (serape effect), but during torso rotation to non-dominant side they perform upper limb blocking action where external rotation plays a key role. These results showed for MMA that symmetry can be a key aspect in order to be able to be offensive with and defensive against different fighting styles that require different demands. Swimmers had shown the most significant relationships between shoulder and trunk performance overall. This complex synergy is important to develop the "swimming shoulder kinetic chain" for performance purposes (Bradley et al., 2019). Swimmers did not have a significant TRS asymmetry which indicates swimmers are well balanced in TRS. This makes sense as swimming is a symmetrical sport without a dominant side. The power generated by the shoulder during swimming can be seen by swimmers having the largest IRD shoulder strength of the sports disciplines studied. This large shoulder strength could have issues if not balanced by the TRS, as a lower contribution of trunk stabilizing muscles during swimming can lead to shoulder pain and injury (Heinlein and Cosgarea, 2010; Matsuura et al., 2022). Coaches can optimise performance of their swimmers and reduce injury risk by analysing the shoulder-trunk relationships. Baseball

TABLE 3 Differences in isometric shoulder rotational strength.

		Mean	Std. Deviation	Std. Error	95% CI for mean		F	p
					Lower bound	Upper bound		
IRD (N)	Baseball	153.59	47.43	14.30	121.73	185.45	0.51	0.68
	MMA	172.79	43.14	17.61	127.52	218.06		
	Swimming	169.66	42.33	12.76	141.22	198.10		
	Tenis	174.22	39.61	11.94	147.61	200.83		
IRDrel (%BW)	Baseball	1.80	0.48	0.14	1.48	2.12	1.25	0.31
	MMA	2.14	0.43	0.17	1.69	2.58		
	Swimming	2.09	0.51	0.15	1.74	2.43		
	Tenis	2.12	0.37	0.11	1.87	2.37		
ERD (N)	Baseball	161.48	36.90	11.13	136.69	186.27	0.51	0.68
	MMA	171.04	38.69	15.79	130.44	211.64		
	Swimming	163.11	22.02	6.64	148.32	177.90		
	Tenis	152.93	23.59	7.11	137.08	168.78		
ERDrel (%BW)	Baseball	1.89	0.28	0.09	1.70	2.08	1.10	0.36
	MMA	2.12	0.40	0.16	1.70	2.54		
	Swimming	2.01	0.25	0.07	1.84	2.17		
	Tenis	1.88	0.30	0.09	1.67	2.08		
IRD:ERD	Baseball	0.96	0.24	0.07	0.79	1.12	1.40	0.26
	MMA	1.01	0.10	0.04	0.91	1.11		
	Swimming	1.05	0.22	0.07	0.90	1.19		
	Tenis	1.15	0.25	0.08	0.98	1.32		

Note: IRD, shoulder internal rotational strength for dominant limb; ERD, shoulder external rotational strength for dominant limb; IRD_{rel}, shoulder internal rotational strength to body weight for dominant side; ERD_{rel}, shoulder rotational strength normalized to body weight for dominant side; IRD: ERD, shoulder rotational strength ratio between external and internal rotation.

TABLE 4 Correlation between trunk and shoulder parameters in MMA (n = 6).

MMA	TRD	TRN	TRdiff	TRDrel	TRNrel	IRD	IRDrel	ERD	ERDrel	IRD_ERD
TRD	1.00									
TRN	0.87*	1.00								
TRdiff	0.34	−0.16	1.00							
TRDrel	0.94**	0.95**	0.04	1.00						
TRNrel	0.59	0.72	−0.34	0.76	1.00					
IRD	0.89*	0.84*	0.19	0.81	0.52	1.00				
IRDrel	0.80	0.81*	−0.02	0.79	0.75	0.93**	1.00			
ERD	0.88*	0.92**	0.08	0.87*	0.64	0.92**	0.87*	1.00		
ERDrel	0.75	0.88*	−0.17	0.83*	0.87*	0.77	0.87*	0.91*	1.00	
IRD:ERD	0.22	0.03	0.21	0.07	−0.06	0.44	0.42	0.06	−0.08	1.00

Note: TRD, trunk rotational strength for dominant side; TRN, trunk rotational strength for non-dominant side; TRDrel, trunk rotational strength to body weight for dominant side; TRNrel, trunk rotational strength normalized to body weight for non-dominant side; TRdiff, trunk rotational strength asymmetry between dominant and non-dominant side; IRD, shoulder internal rotational strength for dominant limb; ERD, shoulder external rotational strength for dominant limb; IRDrel, shoulder internal rotational strength to body weight for dominant side; ERDrel, shoulder rotational strength normalized to body weight for dominant side, IRD: ERD, shoulder rotational strength ratio between external and internal rotation. $^{**}p < .01$, $^{*}p < .05$.

TABLE 5 Correlation between trunk and shoulder parameters in tennis (n = 11).

Tennis	TRD	TRN	TRdiff	TRDrel	TRNrel	IRD	IRDrel	ERD	ERDrel	IRD_ERD
TRD	1.00									
TRN	0.74**	1.00								
TRdiff	−0.30	0.09	1.00							
TRDrel	0.88**	0.54	−0.46	1.00						
TRNrel	0.81**	0.88**	−0.18	0.83**	1.00					
IRD	−0.02	0.49	0.63*	−0.26	0.18	1.00				
IRDrel	0.08	0.51	0.45	0.02	0.40	0.89**	1.00			
ERD	−0.01	0.38	0.09	−0.09	0.26	0.35	0.37	1.00		
ERDrel	0.02	0.22	−0.23	0.19	0.37	−0.02	0.20	0.86**	1.00	
IRD:ERD	0.00	0.23	0.53	−0.20	0.01	0.77**	0.67*	−0.32	−0.59	1.00

Note: TRD, trunk rotational strength for dominant side; TRN, trunk rotational strength for non-dominant side; TRDrel, trunk rotational strength to body weight for dominant side; TRNrel, trunk rotational strength normalized to body weight for non-dominant side; TRdiff, trunk rotational strength asymmetry between dominant and non-dominant side; IRD, shoulder internal rotational strength for dominant limb; ERD, shoulder external rotational strength for dominant limb; IRDrel, shoulder internal rotational strength to body weight for dominant side; ERDrel, shoulder rotational strength normalized to body weight for dominant side; IRD: ERD, shoulder rotational strength ratio between external and internal rotation. **p < .01, *p < .05.

TABLE 6 Correlation between trunk and shoulder parameters in swimmers (n = 11).

Swimming	TRD	TRN	TRdiff	TRDrel	TRNrel	IRD	IRDrel	ERD	ERDrel	IRD_ERD
TRD	1.00									
TRN	0.88**	1.00								
TRdiff	0.05	−0.10	1.00							
TRDrel	0.92**	0.77**	−0.07	1.00						
TRNrel	0.79**	0.88**	−0.26	0.84**	1.00					
IRD	0.68*	0.74**	−0.21	0.64*	0.66*	1.00				
IRDrel	0.63*	0.66*	−0.26	0.65*	0.67*	0.98**	1.00			
ERD	0.70*	0.82**	−0.24	0.69*	0.71*	0.51	0.46	1.00		
ERDrel	0.60	0.69*	−0.36	0.71*	0.74**	0.44	0.45	0.94**	1.00	
IRD:ERD	0.31	0.37	−0.07	0.22	0.26	0.83**	0.81**	0.00	−0.09	1.00

Note: TRD, trunk rotational strength for dominant side; TRN, trunk rotational strength for non-dominant side; TRDrel, trunk rotational strength to body weight for dominant side; TRNrel, trunk rotational strength normalized to body weight for non-dominant side; TRdiff, trunk rotational strength asymmetry between dominant and non-dominant side; IRD, shoulder internal rotational strength for dominant limb; ERD, shoulder external rotational strength for dominant limb; IRDrel, shoulder internal rotational strength to body weight for dominant side; ERDrel, shoulder rotational strength normalized to body weight for dominant side; IRD: ERD, shoulder rotational strength ratio between external and internal rotation. **p < .01, *p < .05.

pitchers showed the strongest associations between TRS asymmetry and internal to external SRS ratio, while also reached high relationship between both sides of TRS and external SRS. Pitching in baseball requires greater shoulder external rotation, which helps increase pitch speed without increasing overall joint torques (Albiero et al., 2021). Furthermore, the art of pitching requires a kinematic chain that involves the entire body, in particular upper trunk rotation (Diffendaffer et al., 2022). The results and tests presented here could additionally aid professionals in baseball to highlight areas of strength improvement of the shoulder and trunk, which can be indicated in instances of poor performance or insufficient movements patterns (Diffendaffer et al., 2022). Furthermore, it could assist in injury prevention strategies, where external rotation performance is a lowering injury risk factor (Stodden et al., 2001; Hurd and Kaufman, 2012; Diffendaffer et al., 2022; Huang et al., 2022). One methodological point from this study was the expression of trunk strength relative to body weight. It may be crucial for precise assessment and fair benchmarking across athletes due to unique biomechanics and body composition. When choosing between strength tests, two main forms exist: isokinetic and isometric. They both have positive and negatives for their choice. Elite male tennis players demonstrated approximately 63% peak torque to body weight at an angular velocity of 60 s^{-1} during seated dynamic performance, with no significant difference between sides (Ellenbecker and Roetert,

TABLE 7 Correlation between trunk and shoulder parameters in baseball (n = 11).

Baseball	TRD	TRN	TRdiff	TRDrel	TRNrel	IRD	IRDrel	ERD	ERDrel	IRD_ERD
TRD	1.00									
TRN	0.94**	1.00								
TRdiff	−0.06	0.18	1.00							
TRDrel	0.77**	0.64*	−0.15	1.00						
TRNrel	0.88**	0.84*	−0.03	0.86**	1.00					
IRD	0.59	0.66*	0.52	0.48	0.40	1.00				
IRDrel	0.38	0.40	0.45	0.53	0.28	0.91**	1.00			
ERD	0.81**	0.80**	−0.18	0.49	0.57	0.52	0.29	1.00		
ERDrel	0.61*	0.54	−0.41	0.58	0.47	0.36	0.31	0.88**	1.00	
IRD:ERD	0.13	0.17	0.67*	0.25	0.06	0.78**	0.86**	−0.12	−0.20	1.00

Note: TRD, trunk rotational strength for dominant side; TRN, trunk rotational strength for non-dominant side; TRDrel, trunk rotational strength to body weight for dominant side; TRNrel, trunk rotational strength normalized to body weight for non-dominant side; TRdiff, trunk rotational strength asymmetry between dominant and non-dominant side; IRD, shoulder internal rotational strength for dominant limb; ERD, shoulder external rotational strength for dominant limb; IRDrel, shoulder internal rotational strength to body weight for dominant side; ERDrel, shoulder rotational strength normalized to body weight for dominant side; IRD: ERD, shoulder rotational strength ratio between external and internal rotation. **p < .01, *p < .05.

2004). We found lower mean result (approximately 30%BW) within isometric "pallof" hold during standing rotational power, which may be more specific for athletic performance (Zemkova, 2018). Static tests may underestimate trunk strength and fail to capture spinal health accurately during dynamic motion (Bayramoglu et al., 2001; Zemkova, 2018). Nonetheless, static tests can aid in assessing spinal health by mitigating shear stresses and torsional compression, critical factors in joint injury mechanisms (McGill and Hoodless, 1990). These stresses, in combination with appropriate extensor torque, are of a size that should be considered in the mechanism of joint injury (McGill and Hoodless, 1990). It's crucial to recognize that various factors such as equipment, muscle lengths, motion axis direction, patient position, and static vs. dynamic protocols can influence test outcomes (Bayramoglu et al., 2001). Dynamic tests likely reveal individual motor strategies more effectively, while isometric tests may assist in standardizing conditions for maximal strength assessment. The main limitation of the study is the small number of participants, particularly in the MMA group, due to the limited availability of elite athletes in this specific discipline in the Czech Republic. This poses a significant challenge for researchers analysing such a unique population. To improve future participant recruitment, a strategy to collaborate with different sports organizations and implement long-term monitoring may be helpful. However, the selection of participants in certain sports may be limited by the small number of athletes who compete at the highest national and international levels. In this study, we contacted sports federations and coaches to explore the possibility of measuring and analysing strength. On the other hand, we focused just on high level athletes from disciplines where core and upper body strength play a pivoting role. Based on athletes' classification framework (McKay et al., 2022), all athletes were recruited at least from Tier 3 (Highly Trained/National Level athletes, ~0.014% of the global population), but most of them were from Tier 2 (Elite/International Level, ~0.0025% of the population). In order to improve the study, we recommend incorporating dynamic tests in a larger range of motion for athletes, in addition to the use of isometric tests for assessing rotational motion in the trunk and shoulder. This will provide a more comprehensive assessment of the athletes' abilities. It is important to note that the use of isometric tests during rotational motion may be limiting from certain perspectives. Future research should use the same load cell and sampling rate for different strength tests to avoid deviations in sensitivity. Moreover, future research should examine the potential implications of imbalances or deficiencies in these strength relationships according to lower back pain and injuries; in various performance levels; different genders and maturation status across another sporting disciplines. We acknowledge the limited number of athletes in our study. As this is a pilot study focusing on a specific population, it is important for future research to continue examining and expanding the sample size. This research aims to highlight the significance and potential differences in relationships between various sports, and a larger sample size is highly recommended for future studies.

5 Conclusion

We examined the differences in rotational strength of the trunk and shoulders, as well as the interactions between these variables, in adult elite athletes from various sports. While no differences in peak force variables were found, unique relationships between trunk and shoulder rotational performance were discovered in MMA, tennis, swimming, and baseball. The results suggest a long-term sport-specific adaptation of the trunk-shoulder interaction in sports that require upper limb power movements. It seems, that the relationship between the various parameters of trunk and shoulder was influenced by the movement stereotype of each sport. Therefore, recognition of sport-specific interactions is critical to the development of effective training programs that enhance performance and potentially reduce injury risk in different sports. Researchers and practitioners should focus on longitudinally monitoring fluctuations in TRS and SRS relationships throughout each sport season and examining potential associations with injury incidence.

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 Ethical Committee of the Faculty of Physical Education and Sports, Charles University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

MH: Conceptualization, Methodology, Writing–original draft, Writing–review and editing. PM: Data curation, Investigation, Writing–review and editing. KF: Formal Analysis, Supervision, Validation, Writing–review and editing. CC: Investigation, Project administration, Validation, Visualization, Writing–review and editing. OI: Writing–review and editing. FV: Formal Analysis, Funding acquisition, Resources, Software, Validation, Writing–review and editing. FZ: Conceptualization, Funding acquisition, Supervision, Writing–review and editing. TM: Data curation, Methodology, Project administration, Software, Supervision, Writing–original draft.

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Conflict of interest

Author CC was employed by AC Sparta Praha, Prague, Czechia.

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The effects of aerobic gymnastics training on performance-related variables in an elite athlete: a 2-year follow-up study

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This study investigates individual performance adaptations on 2 years of training between European Aerobics Championships. An elite, 22-year-old aerobic gymnast performed postural coordination test, Y-Balance test, squat and countermovement jumps, 60 s test of repeated jumps, an isokinetic leg muscle strength test, and the Wingate test. Postural stability and flexibility improved in terms of increased distance achieved in the Y-Balance test in the anterior (by 6.3%), posteromedial (by 2%), and posterolateral (by 4.8%) directions. Lower limb muscular endurance also increased, which can be corroborated by a reduced fatigue index in the 60 s test of repeated jumps (from 42% to 27% after the 1st and to 22% after the 2nd year of training). In addition, mean power increased during dominant (by 23.2% at 60°/s and by 18.5% at 180°/s) and non-dominant leg extension (by 4.9% at 180°/s and by 15.5% at 300°/s), plus dominant leg flexion (by 2.0% at 60°/s and by 6.9% at 300°/s). Similarly, peak torque/body weight ratio increased during dominant (by 24.9% at 60°/s, by 11.5% at 180°/s, and by 2.1% at 300°/s) and non-dominant leg extension (by 0.5% at 60°/s and by 6.4% at 300°/s), plus dominant leg flexion (by 1.7% at 60°/s and by 5.4% at 300°/s). However, 2 years of training failed to show any significant improvements in the explosive power of lower limbs and anaerobic performance. These findings indicate that general aerobic gymnastics training without any specific inputs leads to performance adaptation, namely, in abilities closely related to competition routine (dynamic balance and strength endurance of lower limbs).

KEYWORDS

high-performance laboratory testing, balance and stability, flexibility, isokinetic leg muscle strength test, power, anaerobic test

1 Introduction

Gymnastics is a unique technical-aesthetic sport with a particular training process that demands technical perfection and a high level of physical conditioning (Sands et al., 2003). Qualities such as flexibility, speed, power, agility, strength, and balance are crucial for training (Bobo-Arce and Méndez Rial, 2013; Gateva, 2019) that direct gymnasts' success. They relate to a gymnast's ability to sustain injury-free and long-term participation in this sport (Sands et al., 2011). The development of motor skills through training includes the knowledge of specific skills determining the level of high performance, as well as methods assessing specific abilities (Gateva, 2016). Therefore, it is imperative to objectively measure and monitor an individual gymnast's physical abilities.

So far, scientific research has mainly dealt with different physiological, functional, and technical aspects of Olympic disciplines, such as artistic, rhythmic and trampoline gymnastics (Poblano-Alcalá and Braun-Zawosnik, 2014; Rutkowska-Kucharska et al., 2018; Gateva, 2019; Urzela et al., 2020; Cabrejas et al., 2022; Líška and Kremnický, 2022; Vernetta, 2022; Farana et al., 2023; Jakše and Jakše, 2023). However, there are only a few studies published on non-Olympic discipline, aerobic gymnastics (Puiu and Dragomir, 2020).

Aerobic gymnasts perform short and intense routines either individually, in mixed pairs, in trios, or in groups without apparatus. The routines involve many complex movements, with different technical and artistic requirements. Gymnasts must demonstrate continuous movement patterns together with a variety of perfectly executed elements specified by technical guidelines in Code of Points (FIG, 2021). Different kinds of difficulty and acrobatic elements with precise take-offs, landings, and rotations performed in intense sequences are common demands in gymnastics (Abuwarda, 2020). Similarly, precise spatial and temporal coordination of multi-joint limb movements with postural control (Leskovec and Pavletič, 2019) is also required in aerobics. Considering the high-intensity movements and the short duration of the competitive routine (80 ± 5 s), the anaerobic metabolism is a determinant of aerobic gymnastics performance (Kyselovičová and Danielová, 2012; Aleksandreviciene et al., 2015).

The mastery of the technique of individual elements depends on the level of motor skills that ensure their implementation (Chernykh et al., 2021). Performance is very specific to each athlete. The improvement involves individualization based on a regular objective assessment of the adaptation, corresponding to the competition-specific effort characteristics, training loads, and changes in the process of motor development of each athlete (Lamošová et al., 2021). The gymnasts have to be prepared gradually over several years to sustain and develop their performance to succeed in competition (Stan et al., 2003; Fink and Hofman, 2015). Training demands and high-level competition performance emphasize the importance of controlling individual training. However, the variety and complexity of gymnasts' events require not only different training approaches but also a wide range of physical and physiological assessments to monitor the progress of the gymnasts (Jemni, 2017). General and sport-specific testing represents an integral aspect of performance optimization in gymnastics (Mkaouer et al., 2017). This is ideal scenario, however, standardized tests close to sport-specific performance in gymnastics are very rare. A suitable alternative represents non-sport-specific field tests which also strongly correlate with the competition results in elite gymnasts (Vandorpe et al., 2012). Several attempts have been made to develop tests specific to aerobic gymnastics (Kyselovičová and Zemková, 2010a; Alves, 2015; Gateva, 2019). Despite the efforts of experts in recent years, a valid and reliable field test battery has not been developed yet. In addition, there is still not sufficient scientific data to provide robust optimal elite-level aerobic gymnast body composition and physiological profiles. This study aimed to investigate individual training adaptations on performance variables in an elite aerobic gymnast for 24 months, between the two European Championships.

2 Methods

2.1 Study design

The present study is a follow-up study to previous research by Kyselovičová et al. (2023). The main aim is to evaluate changes in physiological and performance variables of female elite aerobic gymnast. The entire observation period lasted 24 months (September 2021–September 2023). The athlete was instructed to train according to her training programs worked out by her coach before the research project and report their daily training for the whole 24-month period with no changes regarding the annual plan. She was tested on three occasions: beginning (T0), after 1st year of training (T1), and after 2nd year of training (T2). The T0 was set as a baseline, while T2 was the finish line. The study was designed based on multiple testing measurements. Measurements were conducted at the National Sports Centre Laboratory. Written informed consent and ethical committee approval of the Faculty of Physical Education and Sport, Comenius University in Bratislava, Slovakia (No. 1/2020) was obtained before the participation. The procedures followed were under the ethical standards on human experimentation stated in compliance with the 1964 Helsinki Declaration and its later amendments.

2.2 Subject

An elite female aerobic gymnast with the age of 22 years, height 166.5 cm, body mass 58.2 kg, and BMI 21.0 kg/m^2 at baseline volunteered to participate in the study. She was a member of Slovakia's national team and competed at the international level (World Cups, World and European Championships) in aerobic gymnastics for 3 years.

2.3 Testing procedures

To evaluate changes in performance variables, the gymnast was tested on three separate occasions as mentioned above (T0–T2). T0 was performed in September 2021, T1 in September 2022, and T2 in September 2023. All testing procedures were the same at all testing sessions. All tests were performed on 1 day. The athlete was instructed to do only light training the last 24 h before testing. The tests were also conducted at the same time of day in the morning to avoid circadian differences. The testing day started with anthropometric measurements. After analyzing the body composition by a multi-frequency bioelectrical impedance device InBody 770 (Cerritos, CA, United States), the gymnast performed a 15-minute self-conducted warm-up. Then she executed all tests in this order: the Imoove test; the Y-Balance test, followed by 5-min rest; the OptoJump Tests (squat jump–SJ, countermovement jump–CMJ, countermovement jump with arms–CMJarms), the 60-s jump test; the Biodex leg muscle strength test, and the Wingate test. There were additional rests after performing CMJarms (15 min), 60 s repeated jumps (15 min), and isokinetic leg strength test (20 min). Before each test, the gymnast was familiarized with the procedure. The main criteria for tests selection involved 1) assessment of overall abilities related to

TABLE 1 Changes in anthropometric characteristics over 2 years in an elite aerobic gymnast.

Anthropometric variables	T0	T1	T2
Age (years)	22	23	24
Height (cm)	166.5	166.5	166.5
Body mass (kg)	58.2	59.8	59.8
Body mass index (kg/m^2)	21	21.6	21.6
Skeletal muscle mass (kg)	26.9	27.4	26.9
Skeletal muscle mass (%)	46.2	45.8	45.0
Body fat mass (kg)	9.8	10.3	11.2
Body fat mass (%)	16.8	17.2	18.7
Right arm muscle mass (kg)	2.4	2.5	2.3
Left arm muscle mass (kg)	2.4	2.4	2.4
Trunk muscle mass (kg)	20.6	21	20.4
Right leg muscle mass (kg)	7.8	7.7	7.8
Left leg muscle mass (kg)	8.0	7.8	7.8
Body water (l)	35.5	36.2	35.6
Body water (%)	61	60.5	59.5
Extracellular water ratio	0.377	0.377	0.379
Proteins (kg)	9.6	9.8	9.6
Minerals (kg)	3.3	3.5	3.4
Basal metabolism (kcal)	1,416	1,439	1,420

T0–baseline, T1–after the 1st year of training, T2–after the 2nd year of training.

aerobic gymnastics skills and performance; 2) prediction and prevention of injuries (e.g.,: the Y-Balance test, the Imoove test); 3) higher validity and reliability compared to field tests. In addition, the tests were part of the Slovak Gymnastics Federation official test battery as an objective tool for national team members' selection and evaluation.

2.3.1 Postural coordination test

The postural coordination was assessed using the IMOOVE® system (Allcare Innovations, Chabeuil, France), a no-impact platform, based on an exclusive Ellisferic movement stimulating deep proprioception and vertebral movement to restore the muscular and postural balance of the body. The IMOOVE® system assesses the stability and coordination using the check-up program enabled by the presence of a monitor. The protocol (Di Corrado, 2023) is based on processing the results of information from pressure sensors placed in the stand plate, and from movable handles providing information about the reaction of the torso and upper limbs as a reaction to dynamic changes. IMOOVE® system was set to a dynamic mode, an intensity level of 3, a sensitivity level of 2, and a duration of evaluation of 60 s involving visual feedback in real time. The data used for the study included support and trunk stability, side distribution, and postural coordination. Assessment of individual parameters takes place on a scoring scale from 0 to 100 points, where a result of 100 is the best possible. All this information is presented as the final postural strategy index on a scale of 0–10.

2.3.2 Lower quarter Y-Balance test

This test is a valid instrument to measure dynamic balance and postural control stability in anterior, posteromedial, and posterolateral directions. It has been performed according to the previously described protocol by Gribble et al. (2012). The test was conducted by the same procedure as presented by Kyselovičová et al. (2023). Briefly, the gymnast performed three trials, and the maximum reach in each direction was recorded. The results were calculated considering limb length to determine a "composite reach distance".

2.3.3 Isokinetic leg muscle strength test

The isokinetic leg muscle strength of knee extensors and knee flexors was measured using Biodex® System 3 (Biodex® Corporation, Shirley, New York, United States). Selecting low strength speed (60°/s), medium fast speed (180°/s), and high endurance speed (300°/s) as isokinetic testing speeds was essential for optimal strength assessment in gymnasts who utilize both strength and fast speeds (Baltzopoulos and Brodie, 1989). The test protocol consisted of a series of 5 repetitions at 60°/s, followed by 10 repetitions at 180°/s and 15 repetitions at 300°/s. The test was managed the same way as described in detail in previous study by Kyselovičová et al. (2023).

TABLE 2 Changes in body balance and postural coordination during 2 years of training in an elite aerobic gymnast.

Parameters of the Y-balance test	T0	T1	T2	% Changes T2 vs. T0
The distance reached by D leg in anterior direction (cm)	42	40	45.5	8.3
The distance reached by ND leg in anterior direction (cm)	58	53	60.5	4.3
The difference in distance reached by D and ND leg in anterior direction (cm)	16	13	15	−6.3
The distance reached by D leg in posteromedial direction (cm)	100	103	103	3.0
The distance reached by ND leg in posteromedial direction (cm)	106	108	107	0.9
The difference in distance reached by D and ND leg in posteromedial direction (cm)	6	5	4	−33.3
The distance reached by D leg in posterolateral direction (cm)	97	100	102	5.2
The distance reached by ND leg in posterolateral direction (cm)	102	107	106.5	4.4
The difference in distance reached by D and ND leg in posterolateral direction (cm)	5	7	4.5	−10
Composite score of the D leg symmetry (%)	98.35	100	103.09	4.8
Composite score of the ND leg symmetry (%)	109.47	110.29	112.76	3.0
Parameters of balance and postural coordination measured by IMOOVE system®				
Supports stability (pts)	100	100	88	−12
Supports distribution left and right (%)	50	50	49	−1
	50	50	51	+1
Trunk stability (pts)	62	77	78	+16
Trunk distribution left and right (%)	58	49	52	−6
	42	51	48	+6
Postural coordination (pts)	35	34	43	+8
Postural strategy index	7.6	8.2	8.1	+7.9

T0–baseline, T1–after the 1st year of training, T2–after the 2nd year of training, D–dominant, ND, non-dominant.

2.3.4 Maximal vertical jump tests

Jumping performance was tested using optical time system (Optojump®, Microgate, Bolzano, Italy). The Optojump software (version 1.6) calculates the height of vertical jump from flight time using a simple method (9.81 × flight time^2/8) described by Bosco (1983). The gymnast performed three separate jump tests in the following order: squat jump (SJ), countermovement jump (CMJ), and countermovement jump with arm swing (CMJarms). For the SJ tests, the knee-angle were 90°. No countermovements were allowed in this test, whereas no countermovement restrictions were given for the CMJ and CMJarms tests. The gymnast was given three consecutive attempts in each jump-test, and the best attempt was registered as the result.

2.3.5 60 s test of repeated jumps

This test required the subject to execute maximal vertical rebound jumps while attempting to maintain the shortes possible ground contact time. Height of the jumps was measured using the same Optojump® (Microgate, Bolzano, Italy) as described above. Peak and mean power outputs for each jump were used to calculate a fatigue index (FI%) using the following formula: [(highest power output − lowest power output)/highest power output × 100] (Patterson et al., 2014). The blood lactate samples were taken in the 4th minute following the 60 s test of repeated jumps.

2.3.6 Wingate test

Frequent attempts of various jumps and other specific difficulty elements, including acrobatics, and highly intense aerobic movement patterns during the aerobic gymnastics routine indicate predominantly anaerobic energy contribution. For that reason, the standardized Wingate test which measures anaerobic performance has been used. After a standard warm-up, the subject performed a 30-s anaerobic Wingate test on a cycle ergometer (Isokinetic Cycle Ergometer–Monark 894E, Varberg, Sweden) to determine peak power, mean power, and fatigue index. The fatigue index was calculated by subtracting the minimal power from the maximal power, then divided by maximal power, and expressed as a percentage. The blood lactate samples were taken in the 5th minute following the Wingate test. The test was performed according to the protocol described by Vandewalle et al. (1985).

3 Results

3.1 Changes in body composition over 2 years in an elite aerobic gymnast

The anthropometric characteristics of participants are summarized in Table 1. The athlete changed some of her body

TABLE 3 Changes in muscle strength and power during 2 years of training in an elite aerobic gymnast.

Muscle strength and power parameters	T0	T1	T2	% Changes T2 vs. T0
Parameters of a squat jump				
Height of the jump (cm)	24.7	23.3	23.9	−3.2
Power (W/kg)	11.15	11.01	11.13	−0.2
Parameters of a countermovement jump				
Height of the jump (cm)	25.7	23.4	25.0	−2.7
Power (W/kg)	11.52	10.79	11.20	−2.8
Parameters of a countermovement jump with arm swing				
Height of the jump (cm)	30.2	29.2	29.2	−3.3
Power (W/kg)	12.47	12.80	12.62	1.2
Parameters of a 60 s test of repeated jumps				
Fatigue index (%)	42	27	22	−47.6
Post-exercise blood lactate (mmol/L)	3.68	5.05	4.35	18.2
Parameters of knee flexor/extensor strength measured by Biodex Isokinetic Dynamometer®				
Mean power during D and ND leg extension at 60°/s (W)	60.7	73.4	74.8	23.2
	82.9	80.1	78.0	−5.9
Mean power during D and ND leg flexion at 60°/s (W)	54.5	60.8	55.6	2.0
	60.0	80.1	59.5	−14.0
Mean power during D and ND leg extension at 180°/s (W)	120.3	120.8	142.5	18.5
	137.0	125.7	143.7	4.9
Mean power during D and ND leg flexion at 180°/s (W)	107.7	101.1	94.3	−12.4
	103.0	98.2	90.9	−11.7
Mean power during D and ND leg extension at 300°/s (W)	118.4	111.3	151.9	−6.0
	137.6	124.7	158.9	15.5
Mean power during D and ND leg flexion at 300°/s (W)	93.4	78.0	99.8	6.9
	94.8	84.5	94.5	−0.3
Total work during D and ND leg extension at 60°/s (J)	577.1	686.0	692.8	20.0
	777.6	764.6	698.1	−10.2
Total work during D and ND leg flexion at 60°/s (J)	501.4	563.1	512.8	2.3
	581.4	578.2	455.1	−21.7
Total work during D and ND leg extension at 180°/s (J)	861.7	879.5	961.6	11.6
	1,001.4	963.8	1,036.3	3.5
Total work during D and ND leg flexion at 180°/s (J)	768.0	765.6	674.1	−12.2
	815.6	782.5	686.2	−15.9
Total work during D and ND leg extension at 300°/s (J)	859.3	855.1	1,083.2	26.1
	1,019.5	990.0	1,223.5	20.0
Total work during D and ND leg flexion at 300°/s (J)	720.4	662.7	781.4	8.5
	800.0	747.9	782.5	−2.2

(Continued on following page)

TABLE 3 (*Continued*) Changes in muscle strength and power during 2 years of training in an elite aerobic gymnast.

Muscle strength and power parameters	T0	T1	T2	% Changes T2 vs. T0
Peak torque/body weight ratio during D and ND leg extension at 60°/s	158.8	178.9	198.4	24.9
	208.5	205.9	209.5	0.5
Peak torque/body weight ratio during D and ND leg flexion at 60°/s	132.9	131.5	135.2	1.7
	143.5	133.2	117.3	−18.3
Peak torque/body weight ratio during D and ND leg extension at 180°/s	124.7	124.8	139.1	11.5
	147.7	143.9	147.1	−0.4
Peak torque/body weight ratio during D and ND leg flexion at 180°/s	104.0	99.3	91.1	−12.4
	104.8	102.8	89.7	−14.4
Peak torque/body weight ratio during D and ND leg extension at 300°/s	103.3	93.5	105.5	2.1
	108.2	107.4	115.1	6.4
Peak torque/body weight ratio during D and ND leg flexion at 300°/s	78.3	76.2	82.5	5.4
	85.6	79.0	83.2	−2.8

T0–baseline, T1–after the 1st year of training, T2–after the 2nd year of training, D–dominant, ND, non-dominant.

TABLE 4 Changes in anaerobic capabilities during 2 years of training in an elite aerobic gymnast.

Wingate test parameters	T0	T1	T2	% Changes T2 vs. T0
Maximal power (W)	592.18	565.67	616.39	4.1
Maximal power (W/kg)	10.21	9.46	10.31	1.0
Mean power (W)	444.50	440.98	444.05	−0.1
Mean power (W/kg)	7.66	7.37	7.43	−3.0
Fatigue index (%)	42.51	44.41	48.82	14.8
Post-exercise blood lactate (mmol/L)	9.61	9.24	10.04	4.5

T0–baseline, T1–after the 1st year of training, T2–after the 2nd year of training.

composition variables in terms of lightly increased BM (+1.6 kg), BMI (0.6 kg/m^2), and BFM +1.4 kg. However, other anthropometrical and body composition parameters remained relatively unchanged over 2 years.

3.2 Changes in body balance and postural coordination during 2 years of training in an elite aerobic gymnast

The distance reached by both the D and ND leg in the Y-balance test increased by 6.3% in the anterior direction, by 2% in the posteromedial direction, and by 4.8% in the posterolateral direction (Table 2). The composite score of symmetry of both legs increased by 3.9%.

Regarding the IMOOVE® variables (Table 2), there was a 12% decrease in the support stability with a slight change in the left and right-side distribution (−1% and +1% respectively). The gymnast improved her trunk stability by 16% whilst the left and right distribution deteriorated (−6% and +6% respectively). In addition, postural coordination improved by 8%. Overall, postural strategy index increased by 7.9% (from an average value of 7.6 to a very good value of 8.1).

3.3 Changes in muscle strength and power during 2 years of training in an elite aerobic gymnast

The power and height of squat and countermovement jumps slightly decreased over 2 years (Table 3). However, fatigue index during a 60 s test of repeated jumps decreased from 42% to 27% after the 1st year of training and to 22% after the second year of training. This indicates a marked improvement of strength endurance of lower limbs over 2 years. Aerobic gymnast was able to maintain her maximal power while jumping much longer after 2 years of training compared to baseline level.

Regarding the isokinetic strength, mean power increased during leg extension at 60°/s by 23.2% and at 180°/s by 18.5% on the dominant leg whilst on the non-dominant at 180°/s by 4.9% and at 300°/s by 15.5% (Table 3). Mean power increased also during dominant leg flexion at 60°/s by 2.0% and at 300°/s by 6.9%.

Similarly, peak torque/body weight ratio increased during leg extension at 60°/s by 24.9%, at 180°/s by 11.5% and at 300°/s by 2.1% on the dominant leg whilst on the non-dominant leg at 60°/s by 0.5% and at 300°/s by 6.4%. Peak torque/body weight ratio increased also during dominant leg flexion at 60°/s by 1.7% and at 300°/s by 5.4%.

3.4 Changes in anaerobic capabilities during 2 years of training in an elite aerobic gymnast

The anaerobic performance of an aerobic gymnast deteriorated, which may be corroborated by an increased fatigue index from 45.5% to 48.8% after the second year of training (Table 4).

4 Discussion

The present follow-up study examined exclusively the elite female aerobic gymnast, currently the most successful one representing Slovakia. Although the athlete was already considered at an elite level at the beginning of the study, she was not the best in the country at that time as successful as at the end of our observation. During the investigation period, the athlete had an average of 12–14 h of training per week. In addition, the athlete reported regular menstrual status and maintained the same overall dietary pattern throughout the whole 24 months.

Although our athlete was an adult gymnast, we emphasize that she maintained her body height and had slightly increased her body mass and BMI over the study period. The most marked anthropometric change was estimated in % BFM. The baseline value of 16.8%, which means a level "below" the norm, was shifted to the level of "normal" values of 18.7%. The relatively unchanged variables were segmental muscle mass of the limbs and trunk. These results are interesting in the sense that the athlete maintained, in addition to the overall dietary pattern, also the pattern of training. There is not yet a consensus regarding the desired ranges of anthropometric variables and body composition components outdated data for elite female aerobic gymnasts. It could be due to the different assessment technologies, the proper interpretation of the measured body composition, its connection with general nutritional intake, and the use of terms "elite-gymnast" or "high-performance gymnast" (Jakše and Jakše, 2023). However, it is known that success in high-level gymnastics compared with lower competitive levels is associated with smaller size, lower body mass, and body fat percentage (Bacciotti et al., 2017). An optimal amount of leg volume and leg mass contribute to success in elite gymnasts as well (Mohamed, 2011; Bastürg and Marangoz, 2018).

Postural control has been defined as the task of controlling one's body position in space for the dual purposes of stability and orientation (Menant et al., 2021). Core stability is an important source of balance in sports activities (Kibler et al., 2006), and core muscle control is the basis for the successful technical performance of gymnastics balance exercises (Gateva, 2013). Compared with traditional training methods, core exercise is a new strength practice that could potentially improve skill performance among gymnasts (Luo et al., 2022). Indeed, the stronger core muscles not only more economically and harmoniously transfer the strength of athletes to the limbs, but also better maintain the stability of the trunk and hip joints so that gymnasts can show more coherent, coordinated, and stable complex technical movements (Yang and Li, 2010). In our study, we investigated trunk and lower limb stability with IMOOVE® system. The gymnast improved the ability to maintain an optimal posture on the balancing platform. However, despite increasing the postural strategy index of the gymnast over study period, it is necessary to focus on the further development of the perception of symmetry as the prolonged training time might induce structural changes in the gymnasts' motion system (Douda et al., 2002) and affect asymmetries of lower limb due to the prevalence of exercises performed on the preferred side (Frutuoso et al., 2016). Improvement of posture and a feeling of symmetry can be beneficial in aerobic gymnastics as many of the difficulty elements require postural control and coordination (Kyselovičová and Zemková, 2010b). Such a suggestion is within Rodriguez et al. (2023) who demonstrated that core training should be included in training sessions to improve overall athletic performance. However, as underlined by several studies, training programs must respect the functional characteristics of the sports to be transferable (Myer et al., 2005; McGill, 2010). Thus, core strength exercises are functional for a specific sport when these exercises lead to an efficient and specialized motor unit recruitment to achieve the proper coordination of the segments involved in the kinetic chain of sport-specific skills (Lederman, 2010).

Gymnastics performance is based on symmetrical, both-sided movements (FIG, 2021). Moreover, it is crucial to understand what role asymmetries in both functional movement and isolated strength play in injury risk or when returning to sport after injury. Thus, in our study, dynamic balance using the Y-Balance test was assessed. While the differences between the D and ND legs at baseline were insufficient in two directions (anterior & posteromedial), a positive change was noticed at the end of the study with the overall result at a very good level. The differences in the ranges between the limbs were at the optimal level in posteromedial and posterolateral directions; however, the difference in the anterior direction reached significantly above the optimum level. Comparing the changes between T0 and T2, the gymnast achieved slightly higher percentage values of the total composite score for both limbs with the dominance of the left one at the end of the investigation. Persistent problems with the right ankle were probably a significant limitation in reaching better results in this test. On the positive side, at the end of the study, the gymnast achieved a composite score over 95% (103.09 for D leg and 112.76 for ND leg), which is associated with a low risk of injury (Schwiertz et al., 2020). Dynamic balance performance in athletes has a protective effect on lower extremity injuries (Butler et al., 2014; O'Malley et al., 2014). To improve dynamic balance, athletes should practice exercises that increase the isokinetic strength of knee circumference muscles (Aka and Altundag, 2020). This may be documented by the relationship between lower extremity muscle strength and balance performance (Muehlbauer et al., 2015; Myers et al., 2018). Therefore, it is obvious that lower extremity strength is important in displaying balance performance (Deniskina and Levik, 2001).

Regarding the isokinetic strength of our gymnast, the findings showed that a lateral deficit of D knee joint in extension at test speeds of 60°/s and 180°/s (strength and coordination) during the 2-

year training has been eliminated at all. However, a strength deficit of D and ND knee joint extension and flexion at lower test speeds (60°/s and 180°/s) were still noticed at the end of the study. In addition, achieved values are below the limit of the recommended standard which is even more alarming. This can be because the competition routine focus is on turns, balances, and leaps rather than dynamic and static upper body skills (e.g., A-frames, helicopters, cuts, supports). Such elements are technically more difficult to perform, and the skill should be practiced more during training sessions. Additionally, turns and balances in a single-leg stance require a great amount of muscle concentric contraction at the hip, knee, and ankle to maintain body position. Thus, the time spent on the supporting leg is considerably greater. Furthermore, muscle imbalance of quadriceps/hamstring muscle groups at lower speeds was found in both D and ND legs. The finding follows Lanshammar and Ribom (2011), who demonstrated that in sports practice, a considerable asymmetry exists for the force relation between hamstrings and quadriceps in young adult females, with the hamstrings being weaker on the preferred limb and the quadriceps weaker on the non-preferred limb.

The importance of strength and power to successfully perform dynamic and varied gymnastics difficulty skills in sequences (Moeskops et al., 2019; Niespodzinski et al., 2021) has increased during the last decades. Core stability exercises performed in conjunction with plyometric exercises are also recommended to improve sports performance (Willardson, 2007). Accordingly, a variety of studies have been published using vertical jumps as a screening method and predictor of sports performance (Thomas et al., 2005).

The comparison of changes in squat and countermovement jumps variables showed that the gymnast's power and height slightly decreased over 2 years. However, the fatigue index during a 60 s test of repeated jumps decreased, indicating a marked improvement in strength endurance of lower limbs, So, the aerobic gymnast was able to maintain her maximal power while jumping much longer after 2 years of training compared to baseline level. That improvement can be associated with the aerobic gymnastics routines' character. Based on expertise and experience from gymnastics training, we can assume that the volume of rebound jumps in aerobic gymnastics training from a very young age may have an important, albeit different, influence on the dynamic and plyometric ability of gymnasts. Gymnasts need to reach a high level of their rate of force development in an extremely short time. This result could be explained by the fact that performance in aerobic gymnastics is realized mainly in standing, loading predominantly the lower part of the gymnasts' body. In addition, the competitive routine must demonstrate continuous and complex intense movements, which require repeated dynamic rebounds (FIG, 2021) within approximately 80 min.

Considering the high-intensity movement and the total routine time, the anaerobic metabolism is one of the main determinants of aerobic gymnastics performance (Kyselovičová et al., 2012; Alves et al., 2015; Markov, 2020). Similarly, anaerobic metabolism comprises around 50% of energy contribution in rhythmic gymnastics (Guidetti et al., 2000). Greater anaerobic power is also required in artistic gymnastics with increased technical difficulty of acrobatic elements (Brooks, 2003; French et al., 2004; Jemni et al., 2006). Since plasma lactate levels following a simulated aerobic gymnastics competition are comparable to the lactate values after the lower-body Wingate test (Alves et al., 2015), the test is usually used for this purpose as shown by Jemni et al. (2006) in artistic and rhythmic gymnastics.

However, our investigation of gymnasts' anaerobic performance showed no improvement, even deterioration over 2 years in the lower-body Wingate test. Therefore, it is questioned whether Wingate test is suitable to determine the specific anaerobic performance in aerobic gymnastics. This assumption may be corroborated by Wonisch et al. (2003) who demonstrated that it is almost impossible to reflect the specific muscular involvement and movement patterns of a particular sport in laboratory′s physical tests. Thus, low relationship between the real technical demands and the type of effort the gymnast performs in her specific competitive routines during the study period may be expected. Specific field tests in a form of repeated rebound jumps (Kyselovičová et al., 2010a) would be more appropriate to assess the specific aerobic gymnastics performance over the 80 s routine. From practical point of view, it would be interesting to know the relationships between test variables and competition results, representing mostly by execution and difficulty scores. However, this was not applicable in our study due to regular change of rules–Code of Point (between two Olympic cycles) over 2 years of investigation.

The study has some limitations related to the sample size; therefore, the results should be interpreted cautiously. Using laboratory tests instead of field tests to assess physiological variables to explain sport-specific performance changes is also questionable. Thus, the relationships between general abilities and specific performance in aerobic gymnastics should be part of future research.

The novelty of our study with three screenings of the successful elite aerobic gymnast under the same conditions not only enables interpretations of the results obtained but provides some practical recommendations:

1. Physical and physiological tests should be performed regularly as they provide useful information on the progress of gymnasts during long-term training.
2. To assess adaptation, it is necessary to assess individual performance changes during long-term training. The obtained results provide important feedback for the gymnast's coach during the annual training plan.
3. Coaches should consider competition results (difficulty and execution scores) as adequate variables to correlate with the physical and physiological changes over time.
4. Regular basic screening for elite athletes is also recommended, as it provides data on muscle imbalance and thereby supports the decision-making process; for example, despite the improvement in the ability to maintain optimal body posture, it is necessary to focus on further development of the perception of symmetry.

The results of this study provide limited but initial support for a specific test battery to assess the performance in aerobic gymnastics. Although it may be a sign that some changes are needed, this kind of screening and monitoring has shown its usefulness because it is affordable and not time-consuming.

5 Conclusion

This follow-up study is one of the few that investigate a high-performance aerobic gymnast, competing internationally. Over the 24 months between the two European Aerobics Championships, an almost identical year-plan was used with 2-peak periodization while the athlete's changes over the 2-year range were compared. Nevertheless, postural stability and flexibility in the anterior, posteromedial, and posterolateral directions improved. Jumping performance also markedly increased during a 60 s test of repeated jumps. In addition, isokinetic muscle strength during leg extension rather than leg flexion increased. However, there were no improvements in the explosive power of lower limbs and anaerobic capabilities over 2 years of training. From these findings, it is obvious that our elite aerobic gymnast improved in the ability to maintain balance in dynamic conditions and repeated rebounds which represent key abilities of aerobic competition routine.

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 study involving humans was approved by the Faculty of Physical Education and Sport, Comenius University in Bratislava (No 1/2020). The study was conducted in accordance with the local legislation and institutional requirements. The participant provided written informed consent to participate in this study.

Author contributions

OK: Writing–original draft, Writing–review and editing, Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Project administration, Supervision. EZ: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Supervision, Validation, 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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The influence of real-time quantitative feedback and verbal encouragement on adults' performance in maximal and explosive strength and power in bench press exercise

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Background: In sports practice, a wide array of verbal and non-verbal stimuli can elicit diverse motivations and performance changes. Therefore, the primary objective of this study was to compare the impact of various stimuli on maximal strength and power in bench press exercises.

Methods: This study involved 48 university students (average age 20.5 ± 2.8 years; body mass 80.1 ± 20 kg; height 174.6 ± 6.7 cm; BMI 26.2 ± 6 kg/m2) who engaged in an 8-week resistance training program. The students were randomly divided into three experimental groups and one control group. The first group received real-time quantitative feedback (RF) on their power output during the bench press exercise, the second group received verbal encouragement (VE) from an instructor, and the third group exercised without any external stimulus (WS). The control group (CG) underwent only pre- and post-measurements. To compare differences in strength parameters among groups a Two-Way Repeated Measures ANOVA was applied.

Results: The results revealed significant improvements in the mean weight for one repetition maximum in the real-time quantitative feedback group (5 kg, 9.76%, p = 0.001, d = 0.529) and the verbal encouragement group (5.42 kg, 11.51%, p = 0.001, d = 1.201). Positive changes were also observed in the mean power at 20 and 30 kg for the RF, VE, and WS groups, but at 40 kg, significant improvement was only seen in the real-time quantitative feedback group (247 W, 31.30%, p = 0.001, d = 1.199).

Conclusion: These findings underscore the effectiveness of selected stimuli in enhancing maximum strength and power during bench press exercises, with real-time quantitative feedback proving to be the most effective stimulus for improving both maximal strength and power.

KEYWORDS

motivation, resistance training, students, quality education, stimuli

1 Introduction

Body movements are patterns of responses to recognized stimuli (Melzer et al., 2019). These stimuli, which can be visual, kinesthetic, auditory, or a combination of multiple senses, are perceived by individuals (Morgan, 2019). Learning occurs by conditioning responses to specific stimuli (Bam, 2016). Applied behavior analysis has increasingly emphasized the significance of stimuli in regulating human behavior (Winnick and Porretta, 2017).

In the context of physical activity settings, a growing body of research has provided evidence for the influential role of positive feedback as a stimulus in shaping perceptions of competence and intrinsic motivation (Schunk, 1995; Reinboth et al., 2004; Nicaise et al., 2006). The feedback provides information about the objective or subjective results, or the quality and quantity of movements during or after the performance (Kangalgil and Özgü, 2018). According to Doig (2001), feedback is a helpful tool for individuals to achieve desired outcomes according to certain criteria. Badami et al. (2011) have differentiated between two types of feedback employed in teaching and coaching: intrinsic feedback (feedback that arises from learners' sensory systems during and as a consequence of their performance) and augmented feedback (feedback received from an external source that supplements the learner's sensory information). The utilization of these two types of feedback in conjunction assists students and athletes in thriving and enhancing their performance (Smither et al., 2005).

The feedback provided by teachers and coaches significantly influences the achievement of students and athletes in physical education and sports settings (Mouratidis et al., 2008). Practitioners utilize feedback to teach correct movements and skills, enabling students and athletes to assess their performance (Lund and Kirk, 2019). Feedback serves as a tool to rectify mistakes and impact an individual's motivation levels (Coker, 2013). It can be delivered in various forms, including verbal, visual, or written, and does not always require intricate details to enhance motivation (Strube and Strand, 2015).

Koka and Hein (2003) discovered that perceived feedback played a pivotal role in students' perceptions of competence and intrinsic motivation. Similarly, the sports literature is abundant with evidence highlighting the crucial role of positive feedback from coaches in athletes' perceptions of competence and intrinsic motivation (Amorose and Horn, 2000; Chelladurai and Saleh, 1980). One of the most straightforward methods for enhancing motivation and competitiveness is through the effective use of feedback (Wilson et al., 2017; Weakley et al., 2020).

Real-time quantitative feedback is a powerful tool for creating a competitive environment that can lead to acute improvements in performance and, over time, drive adaptation (Argus et al., 2011; Randell et al., 2011; Wilson et al., 2017). This straightforward method is often overlooked but has demonstrated a significant impact on the development of strength and power (Weakley et al., 2020). Studies (Argus et al., 2011; Randell et al., 2011; Singh, 2016; Wilson et al., 2017) have shown that real-time quantitative feedback results in higher movement velocities and can enhance training performance by approximately 3%–6%. It enables individuals to train closer to their optimal capacity (Figoni and Morris, 1984; Graves and James, 1990; Kellis and Baltzopoulos, 1996; Owen, 2014).

Another method for motivating individuals is through verbal encouragement (VE). A recent study has shown that receiving verbal encouragement in conjunction with the presence of practitioners during exercise can lead to enhanced performance (Keegan, et al., 2010). It is also recognized that implementing verbal or visual feedback can yield the same positive effect on performance as having a coach present (Weakley, 2020). In the same study, it is mentioned that verbal encouragement yields comparable improvements in strength training when compared to receiving kinematic feedback. This underscores the importance of this stimulus in maintaining motivation during practice (Standage et al., 2003). However, it is worth noting that a study by Campenella et al. (2000) found no significant effect of verbal encouragement on strength efforts. This indicates that there is limited evidence regarding the effectiveness of verbal encouragement in strength training, especially considering that most studies have focused on endurance performance (Bickers, 1993; Moffatt et al., 1994; Andreacci et al., 2002; Neto et al., 2015). Furthermore, several exercise testing guidelines have included specific steps for using verbal encouragement, but without solid theoretical or empirical justification. Additionally, there has been limited research defining effective verbal encouragement in terms of content, tone, loudness, timing, and frequency of delivery (Midgley et al., 2018).

Until now just a few studies have investigated the chronic effect of resistance training with different stimuli or feedback (Weakley et al., 2023). Therefore, the primary objective of this study is to compare the effectiveness of different stimuli, namely, real-time quantitative feedback, verbal encouragement, and no external incentives. This research aims to shed light on the impact of these stimuli on student motivation and performance, providing valuable insights for both scientists and practitioners. The study is unique in its approach, as it combines several elements: a comparative analysis of selected stimuli within the training program, a group of students, and customized training loads tailored to each participant.

The hypothesis posited that all experimental groups would exhibit significant improvements in maximal strength (one repetition maximum-1RM) and explosive strength (mean power) during bench press exercises, in contrast to the control group (CG). Furthermore, it was expected that the group utilizing real-time quantitative feedback would experience significantly greater improvements compared to the other groups following the implementation of the selected resistance program. Lastly, it was anticipated that the experimental groups would demonstrate greater enhancements in explosive strength as opposed to maximal strength upon completion of the selected resistance program.

2 Materials and methods

2.1 Participants

This study followed a blinded four-group–time-parallel experimental design, with the dependent variables being motoric abilities (maximal and explosive strength). The independent variables were perceived feedback during resistance training (real-

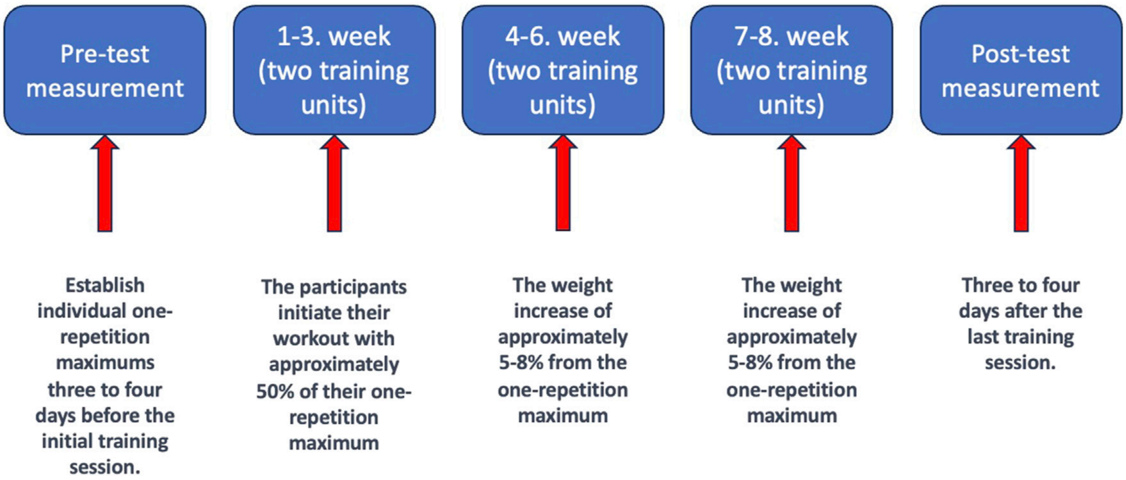

FIGURE 1
Training program.

time quantitative feedback, verbal encouragement). A total of forty-eight male students from Prince Sultan University participated in the study (average age 20.5 ± 2.8 years; body mass 80.1 ± 20 kg; height 174.6 ± 6.7 cm; BMI 26.2 ± 6 kg/m2), and all participants completed the training and measurements. They were all in good physical health, without any injuries, and refrained from taking supplements during the program. Every student had less than 2 years of experience with progressive resistance training and more than 1 month of experience with weightlifting in the gym. Therefore, the purposive sampling method was employed to select participants for our study. Students were informed about the testing procedures, training programs, and potential risks associated with these activities before the pre-test measurement of their explosive and maximal strength abilities. However, they were unaware of the specific interventions and were instructed not to engage in any exercise routines other than the selected program. Each student underwent pre- and post-measurements before and after an 8-week resistance program.

2.2 Instruments

Prior to the actual measurement, they had three practice attempts using a 20 kg barbell for the bench press test. The students were randomly divided into four groups, each one with 12 students. Three of these groups underwent resistance training programs in the gym, with different interventions or without any stimuli, while the fourth group (control group) underwent only pre- and post-measurements. The real-time quantitative feedback group received feedback from a device called FITROdyne Premium (FITRONIC, Bratislava, Slovak Republic) about their performance (power in the concentric phase) after each repetition. This feedback was both visible to the participant and verbally announced by the teacher or their peers. The verbal encouragement group received verbal encouragement from the teacher before each repetition and set. The verbal encouragement consisted of a single word, "hoop," which was loudly spoken by the teacher before each repetition and concentric phase of the movements. The without any external stimulus group (WS) worked out without any feedback. All testing procedures, interventions, and training were administered by a single investigator. The experiment had a duration of 8 weeks, with sessions held twice a week for a total of 16 training units.

2.3 Procedures

Students received individualized training programs based on their pre-test measurements in the bench press (BP) exercise (Figure 1). Each participant began with a standardized warm-up, consistent for all participants, and then proceeded to work with weights starting at approximately 50% and concluding at around 65% of their one-repetition maximum (1RM). Every 3 weeks, weights were incrementally increased by about 5%–8% based on their individual programs. Interval rests between sets ranged from 3–6 min. The training program included two sets with 4-6 repetitions (based on their subjective feelings), emphasizing subjective maximal velocity during the concentric phase. Participants were instructed to stabilize the barbell on their chests for 3 s before beginning the next repetition of the bench press concentric phase. All participants had a minimum of 48 h of rest between training sessions.

The study adhered to ethical standards for human experimentation as outlined in the 1964 Helsinki Declaration and its subsequent amendments. Approval for the project was obtained from the Prince Sultan University Institutional Review Board (PSU IRB-2022-02-0104).

2.4 Data collection and processing

Students were instructed to abstain from engaging in physical activity for at least 2 days prior to the measurements and to avoid consuming solid meals within 2 h before testing. On the day of testing, participants followed a standardized warm-up routine, which included 1 min of running in place, dynamic stretching exercises for the upper body, and five sets of push-ups.

Following the warm-up, an assessment battery was conducted to assess maximal power and maximal strength. The students underwent strength testing to determine their one-repetition maximum (1RM) on the bench press (BP). The bench press is a commonly used exercise for developing upper body strength.

The investigator served as a spotter during the bench press measurements. Firstly, it was checked if participants had the correct grip on the bar (slightly wider than shoulder-width) and provided assistance with unracking the bar when necessary. Students then started the exercise with their arms fully extended and elbows locked. Then the bar was lowered until it touched the chest, followed by a concentric phase, lifting the bar back to full arm extension. A repetition was considered successful only if it included this full range of motion. Any deviation, such as failing to touch the chest or bouncing the bar, was regarded as an unsuccessful attempt. For safety reasons, the spotter remained positioned behind the bar throughout the exercise and intervened by assisting with lifting the bar off the participant if an attempt was unsuccessful or unsafe. However, during successful attempts, the spotter did not touch the bar (Wilk, et al., 2020).

Participants aimed to achieve maximum velocity during the concentric phase while lifting various weights, starting from 20 kg and increasing incrementally. After each successful attempt, the weight was increased by 10 kg. Peak power output was recorded from 20 kg until the one-repetition maximum (1RM) was determined (Pacholek and Zemková, 2020). If a student failed to lift the weight, they were given one more attempt with 5 kg less weight to ensure a more accurate detection of their 1RM.

To assess strength parameters, a monitoring device, the FITROdyne Premium (FITRONIC, Bratislava, Slovak Republic), was utilized. It is a system with a sensor unit containing a linear encoder. This computer-based system for the assessment of strength capabilities and feedback monitoring of strength training. This device is capable of measuring vertical speed and range of motion, particularly during strength exercises. It includes a sensor connected to a barbell. Using data related to weight and acceleration, the system can calculate force, power, and position. The device offers immediate feedback after each repetition (Fitronic, 2017). The device is designed to comprehensively capture biomechanical parameters during workouts, including vertical velocity and the length of motion. Consisting of a sensor unit equipped with a precise encoder and reel. The system utilizes extensive computer software to facilitate the collection, calculation, and real-time display of fundamental biomechanical parameters relevant to the workout. (Pacholek and Zemková, 2020). The reliability of the parameters obtained using this system has been established in various exercises, including squat jumps and biceps curls (Jennings et al., 2005), chest presses on the bench and on a Swiss ball (Zemková et al., 2014), deadlift to high pull on the Smith machine and with free weights (Zemková et al., 2016), and standing cable wood chop exercises (Zemková et al., 2017). The testing took place in a consistent location, with the same timing and on the same days.

2.5 Statistical analysis

Statistical analysis was conducted using IBM SPSS Statistics 23, (IBM Corporation, United States). The basic descriptive parameters, including standard deviation and mean, were computed. The Shapiro-Wilk Test for normality was applied to assess the distribution of all variables. To analyze participant characteristics was employed a one-way analysis of variance (ANOVA) and the Kruskal–Wallis Test. To evaluate statistical changes between pre- and post-tests within groups, the paired samples *t*-test. For nonparametric data, was utilized the Related Samples Wilcoxon signed-rank test. To compare differences in strength parameters among groups a Two-Way Repeated Measures ANOVA with a Tukey *post hoc* test was used. For a practical interpretation of the research findings, was reported the effect size (ES). Cohen's criteria for effect sizes categorize them as small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$). Additionally, for nonparametric data, Pearson's correlation was used, with values of $r = 0.1$ to 0.3 considered small, $r = 0.3$ to 0.5 as medium, and $r = 0.5$ to 1.0 as large (McLeod, 2020).

3 Results

The results from the characteristics of the participants (Table 1) indicate that all groups were homogeneous in terms of height, body mass, and body mass index. However, a significant difference was observed in their age ($p = 0.003$).

The changes in mean weight for one-repetition maximum (Table 2) demonstrate significant improvements in the real-time quantitative feedback and verbal encouragement groups. Following group comparisons, significant differences were identified between real-time quantitative feedback and control group groups ($p = 0.009$). Figures 2A–D illustrate the individual changes (pre-post measurement) in one-repetition maximum within each group.

The mean power produced during the bench press (BP) in the concentric phase at weights 20 kg (Figure 3A) significantly improved all groups except the control group. Real-time quantitative feedback group by about 183W (20,32%, $p = 0.012$, $r = 0.340$), verbal encouragement group by about 125W (16.43%, $p = 0.048$, $d = 0.802$) and without any external stimulus group by about 205W (29.11%, $p = 0.001$, $d = 1.3834$). Following group comparisons, significant differences were identified between real-time quantitative feedback and control group groups ($p = 0.001$), real-time quantitative feedback and without any external stimulus groups $p = 0.004$, verbal encouragement, and control groups $p = 0.43$.

At a weight of 30 kg (Figure 3B), similar results were observed with significant improvements in the real-time quantitative feedback group (239 W, 28.17%, $p = 0.001$, $d = 1.581$), the verbal encouragement group (137 W, 19.40%, $d = 1.159$), and the without any external stimulus group (120 W, 21.25%, $p = 0.002$, $d = 0.862$). The control group did not improve significantly. Following group comparisons, significant differences were identified between real-time quantitative feedback and control group groups ($p = 0.002$), real-time quantitative feedback, and without any external stimulus groups $p = 0.002$.

At a weight of 40 kg (Figure 3C), significant improvements were observed only in the real-time quantitative feedback group (247 W, 31.30%, $p = 0.001$, $d = 1.199$). The other groups did not exhibit

TABLE 1 Characteristic of participants (mean ± SD and n).

Variable	Whole group (n = 48	Real-time quantitative feedback group (n = 12)	Verbal encouragement group (n = 12)	Without stimulus group (n = 12)	Control group (n = 12)	*p*-value
Age (y)	20.52 ± 2.84	22.83 ± 4.20	20.67 ± 2.06	18.83 ± 0.94	19.75 ± 1.48	0.003
Height (cm)	174.63 ± 6.70	175.42 ± 6.67	175.08 ± 6.65	176.08 ± 5.65	171.92 ± 7.73	0.442
Body mass (kg)	80.08 ± 19.96	82.23 ± 18.96	81.24 ± 18.94	86.67 ± 23.67	70.18 ± 16.22	0.220
BMI ($kg.m^{-2}$)	26.16 ± 5.96	26.58 ± 5.18	26.52 ± 6.14	27.90 ± 7.43	23.64 ± 4.64	0.362

TABLE 2 One repetition maximum in bench press exercise.

Variable	Pre-test	Post-test	Percentage of change (%)	*p*-value	d Value
Real-time quantitative feedback group	51.25 ± 9.56	56.25 ± 9.32	9.76	0.001	0.529
Verbal encouragement group	47.08 ± 4.50	52.50 ± 4.52	11.51	0.001	1.201
Without stimulus group	44.58 ± 8.94	46.25 ± 7.45	3.75	0.166	
Control group	42.92 ± 11.02	42.92 ± 9.02	0	1.000	

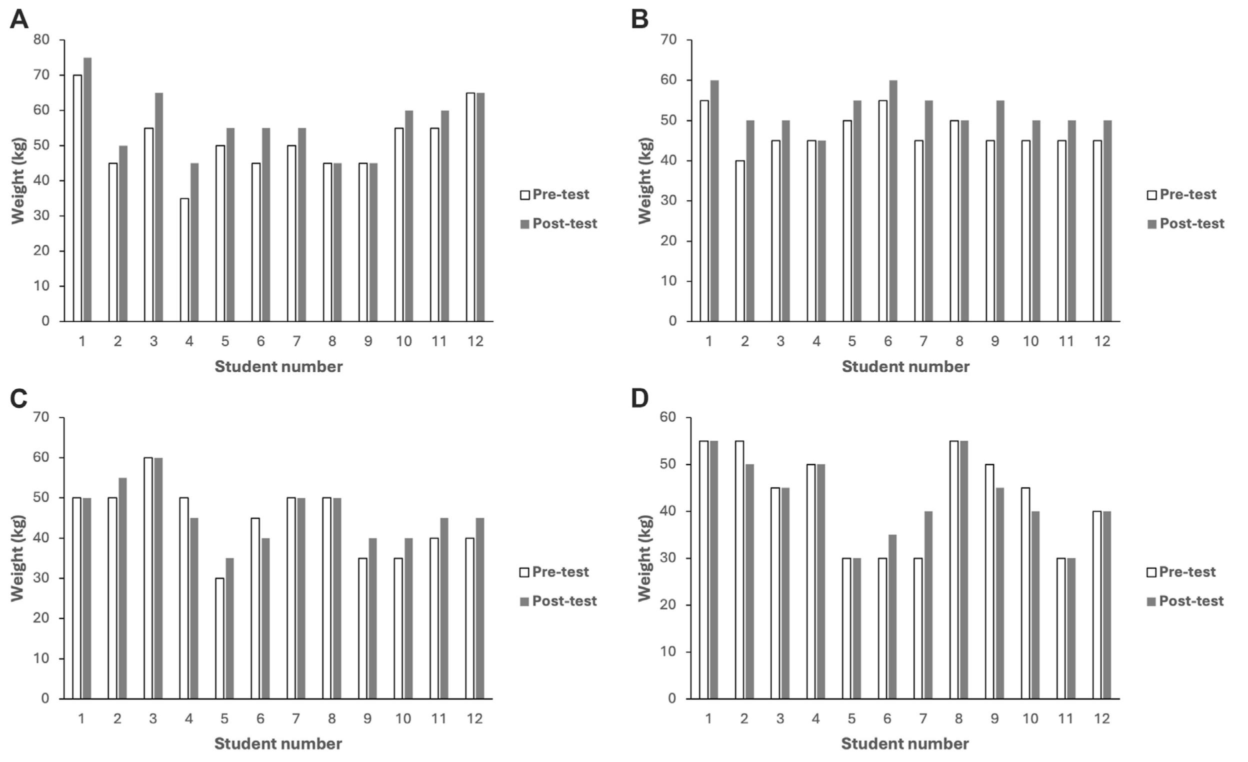

FIGURE 2
(A) The individual changes in one repetition maximum within the real-time quantitative feedback group. **(B)** The individual changes in one repetition maximum within the verbal encouragement group. **(C)** The individual changes in one repetition maximum within the without any external stimulus group. **(D)** The individual changes in one repetition maximum within the control group.

significant improvements. Following group comparisons, significant differences were identified between real-time quantitative feedback and control group groups ($p = 0.017$), real-time quantitative feedback and without any external stimulus groups $p = 0.017$, and real-time quantitative feedback and verbal encouragement groups $p = 0.029$.

Following pairwise comparisons, significant differences in mean power were found between the real-time quantitative feedback and

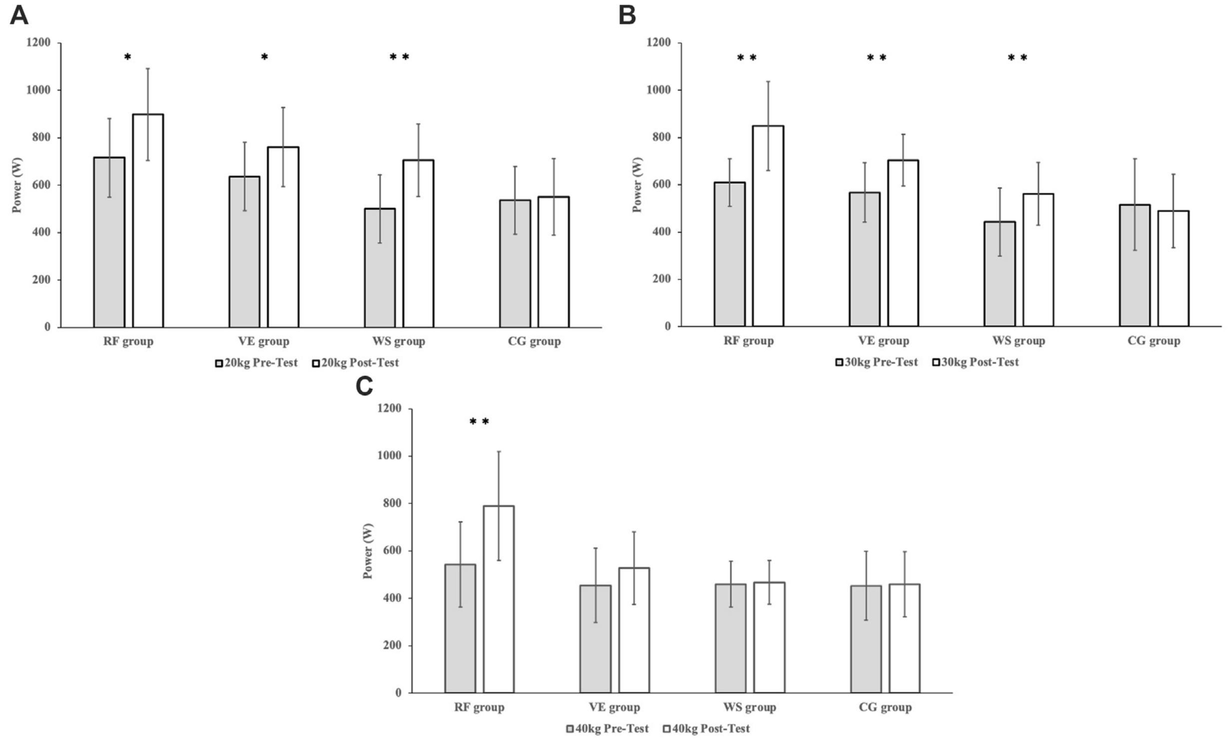

FIGURE 3
(A) The mean power produced during the bench press at weights 20 kg prior to and after 8 weeks of the training program (*$p \le 0.05$, **$p \le 0.01$). **(B)** The mean power produced during the bench press at weights 30 kg prior to and after 8 weeks of the training program (**$p \le 0.01$). **(C)** The mean power produced during the bench press at weights 40 kg prior to and after 8 weeks of the training program (**$p \le 0.01$).

control groups ($p = 0.004$) during the bench press exercise at the weight of 20 kg. Similarly, significant differences were noted between real-time quantitative feedback and without any external stimulus groups ($p = 0.009$), real-time quantitative feedback and control groups ($p = 0.001$), verbal encouragement and control groups ($p = 0.001$), and without any external stimulus and control groups ($p = 0.038$) at the weight of 30 kg. Lastly, significant differences emerged between groups real-time quantitative feedback and verbal encouragement groups ($p = 0.014$), real-time quantitative feedback and without any external stimulus groups ($p = 0.002$), and real-time quantitative feedback and control groups ($p = 0.003$) at the weight of 40 kg. Figures 4A–D illustrate the individual changes (pre-post measurement) in maximum power within each group at the 30 kg weight of the barbell.

4 Discussion

The purpose of the study was to compare the effects of different stimuli on strength parameters in bench press exercises after 8 weeks of a training protocol. The main findings of this study indicate that real-time quantitative feedback and verbal encouragement groups that adhered to the protocol experienced significant improvements in maximal strength and mean power compared to the control group, thus confirming the first hypothesis. The second hypothesis was also confirmed as the real-time quantitative feedback group showed greater improvements in mean power at the weight of 40 kg compared to the other groups. The improvements in other factors, such as mean power at 20 and 30 kg and one repetition maximum, were similar to those of the verbal encouragement group. However, the without any external stimulus group only demonstrated significant improvements in mean power at 20 and 30 kg, without a corresponding improvement in maximal strength. Group comparison has shown superior results of the real-time quantitative feedback group compared to the other groups in mean power mainly at a different weight (20, 30, 40 kg). This outcome aligns with our last hypothesis that the experimental groups would exhibit significantly greater improvements in mean power than in maximal strength.

The study by Pareja-Blanco et al. (2014) documented a positive impact of maximal intended velocity compared to half-maximal concentric velocity on squat performance in a 6-week program. In this study, physically active men demonstrated a greater improvement in maximum strength (effect size: 0.94 vs. 0.54) and in velocity developed against resistance (effect size: 1.76 vs. 0.88). In this study, similar improvements in the mean power of the concentric phase were observed, particularly on lighter loads but different results were yielded particularly in heavy loads and one-repetition maximum performance on the bench press exercise. The without any external stimulus group did not exhibit a significant improvement in the mean one-repetition maximum or the mean power on heavier loads. Several factors may contribute to this discrepancy, including differences in smaller amounts of repetition (4–6 vs. 8), sets (2 vs. 3), and loads in our program. Selected exercise when the bench press utilizes relatively smaller muscle mass than the back squat (Argus et al., 2011) and statistically significantly smaller differences compared to other fitness abilities were also recorded in acute resistance training performance in

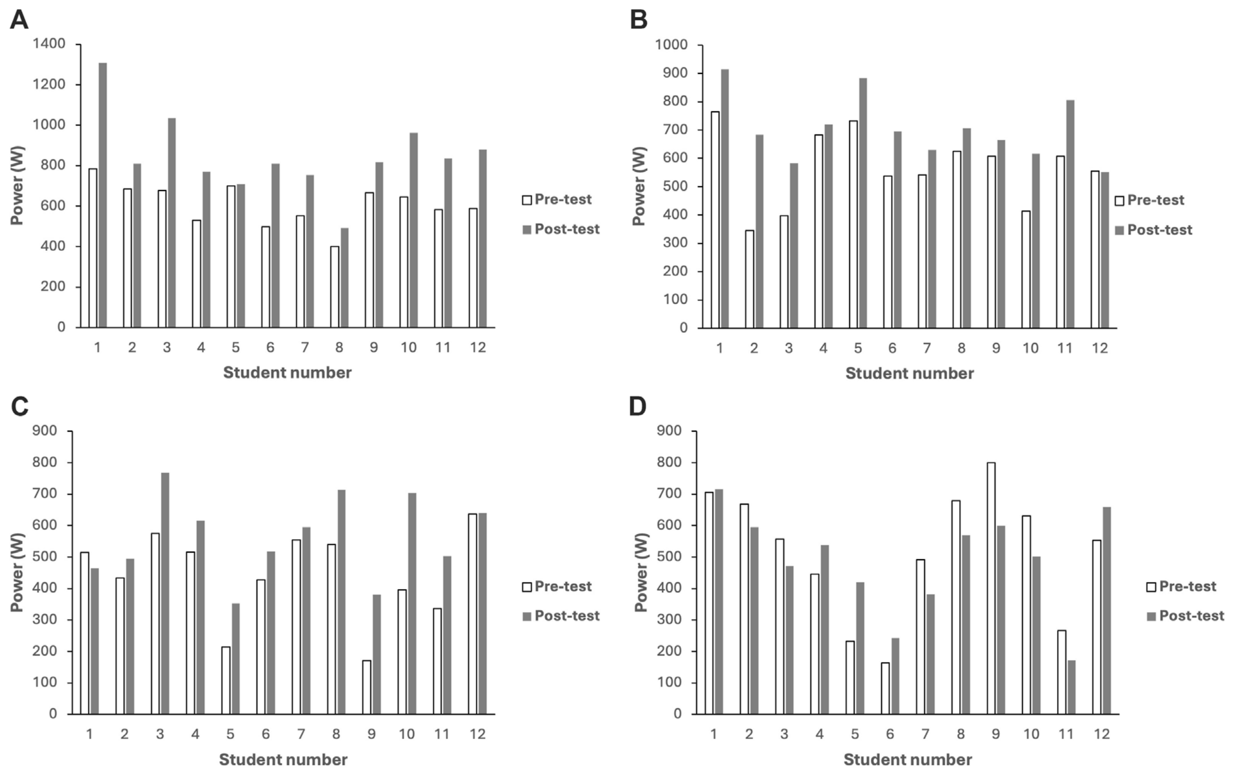

FIGURE 4
(A) The individual changes in maximum power (at the 30 kg weight of the barbell) within the real-time quantitative feedback group. **(B)** The individual changes in maximum power (at the 30 kg weight of the barbell) within the verbal encouragement group. **(C)** The individual changes in maximum power (at the 30 kg weight of the barbell) within the without any external stimulus group. **(D)** The individual changes in maximum power (at the 30 kg weight of the barbell) within the control group.

the bench press exercise. The conclusion was that the performance close to maximal strength might not be sensitive enough to external stimulation (Pacholek and Zemková, 2022). Moreover, motivation could also be a crucial factor, as evidenced by the significant improvements in maximum strength parameters in the real-time quantitative feedback and verbal encouragement groups.

Weakley et al.'s meta-analysis (2023) reveals that various forms of feedback have positive effects on chronic training adaptation, particularly over a 4–6-week period. Notably, improvements were observed in key performance metrics such as velocity, power, and strength when feedback was incorporated during training sessions, in contrast to scenarios where no feedback was given. This aligns with similar findings from studies by Nagata et al. (2018), Randel et al. (2011), and Vanderka et al. (2020), which support the idea that feedback enhances performance. A noteworthy aspect of Weakley et al.'s analysis (2020) is the comparison of different feedback types when differences between verbal encouragement, kinematic feedback, and verbal kinematic feedback were generally minimal, likely to very likely trivial during the back squat exercise. This implies that, for the back squat exercise specifically, athletes may not experience significant distinctions in performance when employing these feedback methods. In contrast, the meta-analysis emphasizes the superiority of visual feedback when it comes to chronic performance gains. It was found that visual feedback had a statistically greater effect on immediate performance improvement compared to verbal feedback (Weakley et al., 2023) and from Keller et al. (2014) study is known that visual feedback decreases mean concentric barbell velocity loss, and improves perceived workload, competitiveness, and motivation. This finding aligns with the present study when real-time quantitative feedback outperformed both verbal encouragement and training without any stimuli in most of the parameters evaluated in the BP.

Pérez-Castilla et al. (2020) describe in their study that to enhance power and velocity performance during the concentric phase of the movement, it is more effective to provide feedback after each repetition rather than after each set. Furthermore, Jiménez-Alonso et al. (2022) found that this feedback is particularly advantageous when emphasizing strength over power, as it leads participants to shift their motivation from internal to external sources of information, fostering a more competitive mindset. Additionally, Weakley et al. (2020) stated that for athletes with low levels of conscientiousness, offering verbally encouraging statements after each repetition may yield the greatest benefit. In our study, we implemented real-time quantitative feedback after each repetition and provided verbal encouragement before every repetition. Furthermore, Nagata et al. (2018) achieved superior results in loaded jump abilities when providing verbal feedback about the bar's velocity after each repetition, compared to kinetic-visual or average feedback, which was given after each set. However, the optimal approach for combining these stimuli remains a subject of inquiry. Notably, the provision of objective information about students' performance in the real-time quantitative feedback group, compared to the verbal encouragement group, resulted in greater improvements, particularly in power parameters, regardless of whether heavy or lighter loads were used.

The study by Lee et al. (2021) indicates that verbal encouragement is effective in maintaining central activation; however, it may not be sufficient to produce significant increases in strength parameters in acute conditions. A similar study conducted by Pacholek (2021) also reported statistically non-significant results in strength parameters, particularly in the bench press exercise. In contrast, Miller et al. (2021) found that a combination of real-time feedback and verbal encouragement leads to significantly better results compared to a group that only received verbal encouragement from the investigator. On the other hand, a study by McNair et al. (1996) suggests that participants in their research significantly improved in strength parameters, although electromyograph activity remained unchanged. The effectiveness of verbal encouragement might be attributed to factors such as the presence of a teacher, their interest in the subject's performance, and the subject's maximal effort, as suggested by Andreacci et al. (2002). Consequently, based on these findings, the impact of verbal encouragement on acute resistance training performance remains unclear. Nevertheless, this study highlights the positive effect of verbal encouragement on chronic adaptation, particularly in the context of power and maximal strength.

The efficacy of real-time quantitative feedback as a modulating factor is underscored by its provision of objective feedback to students during their workout sessions. This feedback not only serves as a source of motivation for improved performance but also fosters a sense of competition as students compare their progress with their peers. The immediacy of information in response to any lapse in concentration plays a pivotal role in enhancing effort and execution. In contrast, verbal encouragement or without any external stimulus lacks these distinct advantages, resulting in a comparatively diminished impact compared to the dynamic and immediate influence of real-time quantitative feedback.

From a physiological point of view, we can distinguish physiological aspects based on motivation and emotion (Bradley and Lang, 2000), which could play a significant role in this research. Hormones and energy levels guide motivation; on the other hand, emotions arise from innate biological response patterns in our brains and bodies when hormones and neurotransmitters chemically affect the activity of the brain (limbic system) and its role in emotional processing (Gross and Canteras, 2012). In our scenario, it was a key point to prepare the body with a motivational stimulus to achieve better performance and focus on the task. This could happen by releasing adrenaline, which increases heart rate, blood pressure, and other physical responses (Stanton and Schultheiss, 2009). Other hormones, like dopamine and serotonin, could also play important roles in selected stimuli, as students might feel they would like to repeat this training or feel satisfaction with their accomplishments and results (Baixauli Gallego, 2017). It appears that real-time quantitative feedback influences these processes the most compared to other selected stimuli.

The study has several notable limitations. Firstly, the limited number of participants who took part in the training program raises concerns about the generalizability of the findings. Additionally, the significant age difference among the selected groups may have introduced confounding variables that could impact the results, potentially skewing the outcomes This is compounded by the significantly superior results of the real-time quantitative feedback group compared to the groups without stimuli and the control group in power at 20 kg. Furthermore, the varying number of training units completed by some participants (14th and 16th) introduces an additional variable that could have influenced the results and made it challenging to attribute improvements solely to the training protocol.

In terms of future research, it would be valuable to conduct studies with larger and more diverse participant samples and exercises to enhance the generalizability of the findings. Additionally, exploring the effects of different stimuli on muscular strength and power, particularly when tailored to specific strength parameters or fitness abilities, could provide valuable insights. Moreover, investigating whether the same stimuli have a similar effect on female students, athletes, and different age groups, including both older and younger populations, would be an interesting avenue for research. This approach could help discern potential differences in response to training stimuli among various demographic groups, contributing to a more comprehensive understanding of maximal strength and power improvements.

5 Conclusion

The purpose of this research was to investigate methods for enhancing motivation and performance among young, healthy participants during physical education (PE) classes at the university level. The study revealed that different stimuli have varying positive effects on students' performance during resistance training, offering valuable insights into how to effectively encourage and motivate students to achieve better results in strength training. Real-time quantitative feedback emerged as a promising choice for PE classes, not only for its role in improving results but also for providing objective information about students' efforts and performance. Verbal encouragement from teachers was shown to lead to greater improvements in maximal strength parameters compared to situations without any stimuli. This underscores the potential for educators to positively influence their students when objective feedback may not be readily available during physical education activities.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Prince Sultan University Institutional Review Board (PSU IRB-2022-02-0104). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

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The author declares 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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In elderly individuals, the effectiveness of sensorimotor training on postural control and muscular strength is comparable to resistance-endurance training

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While classical resistance exercise is an effective way to improve strength and control postural sway, it may not be suitable for some elderly individuals with specific health disorders (e.g., aneurysms). Therefore, there is a need to explore alternative modalities. The study aimed to evaluate the effects of sensorimotor training on muscle strength and postural control in the female elderly population and subsequently compare these effects with a traditional combined resistance-endurance training program. A total of 34 healthy, active elderly women aged from 65 to 75 years, (average age 72.7 ± 4.4 years, height 161.6 ± 5.1 cm, and weight 66.9 ± 8.4 kg) were randomly assigned to three groups undergoing different 10-week interventions: the resistance-endurance training (RET, n = 11), the sensorimotor training (SMT, n = 12) and the control group (COG, n = 11). Prior to and after the interventions all participants underwent tests of maximal voluntary contraction of the dominant and non-dominant leg; postural sway tests with open and closed eyes; novel visual feedback balance test; 10-meter maximal walking speed (10 mMWS) and stair climb test. A T-test and repeated measures ANOVA were used, followed by the Bonferroni *post hoc* test, to compare the pre and post-measurements and assess differences in gains between groups. Results showed a significant main effect of time on strength ($p < 0.001$). In addition, significant differences in time × group interaction on strength ($p < 0.01$), postural control ($p < 01$), and ascendant and descended vertical speed ($p < 0.001$) were observed. Besides, the RET group improved significantly the maximal voluntary contraction of both dominant (16.3%, $p \leq 0.01$) and non-dominant leg (10.9%, $p \leq 0.05$). SMT group improved maximal voluntary contraction of both dominant (16.6%, $p \leq 0.001$) and non-dominant leg (12.7%, $p \leq 0.01$). In addition, they also improved mean velocity of the centre of pressure (COP) in postural sway test with eyes open (24.2%, $p \leq 0.05$) as well as eyes closed (29.2%, $p \leq 0.05$), mean distance of COP in novel visual feedback balance test (37.5%, $p \leq 0.001$), ascendant and descended vertical velocity (13.6%, $p \leq 0.001$ and 17.8%, $p \leq 0.001$, respectively).

Results show not only resistance training but sensorimotor intervention boosts strength too. This intervention also enhances postural control and functional abilities for both ascending and descending movements.

KEYWORDS

aging, seniors, balance abilities, strength abilities, physical performance

1 Introduction

Around 11% of the world's population is currently aged 60 or older, and this is expected to double to 22% by 2050 (Kanasi et al., 2016). Thus, there is a need to find better ways to support healthy ageing (Witham et al., 2022). Physical activities, especially resistance training, are known to promote healthy ageing. Recent studies suggest that combining resistance training with endurance activities is even more beneficial. However, some people may find this type of exercise unsuitable. As a result, the scientific community is actively exploring alternative exercise options that are more efficient and effective for promoting healthier ageing. One such promising option is sensorimotor training.

It is important to realise, that as people age, their physical abilities naturally decline, leading to various challenges and limitations in their daily lives (Maresova et al., 2019). Physical fitness has a significant impact on life expectancy, as it determines a person's capability to independently carry out daily activities without difficulty or assistance (Gill et al., 2016). One notable consequence of aging is the loss of muscle mass, known as sarcopenia, which directly corresponds to a decrease in muscle strength, referred to as dynapenia (Tanaka et al., 2017). Yet, several factors contribute to the inevitable progression of sarcopenia, including dysfunction in mitochondrial and autophagy processes, as well as the limited ability of satellite cells to regenerate. The natural decline in muscle mass and motoneuron function that occurs with ageing (Agostini et al., 2023). Both sarcopenia and dynapenia contribute to a decrease in overall physical fitness and changes in general health status (Garatachea et al., 2015; Tieland et al., 2017). Starting at the age of 60, the ability to generate force through isometric contractions decreases by approximately 1.5% each year (Jubrias et al., 1997). However, both sarcopenia and dynapenia have a more significant impact on a muscle's ability to generate force during movement (Clark and Carson, 2021). Conversely, extensive research supports the notion that regular exercise results in skeletal muscle hypertrophy, increased muscle strength, and enhanced overall physical performance and fitness (Bekfani et al., 2016; Mcleod et al., 2024). Additionally, when planning regular physical activity, it's important to also maintain a balanced diet, which is rich in antioxidants, polyunsaturated fatty acids, vitamins, probiotics, prebiotics, proteins, and short-chain fatty acids. Specifically, paying attention to the intake of vitamin D is crucial as low levels of this vitamin are linked to an increased risk of sarcopenia (Remelli et al., 2019; Agostini et al., 2023; Widajanti et al., 2024). In addition, studies by Agostini et al. (2023) highlight that vitamin D supplementation is particularly beneficial in stimulating skeletal muscle hypertrophy and promoting protein synthesis. Therefore, it is highly important to combine a well-balanced diet with vitamin D supplementation, alongside regular physical activity, to effectively protect aging muscles from the development of sarcopenia.

Besides experiencing a decline in physical strength, the elderly also tend to face a deterioration in their balance skills (Clemson et al., 2012), leading to a significant decrease in their level of physical activity. All these declines are slowly leading to a potential fear of falling and the subsequent risk of injury. Thus, it is important to note that maintaining balance relies on the integration of sensory information from multiple systems, including the somatosensory, visual, and vestibular systems, as well as the neuromuscular system (Hansson et al., 2010; Peterka, 2018). This system incorporates neuroregulatory mechanisms like proprioception and intramuscular coordination, which play a significant role in boosting force production and overall performance. These mechanisms enable the engagement of a greater number of motor units and the efficient utilization of the produced force to complete tasks (Marshall et al., 2022). As a result, as we age, it becomes crucial not to overlook the importance of balance for overall physical performance. By improving their balance capabilities, older individuals can greatly enhance their ability to carry out daily activities, as well as increase their potential for generating force (Willardson, 2007). There are various training options available to enhance the mechanisms mentioned above. Classical resistance training, for instance, remains a key component for improving strength (Kraemer and Ratamess, 2004; Hortobágyi et al., 2021). Another frequently utilized option is aerobic training, which primarily focuses on cardiovascular fitness. However, it is worth noting that these forms of training may not be suitable for every elderly individual. Consequently, sensorimotor training that is physically less demanding should be considered as an alternative approach for improving balance and potentially enhancing strength capabilities.

Sensorimotor training is a specialized type of training that aims to improve coordination and movement control by integrating the sensory and motor systems. Certain studies suggest that sensorimotor training could be beneficial in improving postural sway, balance ability, and coordination in healthy individuals (Bruhn et al., 2004; Di Corrado et al., 2023). However, there is limited research on its effectiveness for senior citizens. Although it can enhance motor skills, it is still uncertain whether sensorimotor training directly increases muscle strength. Thus, additional research is necessary to determine the specific impact of sensorimotor training on strength.

The main objective of the study was to investigate the effects of sensorimotor training on muscle strength and postural sway control in elderly women and subsequently compare these effects with a traditional combined resistance-endurance training program.

2 Methods

2.1 Subjects

A total of 34 female older adults aged from 65 to 75 years (average age 72.7 ± 4.4 years, height 161.6 ± 5.1 cm, weight 66.9 ± 8.4 kg) with no previous experience with exercise, participated in this study All participants were supposed to have no history of regular physical activity training and no more practice than 150 min of moderate or 75 min of vigorous intensity per week. They also were not supposed to perform any regular active recreational sports exercise for at least 3 years before attending the study. All female participants were randomly assigned to the following three groups: 1. group that took part in a 10-week resistance-endurance program (RET), 2. group that underwent sensorimotor training (SMT), and 3. control group (COG) which did not undergo any intervention. Prior to the study inclusion criteria, all female participants were healthy and free from severe mobility impairments and any cardiovascular, neurological, or other chronic diseases that could interfere with any of the training programs. Before pre- and post-intervention testing, participants were strictly verbally and writenely informed by the research supervisors not to take any medication, such as pain drugs, stimulants, etc., or caffeine during the testing day, as it could falsely affect the functional status during muscle strength and physical performance assessments. On the testing day, all participants had to declare verbally their actual health status. All participants provided written informed consent before the beginning of the study and were notified of their rights to withdraw from the study at any time. The study protocol followed the ethical guidelines of the Declaration of Helsinki 2000, and its later amendments from 2013. The study was approved by the ethics committee of the Faculty of Physical Education and Sport, Comenius University in Bratislava (4/2023).

The exclusion criteria were the following:

- Present disorders, injuries, or impaired mobility related to the musculoskeletal system.
- Present acute or chronic infections that would prevent individuals from participating in the study.
- Present cardiovascular, neurological, cancerous, metabolic, autoimmune, or other diseases that would hinder an individual´s participation in the study.
- Individuals with confirmed or suspected malnutrition.
- Significantly underweight Individuals.
- Individuals receiving artificial administration of hormones, for example, insulin or drugs to support immunity.

2.2 Procedures (study design)

Both experimental training programs were conducted by experienced coaches who have previously worked with older adults and were carried out at the Centre of Active Ageing (CAA). Prior to the study, all female participants attended a session to be familiarized with the testing procedures by the study researchers. A week before the training programs began, the participants underwent body composition and physical fitness assessments, including measurements of muscle strength in their lower extremities, motor skills, balance, and coordination abilities. The post-test measurements were taken within a week after the training period concluded. Both testing sessions were performed at similar time points (between 08:00 a.m. and 10:00 a.m.), and the order of tests was strictly set. All tests were conducted at the CAA under the supervision of two or three researchers with previous testing experience. The whole study design is illustrated in Figure 1.

2.3 Resistance - endurance training

The intervention aims to improve the movement system, movement literacy, and overall fitness of seniors by integrating new levels of physical activity into their daily routine. The program is based on the principle of "movement-based training" and includes a combination of complex pulling and pushing exercises for the upper and lower body. The training program mainly included exercises such as free weight sit-to-stand (or using a kettlebell), kettlebell deadlift, leg press, leg extension (lower body exercises), and their various modifications (progression or regression). The upper body exercises consisted of box push-ups, horizontal chest press, TRX Row, horizontal Keiser bilateral Row, and their various modifications (progression or regression). All the individual exercises are part of the Centre of Active-Ageing training manual. Each set (3) consists of 10–12 repetitions using a load equivalent to 10–12 repetition maximum (RM). The first session was used to establish individual baseline training loads. Progressive overload was utilized on a bi-weekly basis by adding 2%–5% of estimated 1RM, based on the individual's ability to perform the current workload. The endurance component of the program is based on "conditioning - interval training" (Laursen and Buchheit, 2019) using equipment such as stationary bikes, airbikes, and exercises like stepping, running, and sled pushing in 6 sets with a load-rest interval ratio of 1:2. All training sessions include a 10-minute warm-up and a 5-minute relaxation after exercise.

2.4 Sensorimotor training

Sensorimotor exercises (Hamar 2008) were performed on an unstable spring supported stabilographic plate (Figure 2) (Fitro Angle Sway Fitronic, Bratislava, Slovakia). The system monitors projection of body's center of gravity (COG) horizontal movements to the ground referred to as center of pressure (COP) and displays it online on the screen (Hamar, 2018).

Three routines were applied using this system.

In the first one, the individual has to, by moving their own body in a horizontal plane, follow the curve generated by the computer and displayed on the monitor screen (Figure 3A) as closely as possible.

In the next exercise, randomly generated targets have to hit with online displayed COP while moving body in horizontal position (Figure 3B).

In the third exercise, a small circle, representing the COP has to be guided into the "cups" generated on the screen, again by shifting body in horizontal plane (Figure 3C).

The values achieved in each of the routines after their completion were displayed to motivate subjects. They were average distances of the COP from the moving curve (first routine), the total path, and the time required to hit the target with the virtual COP in the second and moving virtual COP into the "cup" in the third routine.

In addition to these three routines, participants perform two additional exercises on an unstable plate without visual feedback. In the first exercise, the individuals performed different positions without visual control (Figure 3D). In the second exercise, they were again tasked with transferring an object from a higher pad to a

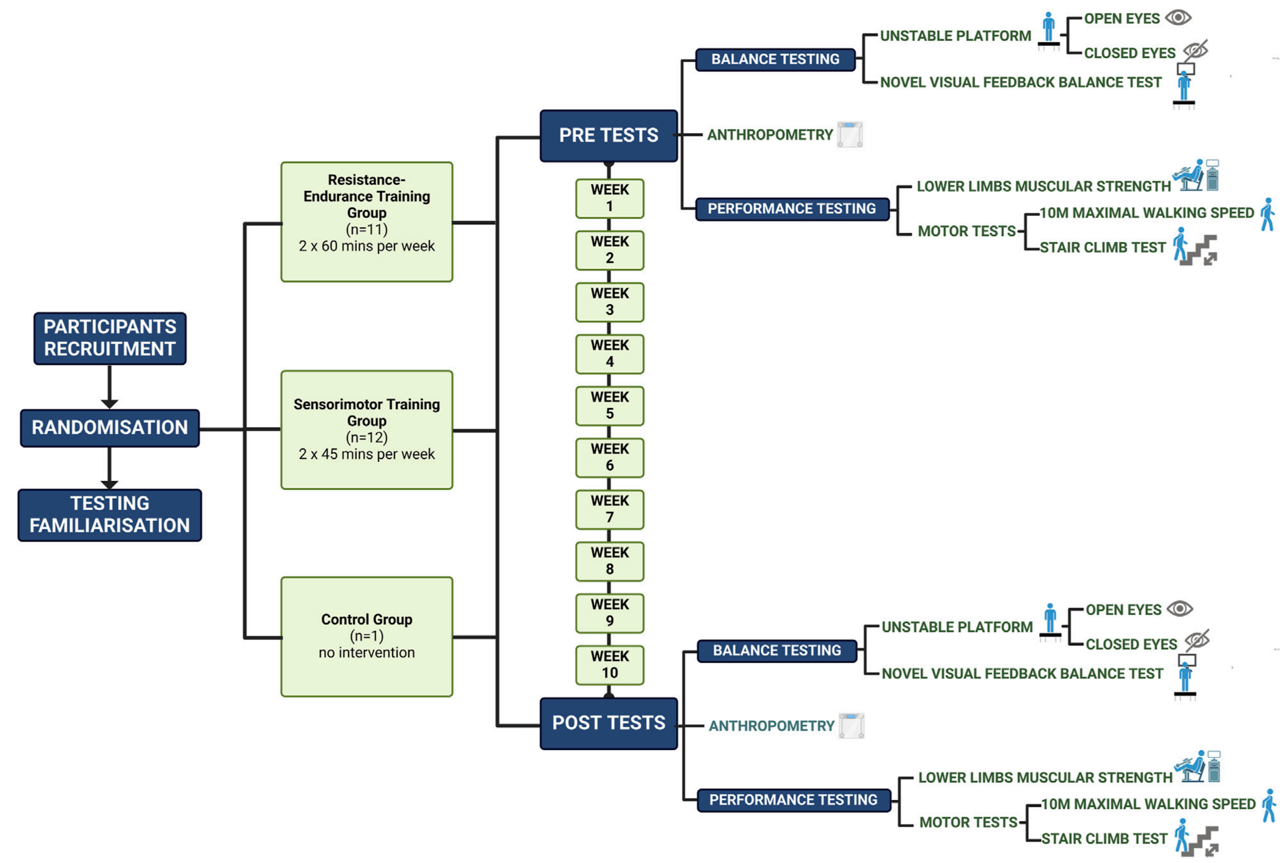

FIGURE 1
Study design (Created with BioRender.com).

FIGURE 2
Unstable stabilographic platform.

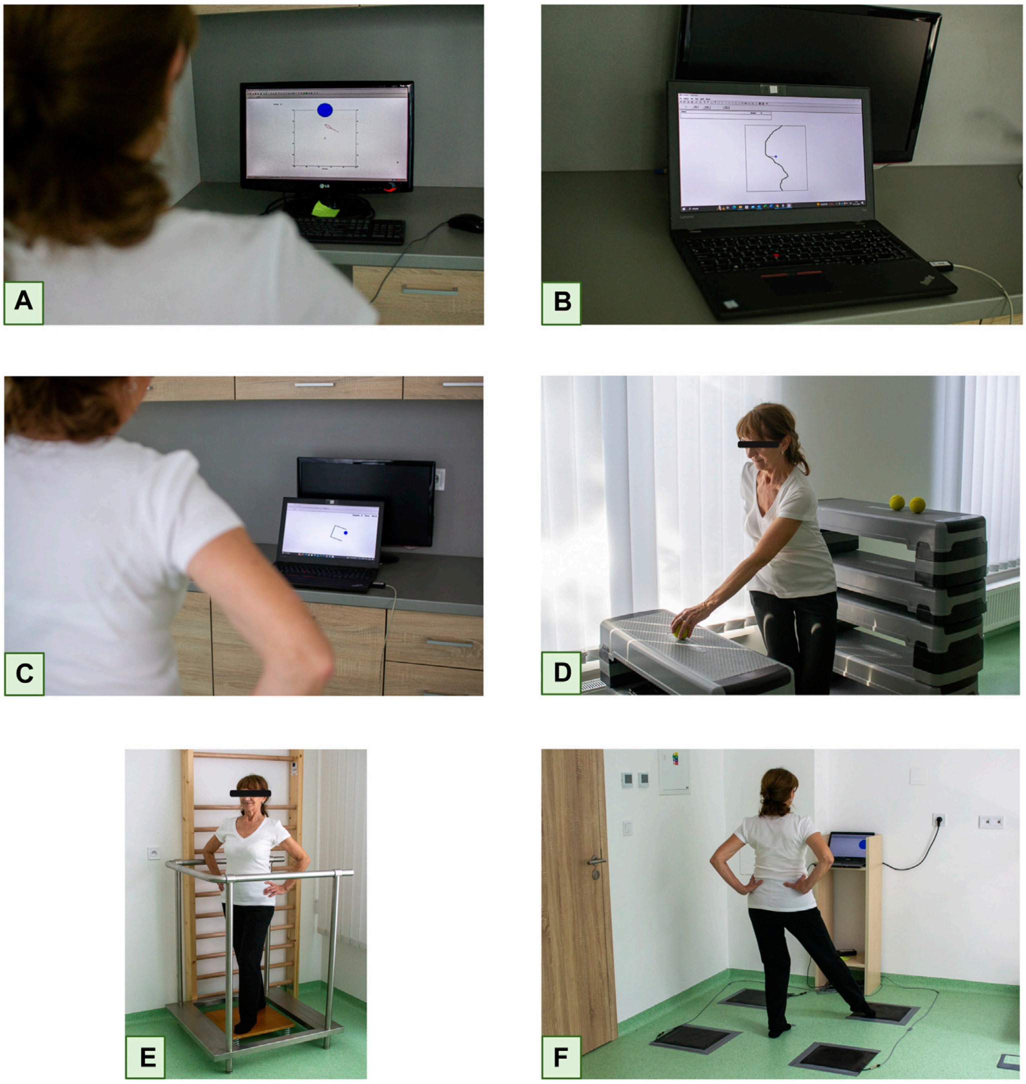

FIGURE 3
Sensorimotor Training Session Legend: Following the curve **(A)**, Hitting randomly generated targets **(B)**, Shifting a small circle into the "cup" **(C)**, Still stance on an unstable platform without visual control **(D)**, Replacing an object from a higher pad to a lower one in different stance positions **(E)**, Stepping as fast as possible on the appropriate contact plate **(F)** (Created with BioRender.com).

lower one in different positions (Figure 3E). In the last exercise, the participants had to step as quickly as possible on the appropriate contact plate (Fitro Agility Fitronic, Bratislava, Slovakia) in response to a stimulus displayed in different corners of the computer monitor (Figure 3F). The average reaction time was calculated from the total number of reactions. The whole session was based on the principle of circuit training in three series with 30 s of load and 30 s of rest. Every second week, the individual exercises were made more difficult by one level according to the protocol report, and the duration of load was increased by 5 s.

2.5 Test protocols

2.5.1 Body composition

Body height was measured using a digital free-standing stadiometer InBody BSM 170 (InBody Co., Ltd., Cerritos, CA, United States) and determined to the nearest centimetre Participants' body weight, muscle mass (kg), and fat mass (kg) were analysed using the bioimpedance method on InBody 230 (InBody CO., Ltd., Cerritos, CA, United States). The body weight was set with participants wearing underwear. Afterwards, the BMI was calculated.

2.5.1.1 Balance test on unstable platform

An unstable stabilographic platform (Fitro AngleSway Fitronic in Bratislava, Slovakia) was used to assess the stability of posture by analyzing the Centre of Pressure (COP) (Ruhe et al., 2010). The unstable posturographic system based on the platform, supported by 4 springs (coefficient of elasticity f - 10 N/mm) and equipped with biaxial inclinometric sensor features comparable reliability r = 0.932 (eyes open), and r = 0.868 (eyes closed) (Hamar, 2018), with traditional stable and force transducer based posturographic system (r = 0.920 and r = 0.887 respectively) (Zemková and

Hamar, 1998), hence represents a reliable and valid alternative for the assessment of balance capabilities (Zemkova and Hamar, 2015). The main differences to traditional systems involved using inclination sensors instead of force transducers to calculate instant COP (Hamar, 2018). To evaluate the postural sway, the velocity mean (VM) of the COP was used. During the test performance, participants were instructed to stand barefeet on the unstable stabilographic platform with their feet hip-width apart and toes slightly pointing outwards. Throughout the 30-second trial, participants were instructed to keep their hands on their hips and knees extended and to minimize their body movement as much as possible. The participants performed a total of three 30-second trials, with a one-minute rest interval between trials. The result was determined based on the best trial's outcome. The test was carried out using two distinct ways - one with visual feedback and another without it (Sedliak et al., 2013).

2.5.1.2 Novel visual feedback balance test

Participants stood on a computer-based stabilographic unstable platform (Fitronic, Bratislava, Slovakia) in a parallel stance with their bare feet shoulder-width apart, toes slightly pointing outwards, and hands on the hips. A computer screen was positioned about 1.5 m from the platform at the subject's eye level. Instantaneous visual feedback of participant's COP was given in the form of a blue cross visible on the screen. Participants were asked to keep the blue cross's movement as close as possible to a predefined flowing curve by moving their bodies the curve was moving from the top of the screen downwards, and the subjects copied its shape by their body movements (COP displacement) in the mediolateral direction (ML). The curve parameters were programmed with custom-made software and were identical in all tests (Hamar 2008). The system monitored the horizontal distance (mean distance, mm) between the projection of the COP on the screen and the flowing curve, as well as its velocity at a rate of 100 Hz (Zemková and Hamar, 2010). The sum of horizontal crossings of the COP trace across the flowing curve was recorded. Each test trial lasted for 30 s, with a familiarization trial carried out before the actual testing. Subsequently, three trials of ML were performed, with a 60-s rest period in between. During the rest period, subjects were free to either stand relaxed or take several slow steps (Sedliak, et al., 2013). The best of three trials was used.

2.5.1.3 10 Meters test for maximal walking speed

Participants were instructed to walk as fast as they could for 10 m without any assistance (Bohannon et al., 1996; Bohannon, 1997; Wolf et al., 1999). Their walking time was measured electronically using a wireless photocell timekeeping system (Microgate, Bolzano, Italy). The maximum walking speed (MWS) in meters per second was calculated based on the fastest time from three trials. Participants were instructed to keep one foot on the ground at all times. The researchers observed the participants' walking technique without giving any verbal encouragement during the test.

2.5.1.4 The lower limbs muscular strength (maximal and relative voluntary contraction)

The strength of the lower limbs was assessed by measuring the maximum voluntary contraction (MVC) of the knee joint, using an adjustable isometric dynamometric chair (ARS dynamometry, S2P Ltd., Ljubljana, Slovenia) (Bily et al., 2016; Šarabon et al., 2020). The proctol was performed according to Sarabon et al. (2013). Each participant's anthropometric parameters were taken into account when adapting the isometric dynamometric chair (90-degree angle in the knee joint). Prior to the testing, participants performed three warm-up trial attempts: at 50%, at 75%, and at 90% of their maximum effort. The resting period was set from 10 to 15 s between each attempt. Subsequently, each participant carried out three trials of unilateral knee isometric extension with maximal effort, with a one-minute rest interval between each trial. The participants' dominant lower limb was determined via a health questionnaire, which was filled out and submitted before entering the study. Verbal encouragement was given to the participants throughout the test. The trial that yielded the highest force was selected for further analysis using the ARS (Analysis & Reporting Software). The relative values of maximal MVC (rel. MVC) were calculated by dividing the maximal MVC of participants by their actual body weight.

2.5.1.5 Stair climb test

A stair climb test (SCT) was conducted to measure lower body strength, balance, and the ability to ascend and descend stairs (Dobson, et al., 2013; Iijima, et al., 2019; Coleman et al., 2020). Participants were instructed to ascend and descend the stairs as quickly as possible while ensuring their safety. They were advised not to overexert themselves and to use handrails if required, which were recorded. A practice trial was conducted with the researcher guarding for safety. The same set of stairs was used for both pre and post-tests. Each participant ascended and descended 11 stairs with a step height of 20 cm. The time was measured manually using a stopwatch by at least two researchers, and the average was taken as the resulting time. Timing begins on the signal to start and terminates when the participant returns with both feet to the ground level. The time was measured separately in the direction of ascent and descent, and no verbal encouragement was provided during the test.

2.6 Statistical analysis

All statistical analyses were carried out using SPSS for Windows (SPSS version 23.0; IBM Corp., Armonk, NY). Data are presented means and standard deviations (SD) were obtained by conventional statistical methods. To begin with, the Shapiro-Wilk test was performed for all variables to determine the normality of data distribution. Then, Levene's test was used to check for homogeneity of variance. If the data were normally distributed, the paired-sample t-test was performed, otherwise, the Wilcoxon signed rank test was performed. The significance level was set at $p <$ 0.05 (two-tailed). Repeated measures analysis of variances (ANOVA) was used to compare time and group interaction (time × group) and training intervention time effect (pre vs. post-testing) × three groups (SMT vs RET vs CG). Post hoc comparisons were performed using the Bonferroni correction. Assumptions of sphericity were evaluated using Mauchly's test. Where sphericity was violated ($p < 0.05$), the Greenhouse-Geisser correction factor was applied. The *post hoc* statistical power of the sample size was calculated with G*Power (Version 3.1.9.6, Institut für Experimentelle Psychologie, Düsseldorf, Germany). The power for the number of subjects within the study sample

TABLE 1 Overall parameters before and after the experimental period.

Parameters	CG	RET	SMT	ANOVA 3 × 2										
	PRE	POST	*p*	ES	PRE	POST	*p*	ES	PRE	POST	*p*	ES	Time	time*group
													p	*p*
BW (kg)	66.99 ± 7.63	67.18 ± 7.90	.529	0.02	67.23 ± 8.82	67.33 ± 9.80	0.823	0.01	66.43 ± 9.38	65.78 ± 9.04	0.092	0.07	0.574	0.209
MM (kg)	23.16 ± 2.22	23.39 ± 2.05	0.345	0.11	23.13 ± 2.23	23.40 ± 2.85	0.346	0.11	22.53 ± 2.27	22.84 ± 2.34	0.173	0.13	0.060	0.968
FM (kg)	24.68 ± 4.71	24.55 ± 5.66	0.800	0.02	24.42 ± 6.58	24.12 ± 6.37	0.350	0.05	24.45 ± 7.00	23.23 ± 7.17	**0.002**	0.28	0.016	0.098
VMeo ($mm.s^{-1}$)	11.48 ± 2.83	11.62 ± 2.73	0.793	0.01	15.24 ± 6.76	15.87 ± 7.44	0.400	0.01	11.98 ± 3.92	9.08 ± 1.94*	**0.028**	0.94	0.164	**0.013**
Vmec ($mm.s^{-1}$)	16.55 ± 4.40	19.68 ± 5.66*	**0.050**	0.60	26.72 ± 14.03	25.34 ± 11.42	0.522	0.11	20.32 ± 8.15	14.38 ± 2.87*	**0.013**	0.97	0.184	**0.006**
MD (mm)	8.26 ± 1.78	8.94 ± 1.47	0.152	0.42	9.29 ± 2.14	8.45 ± 1.44	0.307	0.46	10.29 ± 1.08	6.43 ± 0.80**	**0.000**	4.06	**0.000**	**0.000**
MVCd ($N.m^{-1}$)	112.48 ± 25.53	109.56 ± 27.08	0.476	0.11	100.86 ± 33.32	117.28 ± 35.29**	**0.004**	0.48	106.08 ± 16.93	123.65 ± 21.46**	**0.000**	0.93	**0.000**	**0.001**
MVCnon-d ($N.m^{-1}$)	111.94 ± 24.18	110.01 ± 24.66	0.578	0.08	103.92 ± 36.09	115.24 ± 34.23*	**0.018**	0.31	100.95 ± 19.55	113.79 ± 19.67**	**0.004**	0.65	**0.001**	**0.011**
rel. MVCd ($N.m^{-1}$)	1.70 ± 0.46	1.66 ± 0.49	0.482	0.08	1.52 ± 0.51	1.75 ± 0.48**	**0.001**	0.46	1.62 ± 0.30	1.90 ± 0.37**	**0.000**	0.83	**0.000**	**0.000**
rel. MVCnon-d ($N.m^{-1}$)	1.69 ± 0.40	1.66 ± 0.42	0.556	0.07	1.56 ± 0.54	1.72 ± 0.49**	**0.007**	0.31	1.54 ± 0.33	1.74 ± 0.29**	**0.002**	0.64	**0.000**	**0.000**
10 m MWS ($m.s^{-1}$)	1.95 ± 0.20	2.01 ± 0.15	0.273	0.34	1.86 ± 0.24	1.94 ± 0.24	0.397	0.33	1.80 ± 0.16	1.87 ± 0.20	0.100	0.39	0.062	0.978
SCTa ($m.s^{-1}$)	0.84 ± 0.07	0.79 ± 0.11	0.099	0.54	0.79 ± 0.10	0.81 ± 0.07	0.332	0.25	0.66 ± 0.06	0.75 ± 0.08**	**0.000**	1.27	0.114	**0.001**
SCTd ($m.s^{-1}$)	1.00 ± 0.13	0.91 ± 0.12*	**0.010**	0.71	0.86 ± 0.15	0.89 ± 0.10	0.298	0.29	0.73 ± 0.09	0.86 ± 0.11**	**0.000**	1.17	0.204	**0.000**

Data are presented as mean ± SD. CG, control group; RET, resistance-endurance training; SMT, sensorimotor training; p, *p*-value; ES, effect size; BW (kg), body weight; MM (kg), muscle mass; FM (kg), fat mass; VMeo ($mm.s^{-1}$), velocity-mean with eyes open; VMec ($mm.s^{-1}$), velocity-mean with eyes close; MD (mm), mean-distance; MVCd ($N.m^{-1}$), maximal voluntary contraction of the dominant leg; MVCnon-d ($N.m^{-1}$), maximal voluntary contraction of the non-dominant leg; rel. MVCd ($N.m^{-1}$), relative maximal voluntary contraction of the dominant leg; MVCd ($N.m^{-1}$), relative maximal voluntary contraction of the non-dominant leg; 10 m MWS ($m.s^{-1}$), 10 m maximal walking speed; SCTa ($m.s^{-1}$), Stair climb test–ascend; SCTd ($m.s^{-1}$), Stair climb test - descend. The bold values indicate statistically significant differences.

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was $1 - \beta = 0.701$ with $\alpha = 0.05$. To compensate for the lower sample size power, additional methods were used. Specifically, the effect size was evaluated using a partial eta squared (η^2), with >0.01, >0.059, and >0.139 indicating a small, medium and large effect, respectively. Cohen's d was used to detect effect size in absolute differences (pre vs post-testing) with the following interpretation: small effect ($0.2 \le d \le 0.5$), medium effect ($0.50 \le d < 0.80$), and large effect ($d > 0.8$) (Cohen, 1988).

3 Results

The overall results of the study are shown in Table 1. All data are presented as means and standard deviation (SD).

3.1 Body composition

Body composition parameters, such as body weight (kg), muscle mass (kg), and fat mass (kg) are presented in Figures 4A–C. As the results indicate, there were no significant differences in body weight in any of the groups. Also, there were no significant differences in time × group interaction or effect of time (all $p > 0.05$). Similarly, we did not observe any significant changes in muscle mass in any of the groups after the intervention. However, according to fat mass, a significant decrease was observed in the SMT group (from 24.45 ± 7.00 kg to 23.23 ± 7.17 kg, $p = 0.002$, d = 0.28, small effect). In addition, there were significant main effects of time for FM ($F_{1,31} = 6.44$; $p = 0.016$; $\eta^2 = 0.172$) (Table 1).

3.2 Balance skills

Balance testing results, such as tests of postural sway with eyes open and closed respectively, and visual feedback balance tests are presented in Figures 4D–F. The improvement of the dynamic balance was observed only in the SMT group. Specifically, significant changes in the SMT group were observed in the tests of VM_{eo} (from 11.98 ± 3.92 mm/s to 9.08 ± 1.94 mm/s, $p = 0.028$, d = 0.94, large effect), VM_{ec} (from 20.32 ± 8.15 mm/s to 14.38 ± 2.87 mm/s, $p = 0.013$, d = 0.97, large effect), and MD (from 10.29 ± 1.08 mm to 6.43 ± 0.80 mm, $p = 0.000$, d = 4.06, large effect), while, as may be expected, the VM_{ec} (from 16.55 ± 4.40 mm to 19.68 ± 5.66 mm, $p = 0.050$, d = 0.60, medium effect) deteriorated in the COG group. The RET group did not show significant changes in the parameters of postural control. As shown in Table 1 a significant main effect of time was observed for parameter MD ($F_{1,31} = 24.37$; $p = 0.000$; $\eta^2 = 0.440$). In addition, significant differences in time × group interaction in variables VM_{eo} ($F_{2,31} = 5.06$; $p = 0.013$; $\eta^2 = 0.246$), VM_{ec} ($F_{2,31} = 6.15$; $p = 0.006$; $\eta^2 = 0.28$) and MD ($F_{2,31} = 24.61$; $p = 0.000$; $\eta^2 = 0.614$) was present (Table 1). In this case, a significant main effect of group was also found in variables VM_{eo} ($F_{2,31} = 3.97$; $p = 0.029$; $\eta^2 = 0.204$) and VM_{ec} ($F_{2,31} = 3.94$; $p = 0.030$; $\eta^2 = 0.202$), following Bonferroni *post hoc* test significant differences between SMT vs RET ($p = 0.034$ and $p = 0.044$, respectively) was observed.

3.3 Muscle strength of lower body

The strength metrics of maximal (MVC) and relative muscle voluntary contraction (rel. MVC) are presented in Figures 4D–G. In the RET group, significant changes were observed in both MVC_d (+16.3%, $p = 0.004$, d = 0.48, medium effect) and MVC_{non-d} (+10.9%, $p = 0.018$, d = 0.31, small effect). Similarly, the SMT group also showed improvements in both parameters, MVC_d (+16.6%, $p = 0.000$, d = 0.93, large effect) and MVC_{non-d} (+12.7%, $p = 0.004$, d = 0.65, medium effect). As shown in Table 1 a significant main effect of time in the variables MVC_d ($F_{1,31} = 22.81$; $p = 0.000$; $\eta^2 = 0.424$) and MVC_{non-d} ($F_{1,31} = 13.30$; $p = 0.001$; $\eta^2 = 0.300$) was observed, as well as significant differences in time × group interaction for both variables, MVC_d ($F_{2,31} = 9.29$; $p = 0.001$; $\eta^2 = 0.375$) and MVC_{non-d} ($F_{2,31} = 5.29$; $p = 0.011$; $\eta^2 = 0.255$), respectively. A similar trend was observed in the increments of rel. MVC_d (+15.6%, $p = 0.001$, d = 0.46, medium effect) and rel. MVC_{non-d} (+10.3%, $p = 007$, d = 0.31, small effect) in the RET group, where both parameters improved. The SMT group also displayed enhancements in these parameters, rel. MVC_d (+17,3%. $p = 0.000$, d = 0.83, large effect) and rel. MVC_{non-d} (+13%, $p = 0.002$, d = 0.64, medium effect). Similarly, there were significant main effects of time in rel. MVC_d ($F_{1,31} = 13.30$; $p = 0.000$; $\eta^2 = 0.475$) and MVC_{non-d} ($F_{1,31} = 15.27$; $p = 0.000$; $\eta^2 = 0.330$). In addition, significant differences in time × group interaction in rel. MVC_d ($F_{2,31} = 11.43$; $p = 0.000$; $\eta^2 = 0.424$) and MVC_{non-d} ($F_{2,31} = 6.33$; $p = 0.000$; $\eta^2 = 0.290$) was present (Table 1).

Finally, no significant differences in the MVC and rel. MVC was observed in the COG group.

3.4 Physical performance

The measurements of the 10 m MWS, SCT_a and SCT_d are presented in Figures 4H, I. In all tested groups, there were not observed any significant changes in the 10 m MWS. Also, no significant effect of time or time × group interaction (all $p > 0.05$). However, as shown in Table 1, there were significant differences in time × group interaction in variables SCT_a ($F_{2,31} = 9.26$; $p = 0.001$; $\eta^2 = 0.374$) and SCT_d ($F_{2,31} = 14.57$; $p = 0.000$; $\eta^2 = 0.485$). Also, in this case, the main effect of the group in both variables SCT_a ($F_{2,31} = 7.35$; $p = 0.002$; $\eta^2 = 0.322$) and SCT_d ($F_{2,31} = 5.99$; $p = 0.006$; $\eta^2 = 0.279$) was observed. Using the Bonferroni *post hoc* test, there were significant differences between SMT vs RET ($p = 0.019$) and SMT vs CG ($p = 0.004$) in variable SCT_a. In the second variable, SCT_d the Bonferroni *post hoc* test showed significant differences between SMT vs CG ($p = 0.005$).

4 Discussion

To quantify the effects of interventions on the parameters of static balance while standing upright with and without visual control were evaluated. The results showed that e female older adults, underwenting a 10-week program of sensorimotor exercises significantly improved the mean velocity of COP of postural sway in both upright positions, with eyes open as well as with eyes closed. These results were not particularly unexpected as they

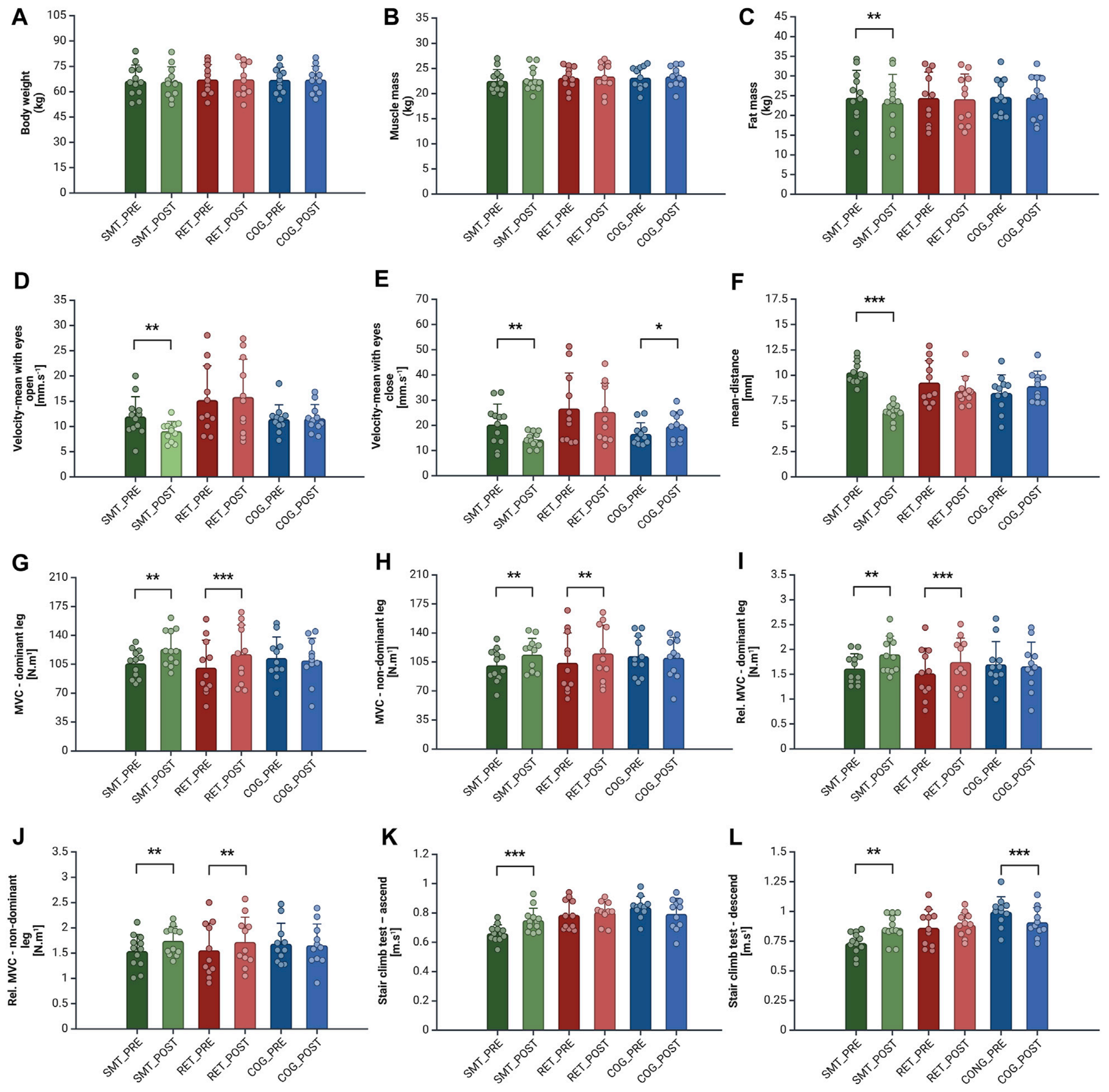

FIGURE 4
Balance and Physical Performance Differences in Measured Parameters in Each Experimental Group Before and After the Intervention. Legend: body weight **(A)**, muscle mass **(B)**, fat mass **(C)**, velocity-mean with eyes open **(D)**,velocity-mean with eyes closed **(E)**, mean-distance **(F)**, maximal voluntary contraction of the dominant leg **(G)**, maximal voluntary contraction of the non-dominant leg **(H)**, relative maximal voluntary contraction of the dominant leg **(I)**, relative maximal voluntary contraction of the non-dominant leg **(J)**, stair climb test–ascend **(K)**, stair climb test - descend **(L)**. Column bars represent the mean, error bars represent the standard deviation (SD) and dots represent individual values. *Represents statistical significance $p < 0.050$, **$p < 0.010$, ***$p < 0.001$ (Created with BioRender.com).

are in line with similar studies. Maćkowiak et al., (2015) showed a significant positive effect on balance in elderly women over 50 years with impaired vision after 6 weeks of sensorimotor intervention. A similar study, however in substantially younger subjects, has been carried out by Pau et al., (2012). After 6 weeks of balance training group of young volleyball players showed smaller sway areas while standing with eyes closed. The intervention also reduced anteroposterior COP displacements while standing on a non-dominant limb.

The improvement of postural stability due to sensorimotor training can be attributed to adaptive changes in the physiological mechanisms involved within its control. This complex motor ability depends primarily on multiple kinesthetic processes (Horak, 2006) providing stimuli to the CNS, which, after appropriate processing, sends efferent control commands to postural sway controlling muscles.

Theoretically, sensorimotor training may enhance the sensitivity of proprioceptors providing more precise signals from muscles, tendons, and joints enabling more efficient CNS processing and more accurate real-time regulation of postural muscle activity. Such a concept is supported by Hewett et al., (2002), who claim that sensorimotor training can improve the activation of proprioceptors, hence providing more precise information on body parts position. In this way, more sensitive proprioceptors can partially compensate for missing visual input in dark environments or in individuals with visual impairments. In addition, according to the study by Aman et al. (2015), stimulation of proprioceptors also leads to cortical reorganization, contributing to more efficient sensorimotor function.

This may be of particular benefit for older adults, in which missing visual control without efficient compensation by proprioceptive input leads to a more pronounced impairment of postural control (Maki and McIlroy, 2006). Such a lack of visual impairment compensation is one of the major factors contributing to an increased risk of falling in older adults. Therefore, improved proprioception due to specific sensorimotor training can be an important factor in the prevention of falls in the elderly population.

As mentioned earlier, sensorimotor (SM) training can also positively affect the reorganization of the sensorimotor cortex. This can be considered as a crucial mechanism for efficient learning and relearning strategies, and also for refining motor patterns that are important for the alignment of the human body to the changing requirements of the environment (Machado et al., 2010). Such a central adaptation could also, at least partially, contribute to better results in the test of visual feedback control of body position after sensorimotor intervention in the SMT group. However, pronounced improvement in this test may also be attributed to the fact that the visual feedback control of the body position was an integral part of sensorimotor training.

An increase in strength can be considered as the third mechanism of improvement of balance parameters observed in the present study. As expected, both RET and SMT groups improved in the absolute as well as the relative muscle strength in both dominant and non-dominant lower extremities without any significant differences between these two groups. These findings are in close agreement following studies of Oreská et al., (2020), Pinto et al., (2014), demonstrating comparable gains in the lower extremities' maximal strength.

As underlying mechanisms of strength gain are traditionally considered functional changes such as enhanced neural activity at the onset of voluntary actions, which may include increases in motor unit recruitment, enhanced maximal motor unit firing rates, refinement of muscle activation patterns, elevated spinal motor neuronal excitability, increased efferent motor drive, changes in the pennation angle or the length-tension relationship of muscles, optimizing force generation as well as changes in agonist coactivation (Hakkinen and Komi, 1986; Aagaard and Andersen, 2010).

Another mechanism to consider is muscle hypertrophy. However, should this mechanism play a role, the intensity of muscle contractions must exceed the minimal intensity of 65% of 1 RM (Kraemer et al., 2002). Progression models in resistance training for healthy adults of 1 RM and training duration should exceed 6–8 weeks and even longer (9–15 weeks) in the older adults (Lam et al., 2018).

As in SMT intensity of muscle contractions necessary to meet requirements of corrective movements were of horizontal body position remained well below level necessary to stimulate morphological changes, muscle hypertrophy was unlikely to take place in subjects undergoing sensorimotor intervention. In addition, this adaptive mechanism could hardly occur because a period of intervention program (10 weeks) was in the range, where hypertrophy could be scarcely barely expected. On the other hand, slight hypertrophy could take place in the RET group, where the intensity of muscle contraction was sufficient and the duration of intervention reaching or slightly exceeding the minimum response time for morphological changes.

Strength improvement without typical resistance exercise only due to sensorimotor intervention has been observed by Granacher et al. (2010). His subjects increased their peak strength of lower extremities after balance training on unstable wobble boards as well as parameters of postural control. He attributes this improvement to real neuroregulatory adaptations rather than learning effects.

It has been shown by several studies (Hess and Woollacott, 2005; Holviala et al., 2006; Zouita et al., 2020; Amato et al., 2022) that improvements in muscle strength were concomitant with better postural sway control.

However, the results of our study did not provide clear evidence to support such a concept. Sensorimotor intervention led to a significant parallel increase in muscle strength (the maximum absolute and relative values of knee extensors on both dominant and non-dominant limbs) and parameters of balance only in SMG. Improvement of strength due to combined RE training was surprisingly not concomitated with balance parameters.

SM training, especially when done on unstable surfaces like a spring-loaded stabilographic board can improve strength and motor coordination. This is because such training increases muscle activation, improves and boosts motor unit recruitment. These neuromuscular alterations are thought to better stabilize the center of mass while standing on a stable or changing base of support (Cuğ et al., 2016). Surprisingly similar effect has been observed after SMT intervention and in addition, there was no significant difference between both groups. This implies that in terms of strength, both types of training had practically the same effect.

An increase in muscle strength observed in the RET group plays a key role in the prevention as well as reverting of functional deterioration caused by ageing. Level of strength directly affects more complex locomotor skills such as walking, namely, at higher speeds. Its impairment is one of the crucial factors affecting older adults' life quality and health status (Bohannon, 1997; Slobodová et al., 2022; Stanaway et al., 2011). However, our results did not support such a simple concept. Despite of increase in strength in both groups, none of them improved 10 m maximum walking speed. On the other hand, in the stair climb test only the SMT group, which improved not only in strength but also in parameters of balance, increased vertical velocity significantly. This indicates that daily living activities may be affected more by sensorimotor functions than strength capabilities itself. This is also in line with the findings of Kim and Jang (2021) showing that balance skills, both static and dynamic, engaging the visual and sensorimotor feedback from the environment have a significant impact on walking speed.

We might presume that sensorimotor function might play a more important role in more demanding daily life activities such as walking up and down the stairs than in simple level walking or parameters of postural sway. Similar findings, however, in young athletes are supported by the results of Zacharakis et al. (2020) who examined the impact of a balance and proprioceptive training program on static and dynamic balance and technical skills in youth basketball players. The experimental group of girls significantly improved in dynamic balance and basketball technical skill passing accuracy scores, but not postural static balance.

The conclusions of this study are also in line with our results showing significant improvement in both stair ascending and descending speed tests only in SMT, but not in RET group. Another factor to consider while explaining the lack of significant changes in 10 m maximal walking speed is the fact that the average maximal speed in both groups before the intervention was on the level of the extremely fit population (Bohannon, 1997; Stanaway et al., 2011). It has been shown that subjects featuring an already high level of a particular function tend to exert less pronounced responses to training stimuli than those staring at a lower level.

Subsequently, it is noteworthy to mention that even earlier mentioned daily tasks such as walking speed on flat surfaces along with ascending or descending stairs are directly determined by individuals' balance skills, which naturally tend to deteriorate throughout the life span, as it is well scientifically proven (Vereeck et al., 2008; Soto-Varela et al., 2016; Park and Lee, 2020). Therefore, it's in the best interest of seniors to take steps to improve this ability as much as possible or, at the very least, slow down its decline. It's important to note that balance is a crucial component of coordination skills and is reflected in virtually all movement structures.

Balance, whether static or dynamic, is the decisive neuromotor ability of humans for everyday activities (Gambetta and Gray, 1995). Static balance refers to the ability to maintain an upright position and other static postures as squatting or sitting under stable conditions.

Dynamic balance is crucial for maintaining balance under unstable conditions, typically during activities such for example, walking, running, skiing, cycling, or climbing stairs. It also affects the quality of performing technically demanding skills in sports like for example, basketball, volleyball, football, or gymnastics (Pau et al., 2012; Zacharakis et al., 2020; Kenville et al., 2021).

Both static and namely, dynamic balance also play important roles in compensation as the sudden distortion of body position, a process of crucial importance in the prevention of falls and resulting injuries. This is especially important in the elderly population.

Our study proves that SM training is highly effective for the elderly population improving their postural stability and visual feedback control of regulation of horizontal corrective body movements following the curve displayed on the monitor.

Results of the study have also revealed, that sensorimotor training increased the maximal and relative strength of the lower extremities and the vertical speed of walking up and down stairs. As seniors age, they may avoid conventional strength training due to cardiovascular problems, injuries, or physical limitations. However, strength and balance decline put them at risk of falls. In terms of strength development, SM training is a promising alternative to improve overall strength and balance, reducing the risk of falls and maintaining independence in the older adults with no previous experience of training.

4.1 Strengths and limitations

Besides the original approach of the current study, there might be several notable limitations. It could be argued that the study had a small number of subjects in each experimental group. The results also may not be directly translated to the overall population of the elderly as only older females were measured. Thus, the inclusion of the male population then may give us a broader picture, of how this sensorimotor training affects the elderly population in general. Additionally, DXA body composition measurement would provide us with more detailed information about the effect of hypertrophy or neuromuscular adaptation on muscle strength, caused by training intervention. Moreover, deeper testing of neuromuscular structural and functional changes, like EMG testing before and after the intervention or each training session, could reveal quicker activation of muscle fibers in the muscles responsible for the balance. Another limitation in explaining the results could be the absence of muscle biopsies, which could offer a more comprehensive view of the morphological changes at the muscle level. The habitual physical activity of the participants was not assessed in this study. The beneficial influence of physical activity in general for the prevention of age-related sarcopenia was suggested in many studies (Steffl et al., 2017). Lastly, it could be hypothesized that in the SMT group, the post-testing results in the specific test of copying the curve might be affected by using a slightly similar stimulus, which was used within the intervention.

On the positive side, the study utilized an innovative system of unstable platforms as a unique training method for the elderly population. Another benefit to consider is the impact on their balance and strength abilities, which are crucial for their daily tasks, as supported by the aforementioned results.

5 Conclusion

In conclusion, sensorimotor training has been proven to be highly effective in improving postural control and muscular strength in older adult individuals, comparable to resistance-endurance training. By targeting sensory integration, motor coordination, and balance control, this form of training helps enhance overall stability, reduce the risk of falls, and improve functional independence in older adults. The study results indicate that sensorimotor training may serve as a suitable alternative for individuals with various health disorders that are in contradiction with classical strength and endurance training. Additionally, sensorimotor training can be beneficial for those who do not prefer or are unable to incorporate this type of exercise into their daily lives.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Ethics Committee of the Faculty of Physical Education and Sport, Comenius University in Bratsilava, Slovakia. 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

MV: Data curation, Formal Analysis, Investigation, Methodology, Supervision, Writing–original draft. ĽB: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing–original draft, Writing–review and editing. ĽO: Formal Analysis, Visualization, Writing–original draft, Writing–review and editing. PS: Investigation, Project administration, Writing–original draft. DH: Supervision, Writing–original draft, Writing–review and editing.

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Conflict of interest

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

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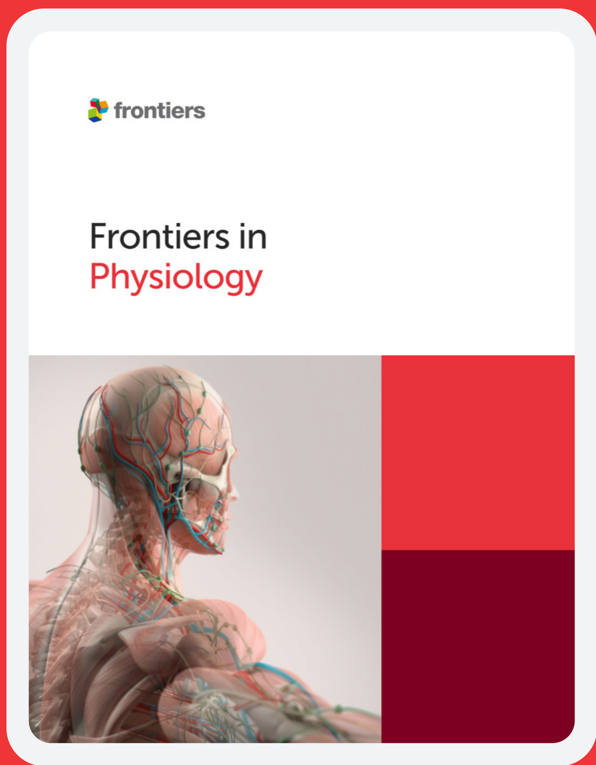

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