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Strength and conditioning in football: driving physical performance through research and innovation

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Strength and conditioning in football: driving physical performance through research and innovation

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Editorial: Strength and conditioning in football: driving physical performance through research and innovation

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soccer, training, technologies, performance, testing

Editorial on the Research Topic
Strength and conditioning in football: driving physical performance through research and innovation

Introduction

Contemporary sports rely on scientific research and technological advancements to enhance performance and promote health (Paul et al., 2016; Beato et al., 2021; Randell et al., 2021). This is particularly evident in football (Bangsbo et al., 2006; Turner and Stewart, 2014; Beato et al., 2024), as the world's most popular sport. Frontiers in Physiology and Frontiers in Sport and Active Living recognize the critical role of strength and conditioning; thus, this Research Topic entitled "*Strength and conditioning in football: driving physical performance through research and innovation*" was designed to promote dialogue and disseminate knowledge within the sports science community. Strength and conditioning refers to the planning, delivering, monitoring, and reviewing of specialized physical training programs designed to enhance athletic performance, reduce the risk of injuries, and optimize fitness for football players (Cormie et al., 2011; Jeffries et al., 2022; Bishop et al., 2023; Turner, 2024). Consequently, our aim was to publish a series of studies that showcase the latest methodological advancements in strength and conditioning for football. We were particularly interested in innovative exercises that enhance adaptive responses and studies that explore effective ways to integrate new technologies, monitoring tools and testing protocols.

This Research Topic of Frontiers in Physiology and Frontiers in Sports and Active Living, contains 11 manuscripts meeting the editorial criteria, including 10 original research articles (Chmura et al.; Chmura et al.; Skala and Zemkova; Asencio et al.; Branquinho et al.; Paravlic et al.; Pimenta et al.; Rocha et al.; Szabo et al.; Zhai and Qin) and 1 brief research report Asimakidis et al.

Chmura et al. aimed to investigate the effects of high-intensity interval training and the anaerobic and psychomotor fatigue thresholds on physiological parameters in young soccer players. They found that both thresholds shifted toward higher loads and the proposed specific high-intensity interval training effectively increased the exercise capacity of soccer players. Practitioners could use these high-intensity interval training methods to effectively increase their players' physical capacities.

Foqha et al. aimed to assess the effects of 10 weeks of FIFA 11+ training on the physical performance of elite seven-a-side soccer players. They found that the 10-week FIFA 11+ program resulted in notable enhancements in acceleration and agility performance compared to standard training for elite seven-a-side soccer players. These favourable results warrant additional research on implementing and optimizing the FIFA 11+ program, offering valuable guidance to coaches and athletes aiming to maximize its benefits in real-world scenarios.

Skala and Zemkova, aimed to investigate the neuromuscular and perceptual-cognitive response to small-sided games, and the relationship between pre- and post-small-sided games performance and exercise load in youth soccer players. They found that small-sided games induced fatigue that impacts planned and reactive agility, decision-making, and explosive strength in youth soccer players, irrespective of internal or external load variables.

Paravlic et al. aimed to investigate the associations between bilateral performance utilizing countermovement jump, squat jump, speed, unilateral jump, isokinetic peak torque in knee extension and flexion, and tensiomyography parameters. They also investigated whether the asymmetries derived from unilateral tests are associated with bilateral tests in elite female soccer players. The authors found several significant, albeit inconsistent, correlations between the diverse performance scores obtained highlight the necessity for a multifaceted and thorough diagnostic strategy in female soccer players.

Pimenta et al. compared the average speed, knee flexor peak torque, and shear modulus of the hamstrings after a repeated sprint task among football players at various competitive levels and playing positions. Surprisingly, the study found that neither the average sprint speed performance parameter nor the mechanical parameters were effective in distinguishing football players based on their competitive levels or positions on the field.

Szabo et al. aimed to examine the effect of a 10-week intervention with the TOCA Football System tool (which is a high repetition technical toolkit practice) and training method on elite youth athletes' sport-specific motor skills and anthropometric variables. They found that this intervention using the TOCA Football System was safe and did not negatively impact athletes' performance. Some significant improvements were observed within groups; however, no significant differences were found between the intervention and control groups.

Branquinho et al. aimed to investigate the ideal training load to be applied during periods of fixture congestion to ensure an adequate dose-response effect for performance maintenance. During a busy season for an elite Brazilian professional team, a positive training load was observed. However, the interference effect arises when high physical training is applied to various skills (such as change of direction and straight-line running) throughout the season. Additionally, the regression tree model proves valuable for identifying optimal loads and potential corrections to enhance athletes' match performance.

Rocha et al. aimed to investigate whether the use of transcranial direct current stimulation on the primary motor cortex improves the performance of soccer players. However, the authors did not find any change in the vertical jump performance as well no improvement in subjective scales (e.g., pain, recovery and rating of perceived exertion). New studies should be developed with different stimulus intensities in different cortical areas and sports modalities, to better understand the effect of transcranial direct current stimulation on soccer performance and subjective scales.

In a study by Zhai and Qin, the impact of traditional resistance training (e.g., squat and deadlift) *versus* complex training on physical and technical performance in amateur futsal players was investigated. Over an 8-week intervention, players from two amateur futsal teams followed different training protocols. The findings suggest that complex training could enhance specific performance parameters, including strength and power, more effectively than resistance training for amateur futsal players.

In their study, Asencio et al. compared the effects of two flywheel resistance training programs: variable intensity and constant intensity. Seventeen amateur footballers were divided into these two groups, both with equal training volumes. While both groups showed similar improvements in one-repetition maximum strength, the constant intensity group exhibited greater enhancements in the 10-m sprint. However, no significant differences were observed in countermovement jump, change of direction, or 30-m sprint performance following the protocols. Further research is necessary to fully understand the distinctions between constant and variable intensity flywheel resistance training.

Asimakidis et al. provided insight into the current fitness testing practices in elite male soccer. One hundred and two practitioners from professional soccer leagues across 24 countries completed an online survey. The authors reported that the scientific literature influences test selection, but practical constraints and professional experience also play a role. Practitioners test less frequently than they consider optimal due to time and competitive schedules. Pre-season is the most common time for fitness testing, while competitive periods leave less time. A "hybrid" approach, combining standalone and integrated testing, may address this Research Topic. Microsoft Excel is the preferred software for data analysis. Finally, the survey suggested that tailored visualizations are more common for coaches and players—the key distinction is that coaches often receive more detailed information than players.

Final considerations

The editors of this Research Topic emphasize the need for further research on the physiological mechanisms and adaptations resulting from strength training in football players. Specifically, they highlight the importance of studying youth and female populations, as well as examining ecological contexts with professional male and female players. Such research could significantly enhance the adoption of strength and conditioning training methods in practical settings. The

11 included articles provide evidence and insights into key aspects of strength and conditioning, potentially informing the implementation of new technologies and inspiring fresh research ideas.

Author contributions

MB: Conceptualization, Supervision, Writing–original draft, Writing–review and editing. CB: Conceptualization, Writing–original draft, Writing–review and editing. Anthony Nicholas AT: Conceptualization, Supervision, Writing–original draft, Writing–review and editing.

Conflict of interest

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

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References

Bangsbo, J., Mohr, M., and Krustrup, P. (2006). Physical and metabolic demands of training and match-play in the elite football player. *J. Sports Sci.* 24, 665–674. doi:10.1080/02640410500482529

Beato, M., Madsen, E. E., Clubb, J., Emmonds, S., and Krustrup, P. (2024). Monitoring readiness to train and perform in female football: current evidence and recommendations for practitioners. *Int. J. Sports Physiol. Perform.* 19, 223–231. doi:10.1123/ijspp.2023-0405

Beato, M., Maroto-Izquierdo, S., Turner, A. N., and Bishop, C. (2021). Implementing strength training strategies for injury prevention in soccer: scientific rationale and methodological recommendations. *Int. J. Sports Physiol. Perform.* 16, 456–461. doi:10.1123/ijspp.2020-0862

Bishop, C., de Keijzer, K. L., Turner, A. N., and Beato, M. (2023). Measuring interlimb asymmetry for strength and power: a brief review of assessment methods, data analysis, current evidence, and practical recommendations. *J. Strength Cond. Res.* 37, 745–750. doi:10.1519/JSC.0000000000004384

Cormie, P., McGuigan, M. R., and Newton, R. U. (2011). Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. *Sport. Med.* 41, 125–146. doi:10.2165/11538500-000000000-00000

Jeffries, A. C., Marcora, S. M., Coutts, A. J., Wallace, L., McCall, A., and Impellizzeri, F. M. (2022). Development of a revised conceptual framework of physical training for use in research and practice. *Sport. Med.* 52, 709–724. doi:10.1007/s40279-021-01551-5

Paul, D. J., Gabbett, T. J., and Nassis, G. P. (2016). Agility in team sports: testing, training and factors affecting performance. *Sports Med.* 46, 421–442. doi:10.1007/s40279-015-0428-2

Randell, R. K., Clifford, T., Drust, B., Moss, S. L., Unnithan, V. B., De Ste Croix, M. B. A., et al. (2021). Physiological characteristics of female soccer players and health and performance considerations: a narrative review. *Sport. Med.* 51, 1377–1399. doi:10.1007/s40279-021-01458-1

Turner, A. N. (2024). What Is evidence-based Practice in strength and conditioning? *Strength Cond. J.* 2024. doi:10.1519/SSC.0000000000000840

Turner, A. N., and Stewart, P. F. (2014). Strength and conditioning for soccer players. *Strength Cond. J.* 36, 1–13. doi:10.1519/SSC.0000000000000054

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The effects of high-intensity interval training at the anaerobic and psychomotor fatigue thresholds on physiological parameters in young soccer players: a prospective study

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This study aimed to investigate the effects of a 4-week specific high-intensity interval training (HIIT) program performed between the anaerobic threshold (ANT) and the psychomotor fatigue threshold (PFT) on physiological parameters in 14 professional soccer players at the under-17 level. The first and second stages of the research protocol included a treadmill running exercise with increasing load and six 3-min four-versus-four games of soccer with a 3-min break between games. Players then participated in a training microcycle involving three specific HIIT exercises twice per week for 4 weeks, after which they repeated stages one and two, followed by an assessment of changes. The measurement of lactate (LA) determined ANT, whereas the choice reaction time (CRT) indicated PFT among other selected physiological parameters. The repeated-measure analysis of variance (ANOVA) compared mean values for the examined variables using Bonferroni *post hoc* test. It demonstrated significantly increased maximal oxygen consumption (VO_2 max) from 45.9 ± 3.0 to 48.7 ± 2.6 at the ANT and from 49.1 ± 3.4 to 52.0 ± 3.6 on the PFT after 4 weeks of training. A significant increase in the running speed (RS) at both thresholds and heart rate (HR) at the ANT ($p \leq 0.05$) was also recorded. Moreover, the players exceeded their intensity of effort during ANT while playing four-versus-four soccer matches, but they did not reach intensity during PFT. In conclusion, the findings of the study demonstrated that both thresholds shifted toward higher loads and the proposed specific HIIT effectively increased the exercise capacity of soccer players.

KEYWORDS

football, heart rate, global positioning system, maximal oxygen consumption, repeated small-sided games

Introduction

High-intensity interval training (HIIT) is very popular in modern soccer (Buchheit and Laursen, 2019), with one of the benefits being its time efficiency in improving performance and physiological parameters (Costigan et al., 2015; García-Hermoso et al., 2016). Furthermore, HIIT provides sufficient stimulus for anaerobic parameter improvements, such as the ability to perform straight-line sprints, repeated sprints, and jumps (Sperlich et al., 2011; Tønnessen et al., 2011; Ferrete et al., 2014). Systematic HIIT training also had a substantial positive effect on cardiovascular and respiratory fitness and increased maximal oxygen consumption (VO_2 max) (Eddolls et al., 2017; Thivel et al., 2019). HIIT involves various interval protocols with varying exercise durations and recovery intervals (Kunz et al., 2019), and studies that have tested the short-interval or long-interval HIIT demonstrated moderate to high benefits (Helgerud et al., 2001; Bravo et al., 2008; Ouerghi et al., 2014).

Effective HIIT requires the identification of the individual intensity that optimally stimulates exercise capacity development. Determining the minimum intensity with which exercises should be performed is often based on an individual anaerobic threshold (ANT), which is usually 75%–85% of the maximum heart rate (HR max), although the maximum load value varies in different protocols and can reach 90%–95% of HR max (Los Arcos et al., 2015; Kunz et al., 2019). However, another threshold observed above the ANT, the psychomotor fatigue threshold (PFT), is crucial in soccer. PFT determines the individual load at which the central nervous system (CNS) reaches its highest operational efficiency and fatigue tolerance (Chmura and Nazar, 2010) and often occurs between 88% and 92% of HR max (Chmura and Nazar, 2010). As such, intensity above the ANT benefits the development of motor skills, while intensities closer to PFT improve cognitive processes (Konefał et al., 2022). To date, there are few studies in this area (Chmura et al., 1998; Andrzejewski et al., 2011). For example, (Irandoust and Taheri, 2017; Paryab et al., 2021) indicated the positive effect of melatonin supplementation on improving psychomotor and physical performance. Therefore, it seems reasonable to propose a modified HIIT protocol that accounts for the level of effort between the two thresholds.

Training exercises performed with the ball are most valued in soccer, meaning that small-sided games (SSGs) are very popular (Moreira et al., 2016; Clemente et al., 2021) and can increase exercise motivation compared to traditional fitness training because they are a soccer-specific method. Furthermore, SSGs are considered to be more time efficient, as physical performance, technical skills, and tactical awareness can develop simultaneously (Aguiar et al., 2012). Additionally, they provide many practical benefits for all ages and sport levels (Clemente et al., 2021). Movement requirements, physiological changes, technical requirements, decision-making under time pressure, opponent, and fatigue are similar to the match effort (Hill-Haas et al., 2011; Aşçı, 2016). Like HIIT protocols, different sizes and formats of SSGs can elicit various physiological and cognitive responses and generate different exercise intensities (Brandes et al., 2012). Most studies report an increase in HR as the playing area increases and the number of players decreases (Hill-Haas et al., 2011; Randers et al., 2014; Arslan et al., 2017). A proven training exercise is the four-versus-four games (Konefał et al., 2023), which generate high-intensity exercise and may increase VO_2 max (Little, 2009).

Nowadays, due to the fact that the schedule is often congested, soccer players play more games per season, and the time available for training is decreasing. Hence, coaches and training staffs are constantly looking for time-efficient and effective exercises to boost players' performance. Traditional HIIT involves repetitive efforts at constant stimulus intensity (Buchheit and Laursen, 2019), although using HIIT training with variable stimulus intensity between ANT and PFT is interesting from a cognitive point of view. Indeed, exercise at an intensity close to PFT will result in the highest CNS efficiency and stimulate the development of cognitive processes while maintaining the widely known benefits of high-intensity repeated effort (Chmura and Nazar, 2010). Furthermore, it is interesting from a practical point of view to determine if playing an SSG of soccer (four versus four on a 25 m by 35 m pitch) elicits any intensity between the ANT and PFT.

Therefore, this study aimed to assess the effects of specific HIIT training performed between ANT and PFT on the physiological parameters of young soccer players. In addition, this study aimed to determine if the participants could exceed the ANT and achieve PFT intensity during a four-versus-four soccer match on a 25 m by 35 m pitch. In this regard, it was assumed that a 4-week HIIT program would significantly increase the physiological parameters and that young soccer players performing repeated SSGs would at least exceed their ANT each time.

Materials and methods

Experimental approach

The research comprised five stages and commenced with a laboratory-based treadmill running exercise test that used an increasing load (Figure 1). The next stage involved participants playing six 3-min soccer matches (four versus four), with a 3-min break between games. During the third stage, participants performed a specific HIIT program involving three exercises twice a week for 4 weeks. The fourth and fifth stages included the assessment of changes in physiological variables during the repeated performances of stages one and two. The physiological variables assessed included lactate (LA) for determining the ANT, choice reaction time (CRT) to determine the PFT, and other selected parameters.

Participants and eligibility

Sixteen soccer players competing at the under-17 level for a professional sports club in the second Polish league participated in the study. During the study, two players were unable to complete the experiment due to muscle or tendon injury and were excluded. Hence, fourteen players were included in the analysis. The physical activity of all outfield players was analyzed, though goalkeepers were excluded from the analysis due to the specificity of the effort. Inclusion criteria included a minimum of 8 years of training experience, participation in training at least four times per week before the start of the study, complete laboratory results, and no recent surgery or injury. All players were instructed not to consume alcohol for at least 24 h before testing, to stay hydrated, and follow a normal varied diet.

All participants were briefed with a detailed explanation of the proposed study and its requirements and provided written informed

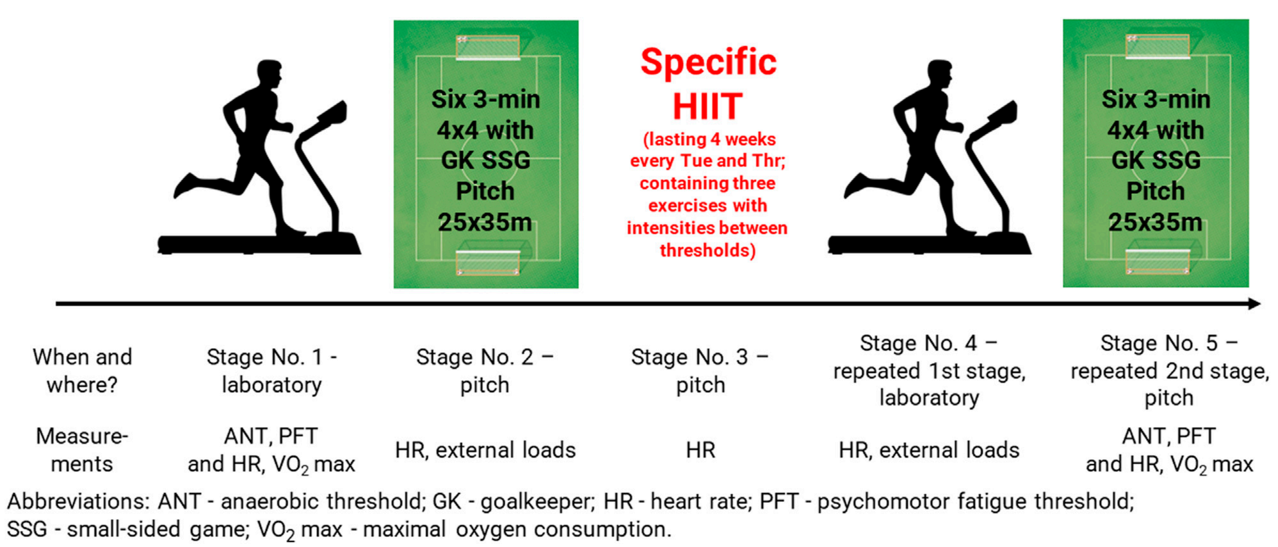

FIGURE 1
Study design.

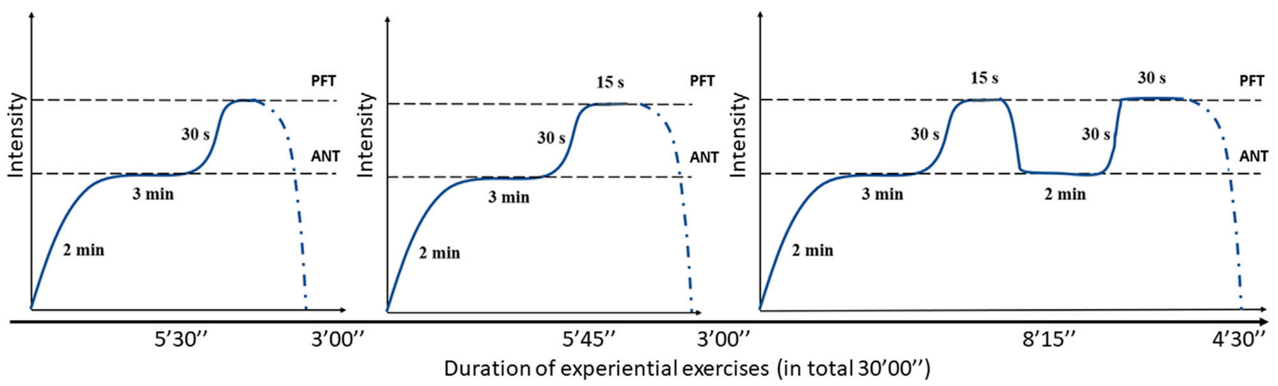

FIGURE 2
Intensity pattern of three specific high-intensity interval training exercises.

consent directly or through a parent or guardian. They were also informed of the potential risks and could withdraw at any time without any consequences. The study followed guidelines approved by the local ethics committee (12/2021) and the requirements set out in the Declaration of Helsinki, and all health and safety procedures were maintained.

Procedures and measurements

The research was carried out by qualified research personnel at the beginning of the pre-season period (from 26 July 2021 to 30 September 2021) and comprised five stages.

Stage one involved a laboratory-based treadmill (Cybex 790T) running exercise tests with increasing loads. Each subject started the test at a speed of 8 km/h, which was increased by 2 km/h every 3 minutes until they could no longer continue.

Immediately before the test and after each load, blood was collected from the fingertip to measure LA concentration, which was used to determine ANT (Konefał et al., 2022). In the last minute of each 3-min load, a CRT psychomotor test was carried out using a reaction meter APR (UNI—PAR, Lubin, Poland). The test determined the PFT using 25 audio–visual stimuli, a detailed description of which was previously published (Chmura et al., 2020). In addition, HR was recorded in beats per minute (bpm) using the Polar RS400, and the Cortex Metamax 3B mobile ergospirometer measured VO_2 (ml/kg/min).

Stage two comprised six 3-min soccer matches (four *versus* four) that included goalkeepers, with a 3-min break between games. The games were played on a 25 (m) by 35 (m) field as described previously (Konefał et al., 2023).

Before testing, players performed a standard 20-min increasing intensity warm-up that included running, stretching, ball exercises, and repeated starts, accelerations, and decelerations. In order to maintain

TABLE 1 Structure of the weekly training microcycle.

	MD+1	MD-5	MD-4	MD-3	MD-2	MD-1	MD
Training content	Day off	Low/moderate intensity, recovery and skill, and upper body strength	High intensity, SSG, sprint, and plyometric	Moderate intensity and MSG or LSG	High intensity, SSG, and tactical focus	Low/moderate intensity, tactical focus, and reaction speed	Match effort
			Additional specific HIIT		**Additional specific HIIT**		

Abbreviations: HIIT, high-intensity interval training; LSG, large-sided games; MD, match day; MSG, medium-sided games; SSG, small-sided games.

TABLE 2 Differences in physiological and kinematic parameters before and after the specific high-intensity interval training program (mean ± standard deviation).

Variable	Before	After	F (*p*-value)
VO_{2ANT} (ml·kg^{-1}·min^{-1})	45.89 ± 3.00	48.73 ± 2.60	**11.665 (0.005)**
HR_{ANT} (bpm)	176.00 ± 3.42	178.98 ± 4.54	**23.40 (0.001)**
LA_{ANT} (au)	3.10 ± 0.13	3.79 ± 0.21	**101.06 (0.001)**
V_{ANT} (km·h^{-1})	13.21 ± 0.97	14.50 ± 0.94	**43.875 (0.001)**
VO_{2PFT} (ml·kg^{-1}·min^{-1})	49.14 ± 3.41	52.03 ± 3.55	**16.833 (0.001)**
HR_{PFT} (bpm)	180.43 ± 5.56	182.07 ± 4.46	1.77 (0.206)
LA_{PFT} (au)	4.22 ± 0.48	5.23 ± 0.66	**85.658 (0.001)**
V_{PFT} (km·h^{-1})	14.29 ± 0.91	15.57 ± 0.94	**43.875 (0.001)**

Abbreviations: VO_{2ANT}, maximal oxygen consumption at the anaerobic threshold; HR_{ANT}, heart rate at the anaerobic threshold; LA_{ANT}, lactate concentration at the anaerobic threshold; V_{ANT}, velocity at the anaerobic threshold; VO_{2PFT}, maximal oxygen consumption at the psychomotor fatigue threshold; HR_{PFT}, heart rate at the psychomotor fatigue threshold; LA_{PFT}, lactate concentration at the psychomotor fatigue threshold; V_{PFT}, velocity at the psychomotor fatigue threshold. The bold value indicates the statistically significant values. Their exact *p*-value is given in parentheses.

the intensity of player efforts during soccer matches, the coach would throw another ball into the field when the ball went out of bounds. In addition to that the coaching staff used verbal motivation.

External loads were determined using a global positioning system (GPS) with sampling at 10 Hz and triaxial accelerometer sampling at 100 Hz using the Vector S7 (Catapult Sports, Melbourne, Australia) (Beenham et al., 2017). Data were collected after each session using Catapult Sports' proprietary software (OpenField) (Pop et al., 2022).

The metrics derived from each of the devices included HR max (bpm), total distance covered (TDC) (m), maximal velocity (V max) (km·h^{-1}), mean velocity (V mean) (km·h^{-1}), acceleration (Acc) (number), and deceleration (Dec) (number).

Stage three of the experiment used a training microcycle program of three specific HIIT exercises twice a week on Tuesdays and Thursdays (Table 1). The total experiment duration was 4 weeks, which equates to eight training sessions. In addition, the players followed a standard training program (Table 2). During specific HIIT, each player used a Polar RS400 HR monitor that encompassed a watch for real-time exercise intensity control.

Stage four assessed changes in physiological parameters caused by the applied training by repeating stage one. Meanwhile, stage five measured changes in external loads by repeating stage two.

Specific high-intensity interval training

Exercise 1: run with increasing intensity until one reaches the ANT (2 minutes), maintain the running intensity at the ANT for 3 minutes, and then accelerate for 30 seconds until one reaches the PFT intensity. The total duration was 5 minutes and 30 seconds, followed by a 3-min jog (Figure 2).

Exercise 2: run with increasing intensity until one reaches the ANT (2 minutes) and continue running with ANT intensity for 3 minutes, accelerate for 30 seconds until one reaches the PFT, and then run at the PFT for 15 seconds. The total duration was 5 minutes and 45 seconds, followed by a 3-min jog.

Exercise 3: run with increasing intensity until one reaches the ANT (2 minutes) and continue running at the ANT for 3 minutes, then accelerate for 30 seconds until one reaches the PFT, and then run for 15 seconds. Reduce the running speed toward the ANT, maintain this speed for 2 minutes, and then increase the running speed for 30 seconds until one reaches the PFT and continue running for 30 seconds. The total activity duration was 8 minutes and 15 seconds, followed by a jog that lasted for 4 minutes and 30 seconds. The specific HIIT workout duration was 30 minutes.

Statistical analysis

All statistical analyses employed Statistica version 13.3 software (Dell Inc., OK, United States). The Shapiro–Wilk test verified the normality of data distribution, and arithmetic means and standard deviations were calculated. A repeated-measure analysis of variance (ANOVA) compared mean values for the examined variables (Park et al., 2009) with a Bonferroni *post hoc* test used to assess differences between means. The level of statistical significance was set at $p \leq 0.05$.

TABLE 3 Differences in kinematic variables over six 3-min small-sided games (mean ± standard deviation).

Variable	Game						F (p-value)	SSD ($p \leq 0.05$)
	1	2	3	4	5	6		
HR max (bpm)	179.75 ± 7.62	179.61 ± 7.69	176.68 ± 8.34	177.68 ± 7.12	178.32 ± 7.62	172.75 ± 13.22	**4.93 (0.001)**	1,2,4,5 > 6
TDC (m)	366.38 ± 32.87	376.80 ± 40.42	360.21 ± 39.01	367.29 ± 34.06	365.46 ± 44.56	362.95 ± 40.60	1.661 (0.148)	—
V max (km·h⁻¹)	19.36 ± 1.72	20.28 ± 1.92	20.26 ± 1.65	20.32 ± 2.02	19.42 ± 1.43	20.52 ± 1.89	2.57 (0.056)	—
V mean (km·h⁻¹)	7.25 ± 0.64	7.22 ± 0.70	6.93 ± 0.74	7.10 ± 0.61	7.03 ± 0.78	6.89 ± 0.84	**3.307 (0.007)**	1 > 6
Acc (number)	22.61 ± 3.55	21.93 ± 4.83	21.71 ± 4.81	20.54 ± 4.40	21.75 ± 3.72	20.71 ± 4.37	1.825 (0.112)	—
Dec (number)	22.43 ± 3.78	23.18 ± 4.34	22.36 ± 5.17	21.61 ± 3.73	22.61 ± 4.58	20.11 ± 4.34	**3.860 (0.003)**	1,2,5 > 6

Abbreviations: Acc, acceleration; Dec, deceleration; HR max, maximal heart rate; TDC, total distance covered; V max, maximal velocity; V mean, mean velocity. The bold value indicates the statistically significant values. Their exact p-value is given in parentheses.

Results

Fourteen soccer players participated in the study. The mean age of participants was 17.3 ± 0.4 years, their stature was 1.76 ± 0.05 m, and their body mass was 69.27 ± 5.43 kg.

The statistical analysis of physiological and kinematic variables before and after the specific HIIT revealed effects on VO_{2ANT} (F = 11.665 (1); p = 0.005), HR_{ANT} (F = 23.400 (1); p = 0.001), LA_{ANT} (F = 101.060 (1); p = 0.001), V_{ANT} (F = 43.875 (1); p = 0.001), VO_{2PFT} (F = 16.833 (1); p = 0.001), LA_{PFT} (F = 85.658 (1); p = 0.001), and V_{PFT} (F = 43.875 (1); p = 0.001). However, there was no significant effect on HR_{PFT} (F = 1.770 (1); p = 0.206) (Table 2).

The statistical analysis of the physiological and kinematic variables during the repeated SSGs revealed effects on HR max (F = 4.930 (5); p = 0.001), V mean (F = 3.307 (5); p = 0.007), and Dec (F = 3.860 (5); p = 0.003). There was no significant effect on TDC (F = 1.661 (5); p = 0.148), V max (F = 2.570 (5); p = 0.056), or Acc (F = 1.825 (5); p = 0.112) (Table 3).

Discussion

This study aimed to assess the impact of specific HIIT performed between ANT and PFT on the physiological parameters of young soccer players. Many recently published studies indicated the high effectiveness of HIIT in sports (Fernandez-Fernandez et al., 2017; Monks et al., 2017), which is reflected in the increased levels of physiological and kinematic parameters (Engel et al., 2018). In practice, such increases shift the ANT toward higher loads (Little, 2009; Kunz et al., 2019) and are more frequently determined by measuring the LA concentration (Hill-Haas et al., 2011; Stanula et al., 2013). The major findings of this study showed that the use of the 4-week physical training, comprising three exercises of a specific intensity above the ANT, is sufficient to significantly increase the physical performance of players.

This finding indicates that the proposed specific HIIT, with intensity between anaerobic and psychomotor fatigue thresholds, caused a shift in the ANT toward higher loads. Indeed, HIIT significantly increased VO_2 by 6.2%, HR by 1.7%, and running speed by 9.8%. Although the training was only carried out over eight sessions, it caused similar increases as 14 training sessions over 6 weeks with threshold intensity (Chmura and Nazar, 2010). As such, the higher intensity (but not significantly above the ANT) specific HIIT used in the current study appears to be more time efficient.

Sperlich et al. (2011) found a 6.5% VO_2 increase in young soccer players during a 5-week HIIT program, which is similar to VO_2 found in our study. Therefore, it follows that the training comprising three exercises carried out between ANT and PFT, each of which generates longer duration, increased intensity, and greater stimulus variability, is a practical proposal that effectively increases the exercise capacity of soccer players.

These findings may also suggest that the specific HIIT proposed herein affects cognitive aspects. Indeed, PFT defining the highest CNS efficiency (shortest reaction time, best anticipation, perception, and optimal decision making) also shifted toward higher loads during this training (Chmura and Nazar, 2010), with significant increases in VO_2 (5.9%), running speed (9.0%), and HR (0.9%). Such progression of PFT toward higher loads means, in practice, that the athlete can make optimal decisions at higher running speed and higher fatigue tolerance (Konefał et al., 2022). Given the very high intensity in modern soccer (Andrzejewski et al., 2018; Chmura et al., 2018; Konefał et al., 2019), such an effect is extremely desirable, as it allows players to perform actions efficiently at extremely intense moments of a match.

It makes sense for HIIT to include SSGs since the players would also improve technical and tactical elements and their decision-making processes, which are required for playing soccer (Davids et al., 2013; Trecroci et al., 2020) Therefore, the next aim was to determine if participants would exceed the ANT and achieve PFT intensity during four-versus-four matches on a 25 m × 35 m pitch that reflect the game conditions required in the specific HIIT proposed. The parameter frequently used in coaching practice to determine the effort intensity during the game is HR (Brandes et al., 2012; Aşçı, 2016; Konefał et al., 2023), which can be measured with precision and accuracy using available measurement technologies (Beenham et al., 2017; Gómez-Carmona et al., 2020; Pop et al., 2022). In this study, soccer players achieved HR max values that exceeded the intensity found at the ANT five-fold during six 3-min matches, even though they did not reach such intensity at the PFT during any of the games. However, it is worth noting that the HR max values were slightly lower than this intensity in the first two games.

It appears that the format used (four versus four) generated too little intensity in relation to the PFT. Therefore, the pitch size should be modified to slightly increase the game intensity (Aguiar et al., 2012), and the repetitions decreased to five to achieve the desired effects. Indeed, the analysis of kinematic parameters demonstrated a requirement of six consecutive games for the players to maintain their TDC, V max, and Acc levels. Nonetheless, values for V mean and Dec indicated a need to reduce the number of games to five since these parameters significantly decreased in the final game (Konefał et al., 2023).

The strength of this study is to find an appropriate exercise program that effectively increases the studied physiological variables in a short period of time while boosting performance. A high level of exercise capacity will allow coaches to concentrate more in training and on bringing out the technical and tactical potential of players. The authors are fully aware of various factors that could have influenced the results of the presented analyses. Indeed, experimenting on young players who are still developing their biological and psychomotor potential is a limitation of the study. A small sample size is another limitation. Therefore, these results should be treated with caution. In order to better understand the relationship between the specific HIIT proposed and the game format used (four versus four), further research should take into account various pitch size modifications (Hill-Haas et al., 2011; Arslan et al., 2017). Furthermore, it would be advisable to continue research on the relationship between ANT and PFT in the context of new training exercises (with and without the ball) that helps in developing both physical performance and decision-making, while accounting for different age groups and fitness levels.

Conclusion

It was found that 4 weeks of specific HIIT significantly increased VO_2 and running speed at the ANT and PFT, as well as HR at the ANT. These findings demonstrated that both thresholds shifted toward higher loads, which may be the result of adaptation to the applied training loads.

The participants exceeded ANT intensity but did not reach PFT intensity during four-versus-four soccer matches on a 25 m × 35 m pitch. However, they did approach PFT intensity during the first two games. Therefore, it would be advisable to modify the dimensions of the pitch in order to increase the intensity of the game. In addition, the analysis of kinematic parameters suggested that using five games would be more effective.

Practical applications

Bringing out the full potential of players during the starting effort is invariably one of the most important goals of coaches, strength and conditioning coaches, and training staff. The proposed HIIT comprising three exercises carried out between ANT and PFT, each generating greater intensity, greater variability of the stimulus, and longer duration, is a practical proposal that effectively increases the exercise capacity of soccer players.

Data availability statement

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

Author contributions

Conceptualization: PC, JC, and MK; methodology: PC and JC; software: WC and AD; validation: MK; formal analysis: MK; investigation: PC, JC, WC, AD, and MK; resources: PC; data curation: AR; writing—original draft preparation: PC, JC, and MK; writing—review and editing: PC and MK; visualization: WC; supervision: JC; project administration: PC; funding acquisition: AR. 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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References

Aguiar, M., Botelho, G., Lago, C., Maças, V., and Sampaio, J. (2012). A review on the effects of soccer small-sided games. *J. Hum. Kinet.* 33, 103–113. doi:10.2478/v10078-012-0049-x

Andrzejewski, M., Chmura, J., Wiacek, M., and Zubrzycki, I. Z. (2011). Influence of individualized training on psychomotor performance of young soccer players. *J. Strength Cond. Res.* 25, 374–378. doi:10.1519/JSC.0b013e3181bac390

Andrzejewski, M., Chmura, P., Konefał, M., Kowalczuk, E., and Chmura, J. (2018). Match outcome and sprinting activities in match play by elite German soccer players. *J. Sports Med. Phys. Fit.* 58, 785–792. doi:10.23736/S0022-4707.17.07352-2

Arslan, E., Alemdaroglu, U., Koklu, Y., Hazir, T., Muniroglu, S., and Karakoc, B. (2017). Effects of passive and active rest on physiological responses and time motion characteristics in different small sided soccer games. *J. Hum. Kinet.* 60, 123–132. doi:10.1515/hukin-2017-0095

Aşçı, A. (2016). Heart rate responses during small sided games and official match-play in soccer. *Sports* 4, 31. doi:10.3390/sports4020031

Beenham, M., Barron, D. J., Fry, J., Hurst, H. H., Figueirdo, A., and Atkins, S. (2017). A comparison of GPS workload demands in match play and small-sided games by the positional role in youth soccer. *J. Hum. Kinet.* 57, 129–137. doi:10.1515/hukin-2017-0054

Brandes, M., Heitmann, A., and Müller, L. (2012). Physical responses of different small-sided game formats in elite youth soccer players. *J. Strength Cond. Res.* 26, 1353–1360. doi:10.1519/JSC.0b013e318231ab99

Bravo, D., Impellizzeri, F., Rampinini, E., Castagna, C., Bishop, D., and Wisloff, U. (2008). Sprint vs. Interval training in football. *Int. J. Sports Med.* 29, 668–674. doi:10.1055/s-2007-989371

Buchheit, M., and Laursen, P. B. (2019). *High-intensity interval training, solutions to the programming puzzle*.

Chmura, J., and Nazar, K. (2010). Parallel changes in the onset of blood lactate accumulation (OBLA) and threshold of psychomotor performance deterioration during incremental exercise after training in athletes. *Int. J. Psychophysiol.* 75, 287–290. doi:10.1016/j.ijpsycho.2009.12.011

Chmura, J., Krysztofiak, H., Ziemba, A. W., Nazar, K., and Kaciuba-Uścilko, H. (1998). Psychomotor performance during prolonged exercise above and below the blood lactate threshold. *Eur. J. Appl. Physiol.* 77 (1-2), 77–80. doi:10.1007/s004210050303

Chmura, P., Konefał, M., Chmura, J., Kowalczuk, E., Zajac, T., Rokita, A., et al. (2018). Match outcome and running performance in different intensity ranges among elite soccer players. *Biol. Sport* 35, 197–203. doi:10.5114/biolsport.2018.74196

Chmura, J., Chmura, P., Konefał, M., Batra, A., Mroczek, D., Kosowski, M., et al. (2020). The effects of a marathon effort on psychomotor performance and catecholamine concentration in runners over 50 Years of age. *Appl. Sci.* 10, 2067. doi:10.3390/app10062067

Clemente, F. M., Ramirez-Campillo, R., Nakamura, F. Y., and Sarmento, H. (2021). Effects of high-intensity interval training in men soccer player's physical fitness: A systematic review with meta-analysis of randomized-controlled and non-controlled trials. *J. Sports Sci.* 39, 1202–1222. doi:10.1080/02640414.2020.1863644

Costigan, S. A., Eather, N., Plotnikoff, R. C., Taaffe, D. R., and Lubans, D. R. (2015). High-intensity interval training for improving health-related fitness in adolescents: A systematic review and meta-analysis. *Br. J. Sports Med.* 49, 1253–1261. doi:10.1136/bjsports-2014-094490

Davids, K., Araújo, D., Correia, V., and Vilar, L. (2013). How small-sided and conditioned games enhance acquisition of movement and decision-making skills. *Exerc Sport Sci. Rev.* 41, 154–161. doi:10.1097/JES.0b013e318292f3ec

Eddolls, W. T. B., McNarry, M. A., Stratton, G., Winn, C. O. N., and Mackintosh, K. A. (2017). High-intensity interval training interventions in children and adolescents: A systematic review. *Sports Med.* 47, 2363–2374. doi:10.1007/s40279-017-0753-8

Engel, F. A., Ackermann, A., Chtourou, H., and Sperlich, B. (2018). High-intensity interval training performed by young athletes: A systematic review and meta-analysis. *Front. Physiol.* 9, 1012. doi:10.3389/fphys.2018.01012

Fernandez-Fernandez, J., Sanz, D., Sarabia, J. M., and Moya, M. (2017). The effects of sport-specific drills training or high-intensity interval training in young tennis players. *Int. J. Sports Physiol. Perform.* 12, 90–98. doi:10.1123/ijspp.2015-0684

Ferrete, C., Requena, B., Suarez-Arrones, L., and de Villarreal, E. S. (2014). Effect of strength and high-intensity training on jumping, sprinting, and intermittent endurance performance in prepubertal soccer players. *J. Strength Cond. Res.* 28, 413–422. doi:10.1519/JSC.0b013e31829b2222

García-Hermoso, A., Cerrillo-Urbina, A. J., Herrera-Valenzuela, T., Cristi-Montero, C., Saavedra, J. M., and Martínez-Vizcaíno, V. (2016). Is high-intensity interval training more effective on improving cardiometabolic risk and aerobic capacity than other forms of exercise in overweight and obese youth? A meta-analysis. *Obes. Rev.* 17, 531–540. doi:10.1111/obr.12395

Gómez-Carmona, C. D., Bastida-Castillo, A., Ibáñez, S. J., and Pino-Ortega, J. (2020). Accelerometry as a method for external workload monitoring in invasion team sports. A systematic review. *PLoS One* 15, e0236643. doi:10.1371/journal.pone.0236643

Helgerud, J., Eegen, L. C., Wisloff, U., and Hoff, J. (2001). Aerobic endurance training improves soccer performance. *Med. Sci. Sports Exerc* 33, 1925–1931. doi:10.1097/00005768-200111000-00019

Hill-Haas, S. v., Dawson, B., Impellizzeri, F. M., and Coutts, A. J. (2011). Physiology of small-sided games training in football: A systematic review. *Sports Med.* 41, 199–220. doi:10.2165/11539740-000000000-00000

Irandoust, K., and Taheri, M. (2017). The Effect of Strength Training on quality of sleep and psychomotor performance in elderly males. *Sleep Hypn* 20, 160–165. doi:10.5350/Sleep.Hypn.2017.19.0148

Konefał, M., Chmura, P., Kowalczuk, E., Figueiredo, A. J., Sarmento, H., Rokita, A., et al. (2019). Modeling of relationships between physical and technical activities and match outcome in elite German soccer players. *J. Sports Med. Phys. Fit.* 59, 752–759. doi:10.23736/S0022-4707.18.08506-7

Konefał, M., Chmura, J., Charmas, M., Kotowska, J., Błażejczyk, K., and Chmura, P. (2022). Lactate threshold and psychomotor fatigue threshold in hot conditions: suggestions for soccer players participating in the Qatar world cup 2022. *Int. J. Environ. Res. Public Health* 19, 17028. doi:10.3390/ijerph192417028

Konefał, M., Chmura, J., Zacharko, M., Zając, T., and Chmura, P. (2023). The relationship among acceleration, deceleration and changes of direction in repeated small sided games. *J. Hum. Kinet.* 85, 96–103. doi:10.2478/hukin-2022-0113

Kunz, P., Engel, F. A., Holmberg, H.-C., and Sperlich, B. (2019). A meta-comparison of the effects of high-intensity interval training to those of small-sided games and other training protocols on parameters related to the Physiology and performance of youth soccer players. *Sports Med. Open* 5, 7. doi:10.1186/s40798-019-0180-5

Little, T. (2009). Optimizing the use of soccer drills for physiological development. *Strength Cond. J.* 31, 67–74. doi:10.1519/SSC.0b013e3181a5910d

Los Arcos, A., Vázquez, J. S., Martín, J., Lerga, J., Sánchez, F., Villagra, F., et al. (2015). Effects of small-sided games vs. Interval training in aerobic fitness and physical enjoyment in young elite soccer players. *PLoS One* 10, e0137224. doi:10.1371/journal.pone.0137224

Monks, L., Seo, M.-W., Kim, H.-B., Jung, H. C., and Song, J. K. (2017). High-intensity interval training and athletic performance in Taekwondo athletes. *J. Sports Med. Phys. Fit.* 57, 1252–1260. doi:10.23736/S0022-4707.17.06853-0

Moreira, A., Saldanha Aoki, M., Carling, C., Alan Rodrigues Lopes, R., Felipe Schultz de Arruda, A., Lima, M., et al. (2016). Temporal changes in technical and physical performances during a small-sided game in elite youth soccer players. *Asian J. Sports Med.* 7, e35411. doi:10.5812/asjsm.35411

Ouerghi, N., Feki, M., Kaabachi, N., Khammassi, M., Boukorraa, S., and Bouassida, A. (2014). Effects of a high-intensity intermittent training program on aerobic capacity and lipid profile in trained subjects. *Open Access J. Sports Med.* 5, 243–248. doi:10.2147/OAJSM.S68701

Park, E., Cho, M., and Ki, C.-S. (2009). Correct use of repeated measures analysis of variance. *Ann. Lab. Med.* 29, 1–9. doi:10.3343/kjlm.2009.29.1.1

Paryab, N., Taheri, M., H'Mida, C., Irandoust, K., Mirmoezzi, M., Trabelsi, K., et al. (2021). Melatonin supplementation improves psychomotor and physical performance in collegiate student-athletes following a sleep deprivation night. *Chronobiol Int.* 38, 753–761. doi:10.1080/07420528.2021.1889578

Pop, R.-M., Grosu, V. T., Grosu, E. F., Zadic, A., Mâță, L., and Dobrescu, T. (2022). The effects of small-sided games and behavioral interventions on the physical and motivational outcomes of youth soccer players. *Int. J. Environ. Res. Public Health* 19, 14141. doi:10.3390/ijerph192114141

Randers, M. B., Nielsen, J. J., Bangsbo, J., and Krustrup, P. (2014). Physiological response and activity profile in recreational small-sided football; No effect of the number of players. *Scand. J. Med. Sci. Sports* 24, 130–137. doi:10.1111/sms.12232

Sperlich, B., de Marées, M., Koehler, K., Linville, J., Holmberg, H.-C., and Mester, J. (2011). Effects of 5 Weeks of high-intensity interval training vs. Volume training in 14-year-old soccer players. *J. Strength Cond. Res.* 25, 1271–1278. doi:10.1519/JSC.0b013e3181d67c38

Stanula, A., Gabrys, T., Szmatlan-Gabrys, U., Roczniok, R., Maszczyk, A., and Pietraszewski, P. (2013). Calculating lactate anaerobic thresholds in sports involving different endurance preparation. *J. Exerc Sci. Fit.* 11, 12–18. doi:10.1016/j.jesf.2012.12.001

Thivel, D., Masurier, J., Baquet, G., Timmons, B. W., Pereira, B., Berthoin, S., et al. (2019). High-intensity interval training in overweight and obese children and adolescents: systematic review and meta-analysis. *J. Sports Med. Phys. Fit.* 59, 310–324. doi:10.23736/S0022-4707.18.08075-1

Tønnessen, E., Shalfawi, S. A., Haugen, T., and Enoksen, E. (2011). The effect of 40-m repeated sprint training on maximum sprinting speed, repeated sprint speed endurance, vertical jump, and aerobic capacity in young elite male soccer players. *J. Strength Cond. Res.* 25, 2364–2370. doi:10.1519/JSC.0b013e3182023a65

Trecroci, A., Boccolini, G., Duca, M., Formenti, D., and Alberti, G. (2020). Mental fatigue impairs physical activity, technical and decision-making performance during small-sided games. *PLoS One* 15, e0238461. doi:10.1371/journal.pone.0238461

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Neuromuscular and perceptual-cognitive response to 4v4 small-sided game in youth soccer players

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The physical and psychological load of small-sided games (SSGs) can affect players' neuromuscular and cognitive functions. Yet, little is known about the acute performance changes after such a specific exercise in young soccer players and their association with exercise load applied. This study investigates i) the neuromuscular and perceptual-cognitive response to the SSG exercise load, and ii) the relationship between pre- and post-SSG changes in variables of performance and the respective exercise load in youth soccer players. Sixteen participants (13.6 ± 0.5 years) underwent a 30-min SSG 4v4 + GK protocol. Prior to and after the SSG they performed countermovement jump (CMJ), planned and reactive Y-shaped agility tests (PA, RA), and go/no-go task (GNG). Their subjective perception of fatigue was evaluated by visual analog scale. Fatigue induced by SSG (perception of fatigue increased by 41.56%, p = .001, g = 4.15) increased PA time (4.04%, p = .002, g = .97), RA time (6.45%, p = .003, g = 1.16), and number of errors in the response inhibition task (87.1%, p = .023, r_c = .57), whilst decreased CMJ height (−6.65%, p = .014, g = .56). These performance deteriorations were not significantly associated with neither internal nor external load variables. However, a less pronounced drop in performance was related to external load variables, i.e., ΔCMJ height and ΔRA time correlated with very high-speed running (r_s = .66, p = .006; r_s = −.50, p = .022; respectively) and maximal speed (r = .54, p = .032; r = −.52, p = .037; respectively), whilst ΔPA time was associated with high-intensity accelerations (r_s = −.76, p = .002). These findings indicate that fatigue induced by SSG affects both planned and reactive agility, decision-making in response inhibition task, and explosive strength in youth soccer players regardless of significant contribution of any robust internal or external load variables. Nonetheless, high-intensity actions within SSG partially compensate for the decrements in their agility performance and explosive strength. The load variables encountered during SSG do not fully reflect youth players' neuromuscular and perceptual-cognitive responses to sport-specific exercise.

KEYWORDS

fatigue, agility, cognitive functions, reaction time, load management, soccer training

1 Introduction

Small-sided games (SSGs) provide an effective tool for conditioning team sport players in a specific game environment (Gabbett, 2006). Their intermittent character produces a relatively high neuromuscular and metabolic load (Owen et al., 2012; Sarmento et al., 2018), which can induce temporal decrements in players' physical performance (Faude et al., 2014; Martínez-Serrano et al., 2023). SSGs also demand players' cognitive functions (Figueira et al., 2019; Mitrotasios et al., 2021). Therefore, proper prescription of SSGs and respective exercise load monitoring is important for the performance optimization of soccer players (Branquinho et al., 2021a; Branquinho et al., 2021b).

Crucial abilities for soccer performance, such as explosive strength, sprinting, and change of direction speed (Rampinini et al., 2007; Nygaard Falch et al., 2019), all depend on the neuromuscular system. Neuromuscular performance temporarily decreases in parallel with accumulated exercise load in SSGs (Rebelo et al., 2016; Bujalance-Moreno et al., 2020). This is mainly contributed to the high amount of mechanical work produced by numerous in-game changes in speed and direction of movement, in terms of high-intensity accelerations and decelerations (Gaudino et al., 2014). External load is to a high extent responsible for muscle damage (Silva et al., 2018). The impairment of muscle cells' contractile functions results in lower muscle force production (Thorlund et al., 2009). This neuromuscular fatigue can also be accentuated by acute depletion of muscles' energy stores (i.e., glycogen, phosphocreatine) as a result of intermittent exercise (Gaitanos et al., 1993; Reilly et al., 2008). Temporal performance declines induced by sport-specific exercise load are typical for players' explosive strength and speed (Katis and Kellis, 2009; Rebelo et al., 2016; Rowell et al., 2017).

Besides the high neuromuscular and metabolic demands of SSGs, sufficient attention, perception, and visual information processing from a dynamic environment are of special importance for soccer players (Klatt and Smeeton, 2022). Cognition needs to be activated more often and in different ways during situations experienced in the game (Rodrigues et al., 2022). Cognitive performance can be enhanced by acute bouts of exercise (Dupuy et al., 2018). Positive effects may be attributed to the sympathetic functions increasing heart rate, levels of excitatory neurotransmitters in the brain, and cortisol secretion (Tomporowski, 2003). On the contrary, physical and mental effort can also produce negative effects on players' perceptual and cognitive performance (Skala and Zemková, 2022). These effects are often ascribed to the increased levels of brain catecholamines (McMorris et al., 2008) and limited activation in centers responsible for higher-order cognitive functions (Dietrich, 2006).

Several studies reported a decline in cognitive performance following acute bouts of exercise (Del Giorno et al., 2010; Donnan et al., 2022; Teoldo et al., 2022). For example, longer reaction time and impaired object detection were found in sport-specific visual tasks (Frýbort et al., 2016; Klatt and Smeeton, 2021). However, these declines may be task-specific and related to the time of post-exercise testing (Moore et al., 2012). Accumulated repetitions of SSGs were found to impair decision-making ability in terms of progressive deterioration of passing accuracy (Mitrotasios et al., 2021). In addition, decision-making and perception are important factors of agility performance in invasive sports (Young et al., 2015). The decline in agility performance occurs sooner when players react to external cues than when changing the direction of movement without reactions to visual stimuli (Ciocca et al., 2022). However, discrepancies in the literature exist regarding the effects of exercise on reactive and planned agility (Almonroeder et al., 2020).

Nevertheless, recent literature reviews have shown that the majority of studies explore the acute effects of exercise on performance of adult and adolescent athletes (Skala and Zemková, 2022; Teoldo et al., 2022). Children are more resistant to neuromuscular fatigue and recover faster from high-intensity physical exertion compared to adults (Falk and Dotan, 2006; Ratel et al., 2006). Yet, little is known about the effects of SSGs in youth players and their neuromuscular and perceptual-cognitive performance under fatigue conditions. Since SSGs are widely used in both adult and youth soccer training, it is of our interest to investigate i) the neuromuscular and perceptual-cognitive performance response to the SSG exercise load, and ii) the relationship between pre- and post-SSG changes in variables of performance and respective exercise load in youth soccer players. Here, we hypothesized neuromuscular and perceptual-cognitive performance impairment after the SSG. While the external load variables would be associated with decrements in explosive strength and agility, the internal load variables would be related to impaired accuracy during the response inhibition task.

2 Materials and methods

2.1 Participants

Sixteen youth soccer players (13.6 ± 0.5 years; 163.4 ± 5.9 cm; 50.4 ± 7.1 kg; Table 1) from a local first-tier academy were voluntary recruited to participate in this study. All participants had a minimum of 5-year experience with the academy soccer training. They performed 4 training sessions (80–100-min) per week and played an official eleven-a-side match (2 × 35-min) during the weekend on the regular-sized soccer field. Two goalkeepers participated in the SSG, but were not included in the analysis. The players were asked to avoid physical activity for 24-h prior to the

TABLE 1 Descriptive statistics for somatometric and physical fitness assessments of participants. SD (±), standard deviation; CV (%), coefficient of variation.

	Mean	SD (±)	CV (%)
Age (years)	13.6	0.5	3.7
Height (cm)	163.4	5.9	3.7
Body mass (kg)	50.4	7.1	15.5
10-m sprint (s)	1.88	0.06	3.0
Maximal speed (km/h)	26.5	1.8	6.6
Countermovement jump (cm)	30.5	3.7	12.1
Yo-Yo intermittent recovery 1 test (m)	1,299	216	16.6

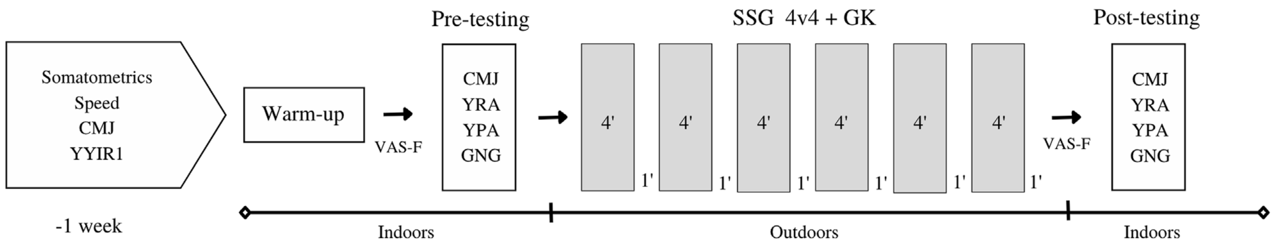

FIGURE 1
Experimental design. CMJ, countermovement jump; YYIR1, Yo-Yo intermittent recovery level 1; VAS-F, Visual analog scale of fatigue; YRA, Y-shaped reactive agility test; YPA, Y-shaped planned agility test; GNG, Go/No-go test; SSG 4v4 + GK, Small-sided game 4 vs. 4 + Goalkeepers.

experiment and to sleep at least 8-h a night. They were instructed to consume water and light meal 2–3-h before the testing session. Participants were free from neuromuscular injuries or any disorders. Written informed parental consent was obtained before the study. Each participant and his parents agreed to participate in the experiment and were notified about the withdrawal from the study at any time. The procedures followed were in accordance with the ethical standards on human experimentation stated in compliance with the 1964 Helsinki Declaration and its later amendments. The project was approved by the ethics committee of the Faculty of Physical Education and Sport, Comenius University in Bratislava (no. 3/2022, date: 22 September 2022).

2.2 Study design

This study was constituted as a quasi-experimental investigation without the random assignment of participants to conditions or their order. The pretest-posttest design was used. The dependent variable was measured once before the exercise was implemented and once after it was implemented. Measurements were performed as part of regular in-season training. One week before the experiment, the participants completed an assessment of body height, body mass, acceleration speed in a 10-m sprint, maximal speed obtained from the lowest 10-m split time in a 40-m run, explosive strength in a countermovement jump, and aerobic endurance in a Yo-Yo intermittent recovery test level 1 (Table 1).

Prior to the experiment, the participants underwent a warm-up that included low-intensity running, dynamic stretching, and running drills. No specific exercise with a ball was included. The warm-up and testing of neuromuscular and perceptual-cognitive performance were executed indoors to secure standardized conditions. The participants wore standard indoor soccer footwear. Afterwards they were individually asked to evaluate their subjective perception of fatigue. They changed the footwear to standard football boots and moved to the soccer field located right outside the testing room. The SSGs were performed outdoors on a regular artificial grass soccer field, between 3 and 6 p.m. in temperatures 7 to 10°C (Meteoblue, Basel, Switzerland). After the SSG protocol, the participants immediately moved to the testing room and underwent the same testing procedure within 10-min of its completion. Tests were executed in randomized order. A whole experimental design is shown in Figure 1.

2.3 Small-sided game

The SSG (4v4 + Goalkeepers) was performed on the outdoor soccer field with artificial grass using formal 11-a-side goals. The size of the pitch 40 × 25-m (length × width) provided a relative field space of 125 m^2 per player (Calderón Pellegrino et al., 2020). The exercise included six 4-min bouts separated by 1-min passive recoveries (overall game time of 24-min). The players were divided into two teams by the head coach in accordance with his perception of their physical, technical, and tactical skills (Torrents et al., 2016). Standard 11-a-side soccer rules were followed except for the offside rule. Field players were able to pass to goalkeepers. Verbal encouragement from coaches was permitted, but not feedback related to the players' technical and tactical performance. Several balls were located near the sidelines around the pitch to increase the effective play time (Hill-Haas et al., 2008). The players were familiar with this SSG format as it was used regularly in training.

2.4 Data collection

2.4.1 Load monitoring

The physical activity profiles of players in SSG were assessed using 10-Hz GPS units with heart rate (HR) sensors Polar Team Pro (Polar, Kempele, Finland). This system is valid and reliable for the assessment of the external and internal load of soccer players (Scott et al., 2016; Akyildiz et al., 2022). Units were mounted with adjustable straps on the front of participants' chests. The variables of the external load included total distance covered (TDC), number of accelerations (ACC), number of decelerations (DEC), maximal speed (MSP), and distance covered in speed zones. These zones were categorized as follows: low-speed running (LSR = 0.70–6.99 km h^{-1}), medium-speed running (MSR = 7–13.99 km h^{-1}), high-speed running (HSR = 14–20.99 km h^{-1}), and very high-speed running (VHSR; >21 km h^{-1}). Accelerations and decelerations were characterized as low to moderate intensity (LMACC and LMDEC; 1–2.99 m s^{-2}), and high-intensity (HACC and HDEC; >3 m s^{-2}). Internal load variables included absolute heart rate (HR_{avg}) and relative heart rate (%HR_{avg}). Relative HR zones were categorized as <59%, 60%–69%, 70%–79%, 80%–89%, and >90% HR_{max} (%). Relative HR percentages were calculated using the equation 208 – 0.7 × age (Tanaka et al., 2001; Nikolaidis, 2014).

2.4.2 Subjective perception of fatigue

Participants were individually asked to evaluate their subjective perception of fatigue prior to and after the SSG by marking a vertical line on the 100-mm visual analog scale of fatigue (VAS-F). This type of assessment was previously found valid and reliable for assessing the subjective perception of fatigue (Lee et al., 1991). The scale was anchored with the words "no fatigue" on the left end, and "extremely fatigued" on the right end. The VAS-F score in an arbitrary unit (A.U.) was determined as the distance in millimeters from the left end to the marked vertical line (Abbasi et al., 2018).

2.4.3 Countermovement jump

The countermovement jump (CMJ) height was assessed using a portable optical system OptoGait (Microgate, Bolzano, Italy). Participants were instructed to lower their body to a squat position with a knee joint at approximately 90° and jump as high as possible without stopping in a lower position while keeping their hands on their waist (Bosco et al., 1983). They were also asked to avoid lateral and frontal movements and to keep their legs straight during the flight and landing phases. Since CMJ was precisely described in the familiarization session, the highest values of two jumps prior to and after the SSG were analyzed. Jumps were separated by 30-s rest periods. Sufficient reliability was reported when assessing two repetitions of jump height using the same device as in our study (ICC = 0.97; CV = 5.1%) (Krzysztofik et al., 2021).

2.4.4 Y-shaped agility tests

A single light-based timing system Witty GATE and LED indicator Witty SEM (Microgate, Bolzano, Italy) were used to evaluate participants' reactive agility (RA) time. This test is valid and reliable for the assessment of agility in team sports players (Oliver and Meyers, 2009; Horníková et al., 2021). All gates were set up in 1.2-m height and width of 1.5-m. Participants started approximately 0.3-m behind the starting gate. They were instructed to sprint straight and change the direction of running through the gate made of cones which was 5-m apart from the starting gate. A LED indicator in front of the subject (i.e., 3-m apart from the cone gate) randomly displayed a green arrow to the left or right after 500-ms since passing the starting gate. Participants responded to this signal by running to the arrow-pointing gate. The final gates were located 5-m apart from the middle gate at 45° angles. In case of execution errors (e.g., fall, slide, run to the incorrect gate), they were allowed to repeat the trial. Participants performed three pre-SSG trials with 30 s of rest between the repetitions and two post-SSG trials. The fastest trials prior to and after the SSG were analyzed.

The planned agility (PA) time was evaluated by an identical setup as the Y-shaped reactive agility test, excluding the visual signal. Participants were instructed to sprint to the particular gate before the beginning of this test. Two trials for each side with a 30-s rest were performed before the SSG. Post-SSG trials were performed twice. The sides of post-SSG trials were selected based on the stimuli generated in the previously performed reactive agility test.

2.4.5 Go/no-go task

Perceptual cognitive performance was evaluated using a customized computer-based response inhibition task. The Go/no-go task (GNG) was performed through the online software Psytoolkit v3.4.1 (Stoet, 2010; 2017). Testing consisted of one set of 20 familiarization trials, followed by one set before the SSG, and one set after the SSG. Each set included 50 randomly generated trials with a correct:error response ratio of 4:1. Fixation point was presented for 1000-ms in the center of a 13-inch computer screen. Presentations of go/no-go signals were separated by a 1000-ms interstimulus pause. Signals were shown as a green/red silhouette of a soccer player with a white "GO"/"NO-GO" symbol written in the middle of the image. Participants were instructed to press a spacebar button as soon as the green "go" signal appeared and to suppress the "no-go" signal. In case of an error, a pause of 2000-ms was included before the next fixation. The mean "go" trials response time in milliseconds (GNGt) and the number of trials with an error of commission (GNGe) were recorded as outcome measures. Trials with a response time of less than 150-ms were excluded from the analysis (Zhao et al., 2015).

2.5 Statistical analysis

Data are presented as mean ± SD. The coefficient of variation (CV%) and 90% confidence intervals (CI 90%) were calculated to describe the physiological response of players to the SSG and the kinematic profile in the SSG. The normality of data distribution was determined using the Shapiro-Wilk test. In the case of normal data distribution, the paired-sample *t*-test was performed. Otherwise, the Wilcoxon signed rank test was performed. Significance was set at $p < 0.05$ (2-tailed). The smallest worthwhile change was calculated as between subjects' SD multiplied by 0.2 (Tomczak and Tomczak, 2014). 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 was $1 - \beta = 0.604$ with $\alpha = 0.05$. To compensate for the lower sample size power, additional methods were used. The effect sizes for Hedges' g were as follows: <0.2 trivial; 0.2–0.5 small; 0.5–0.8 moderate; >0.8 large effect. The Cohens' r (r_c) for non-parametrical data was as follows: <0.1 small; 0.3–0.5 moderate; >0.5 large effect size. Uncertainties in the true effects of the respective conditions were evaluated by magnitude-based inferences using customized spreadsheets. Magnitudes of clear effect were considered according to the following scale: 25%–75%, possibly; 75%–95% likely; 95%–99%, very likely; >99% most likely (Hopkins, 2007). Differences in the pre- and post-SSG performance variables were expressed as the mean of individual differences (Δ = post-SSG–pre-SSG). Associations between individual performance changes (Δ) and exercise load variables were reported using the Pearson/Spearman correlation coefficient (r/r_s) with lower and upper confidence intervals (90%). The correlation strength was interpreted as follows: r/r_s = <0.1, trivial; 0.1–0.3, small; 0.31–0.49, moderate; 0.5–0.69, large; 0.7–0.89, very large; and 0.9–1, perfect correlation. Additionally, the amount of explained variance (R^2) was determined for the parametric data (Hopkins et al., 2009). Statistical analyses were performed using Graph Pad Prism

TABLE 2 Physiological response and kinematic profiles of players in the SSG protocol.

	MEAN	SD (±)	CI (90%)	CV (%)
HR_{avg} (bpm⁻¹)	171.71	7.15	169, 175.5	4.2
HR_{avg} (%)	86.57	3.64	85, 88.3	4.2
TDC (m)	2,753	175.29	2,674, 2,834	6.4
TDC (m/min)	91.79	5.92	89.1, 94.5	6.4
<59% HR_{max} (%)	9.10	8.77	4.66, 13.7	96.4
60%–69% HR_{max} (%)	3.83	3.32	2.09, 5.57	87.7
70%–79% HR_{max} (%)	12.34	3.24	10.64, 14.04	26.3
80%–89% HR_{max} (%)	29.00	11.35	23.04, 34.97	43.43
>90% HR_{max} (%)	45.85	17.99	36.4, 55.29	43.52
LSR (m)	1,101	102.78	1,055, 1,148	9.3
MSR (m)	1,250	159.53	1,178, 1,322	12.8
HSR (m)	379	74.30	346.4, 425.9	19.6
VHSR (m)	13.50	11.57	8.3, 18.8	85.7
LMACC (n)	171.88	14.91	164.5, 180.7	8.7
HACC (n)	5.43	2.33	4.4, 6.4	42.9
LMDEC (n)	172.63	18.47	165.4, 178.5	10.7
HDEC (n)	9.75	4.89	7.9, 12.1	50.2
MSP (km/h)	22.32	1.53	21.49, 23.12	6.9

CI (90%), 90% lower and upper confidence intervals; CV%, coefficient of variation; HR_{avg} (bpm⁻¹), average heart rate; HR_{avg} (%), average heart rate from maximum; HR_{max} (%), time spent in respective heart rate zone; TDC (m), total distance covered; TDC (m/min), relative total distance covered; LSR, low-speed running (0–6.99 km/h); MSR, medium-speed running (7–13.99 km/h); HSR, high-speed running (14–20.99 km/h); VHSR, very high-speed running (>21 km/h); LMACC, low to moderate accelerations (1–2.99 m/s); LMDEC, low to moderate decelerations (1–2.99 m/s); HACC, high-intensity accelerations (>3 m/s); HDEC, high-intensity decelerations (>3 m/s); MSP, maximal speed achieved during SSG.

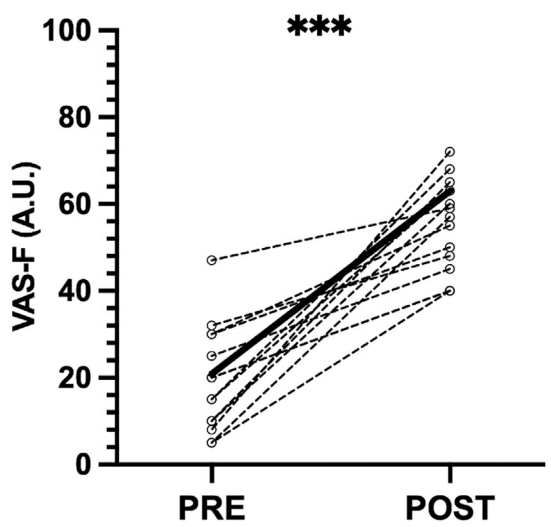

FIGURE 2
Individual pre- and post-SSG differences in perceived fatigue. Circles connected with dashed line indicate the individual data of each participant; black bold line indicates mean values. Significant changes between pre- and post-SSG assessment. ***$p < 0.001$. VAS-F, visual analog scale of fatigue.

software 9.5.0 (Graph Pad Software, San Diego, CA, United States).

3 Results

The subjective perception of fatigue (VAS-F) increased after the SSG (41.56 ± 14.02 A.U, $p = .001$, g = 4.15, large effect; Figure 2). The internal and external load variables measured during SSG are shown in Table 2.

3.1 Neuromuscular and perceptual-cognitive response to SSG

After the SSG, a CMJ height decreased (−6.65% ± 6.23%, $p = .014$, g = .56, moderate effect, Table 3; Figure 3A), PA time (4.04% ± 2.53%, $p = .002$, most likely, g = .97, large effect, Table 3; Figure 3B), and RA time increased (6.45% ± 7.37%, $p = .003$, likely, g = 1.16, large effect, Table 3; Figure 3C). The response time in the GNG task did not change after the SSG (−3.36% ± 8.04%, $p = .119$, g = .29, small effect, Table 3; Figure 4A), whereas errors of commission increased (87.10% ± 138.99%, $p = .023$, $r_c = .57$, moderate effect, Table 3; Figure 4B).

TABLE 3 Pre- and post-SSG neuromuscular and perceptual-cognitive performance differences.

	PRE-SSG	POST-SSG	Δ MEAN	CI (90%)	SWC	Δ %	MBI	p	ES
VAS-F (A.U.)	21.31 ± 11.12	62.88 ± 9.87	41.56 ± 14.02	26.56, 43.44	2.80	41.56 ± 14.02	100/0/0 Most likely	<.001	4.15[a]
GNGt (ms)	366.73 ± 34.24	354.4 ± 38.9	−12.34 ± 28.63	−25.11, 0.73	5.89	−3.36 ± 8.04	1.4/18.7/79.9 Possibly	.119	.29[a]
GNGe (n)	0.93 ± 1.14	1.71 ± 1.48	0.81 ± 1.13	0.30, 1.32	0.28	87.10 ± 138.99	92.7/7.3/0.1 Likely	.023	.57[b]
CMJ (cm)	29.70 ± 3.65	27.72 ± 3.34	−1.98 ± 1.85	−2.85, −1.12	0.37	−6.65 ± 6.23	0.2/1.8/97.9 Likely	.014	.56[a]
PA (s)	1.98 ± 0.07	2.06 ± 0.09	0.08 ± 0.05	0.05, 0.10	0.02	4.04 ± 2.53	99.8/0.1/0 Most likely	.002	.97[a]
RA (s)	2.17 ± 0.11	2.31 ± 0.13	0.14 ± 0.16	0.06, 0.22	0.03	6.45 ± 7.37	99.2/0.8/0 Most likely	.003	1.16[a]

CI (90%), lower and upper confidence intervals; SWC, the smallest worthwhile change; Δ %, the percentual difference between pre- and post-SSG, measurements; MBI, magnitude based interference; p, statistical significance; ES, effect size (a, Hedges' g; b, Cohens' r); VAS-F, visual analog scale of fatigue; GNGt, average Go/No-go task response time to "go" stimuli; GNGe, number of errors in Go/No-go task; CMJ, countermovement jump height; PA, planned agility time; RA, reactive agility time.

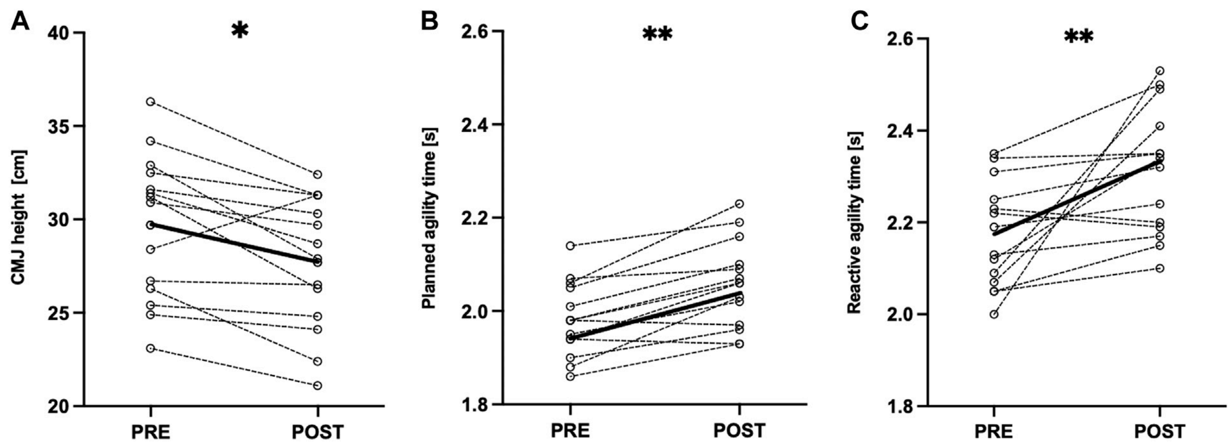

FIGURE 3
Individual pre- and post-SSG differences in **(A)** countermovement jump height; **(B)** planned agility time; **(C)** reactive agility time. Circles connected with dashed line indicate the individual data of each participant; black bold line indicates mean values. Significant changes between pre- and post-SSG assessments. *$p < 0.05$; **$p < 0.01$.

3.2 Relationship between changes in performance and exercise load

Significant correlations were found between ΔCMJ height and VHSR ($r_s = .660, p = .006$), ΔCMJ height and MSP ($r = .536, p = .032, R^2 = .286$), ΔPA time and HACC ($r_s = -.764, p = .002$), ΔRA time and VHSR ($r_s = -.501, p = .022$), and ΔRA time and MSP ($r = -.524, p = .037$). In addition, ΔGNG errors correlated significantly with absolute and relative TDC ($r = -.576, p = .021$; $r = -.631, p = .009$; respectively), and ΔGNG response time with MSR ($r = -.596, p = .015, R^2 = .319$). Moderate, large, and very large correlations between performance differences (Δ) and respective exercise load are shown in Table 4.

4 Discussion

As shown, exercise load in SSG leads to a significant increase in youth players' subjective perception of fatigue. Considering fatigue as a multifactorial process, it may interfere with physical, mental, metabolic, morphological, and biochemical alterations, among others (Mohr et al., 2005). The exercise load included in the SSG

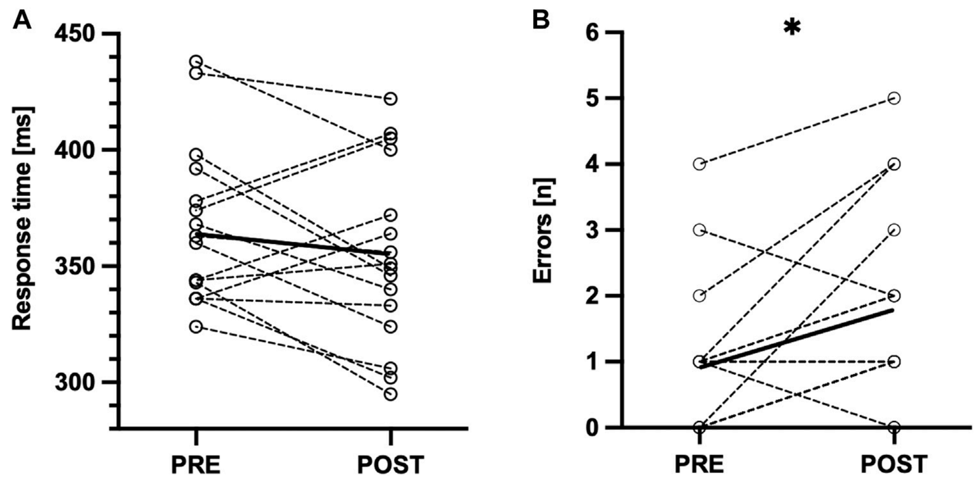

FIGURE 4
Individual pre- and post-SSG differences in Go/No-go task for **(A)** response time to "Go" stimuli; **(B)** incorrect responses to "No-go" stimuli. $*p < 0.05$.

led to changes in the neuromuscular and perceptual-cognitive performance of youth soccer players. More specifically, their explosive strength, planned and reactive agility, and accuracy in the response inhibition task were significantly affected by the 30-min SSG 4v4 protocol. These deteriorations were not significantly associated with neither internal nor external load variables. However, a less pronounced drop in agility performance and explosive strength after SSG was related to some variables of external load such as HACC, VHSR, and MSP. This indicates that the high-intensity efforts performed during the SSG could, to some extent, compensate for their decrements in youth soccer players. The deterioration of reactive agility and accuracy in response inhibition task points to the fact that SSG affects not only neuromuscular but also sensory and cognitive components of players' motor performance.

4.1 Effects of SSG on neuromuscular performance

Neuromuscular performance was affected by SSG in terms of decreased CMJ height and increased PA time. These reductions can be ascribed to players' high mechanical load in SSGs produced by numerous changes in speed and direction. This requires the eccentric strength of knee extensors to reduce movement velocity in the deceleration phase, and concentric strength in the acceleration phase (Jones et al., 2009). Repeated muscle contractions produce muscle damage which may temporarily decrease players' force production (Greig and Siegler, 2009; Thorlund et al., 2009). In addition, the fast transition from concentric to the eccentric phase of movement relies on a muscle and tendon complex utilizing a stretch-shortening cycle (Nicol et al., 2006). Fatigue induced by mechanical load alters the neuromuscular activation patterns of human skeletal muscle (Gollhofer et al., 1987). Thus, the observed declines in CMJ height (−6.65%) are in agreement with Rebelo et al. (2016) who reported decreased CMJ height (−9.4%) after two sets of three repetitions of 6-min SSG 4v4. Bujalance-Moreno et al. (2020) applied four 4-min game intervals separated by 2-min passive recoveries between the bouts. Significant changes were observed in the linear 20-m sprint time (1.3%) but not in the 5-m sprint and CMJ height. A different result could be explained by a lower overall work time in the SSG protocol compared to ours.

Furthermore, repeated high-intensity efforts tend to decrease the power generated by hamstring and gluteal muscle groups (Small et al., 2010; Edouard et al., 2018) and affect the change of direction speed by impaired lower-limbs biomechanics (Cortes et al., 2012). These presumptions point to the increments of PA and RA times, which were observed in our study (4.04% and 6.45%; respectively). It is suggested that neuromuscular performance decrease is likely associated with the number of accelerations and decelerations. However, we did not find significant relationships between the number of high-intensity accelerations and decelerations with neither CMJ height nor PA time deterioration. On the other hand, moderate correlations were observed in low to moderate intensity decelerations with ΔCMJ height ($r = -.376$) and ΔPA time ($r = .481$). This may be ascribed to 4v4 SSGs' pitch dimensions which do not allow players to cover enough high-intensity distances and perform high-intensity accelerations and decelerations.

It needs to be stated that SSGs are adjustable in load variables, e.g., number of players, pitch size, rules, or work/rest duration (Sarmento et al., 2018). These factors influence the internal and external load of players (Hill-Haas et al., 2011), resulting in their differential response. Specifically, one study suggested that small formats of SSG (i.e., 1v1 and 3v3) do not have a significant impact on the lower limb power in CMJ. Even though these players surpassed our subjects in the relative distance covered in the game (m/min^{-1}) and the internal load ($\%HR_{max}$), probably a short exercise duration could not produce a sufficient external load to induce neuromuscular fatigue (Clemente et al., 2017). A lower number of repetitions and longer resting periods compensate for players' neuromuscular performance decrement. This can also be achieved by reducing the pitch size of SSGs (Castillo et al., 2019). The question

TABLE 4 Correlations and simple linear regressions between the exercise load variables and the performance differences (Δ). Only moderate correlations are reported.

Dependent variable	Independent variable	r	p	CI (90%)	R^2	SE
ΔCMJ	TDC (m)	.379[a]	.148	−.14, .74	.144	.028
	TDC (m/min)	.392[a]	.132	−.13, .74	.154	.836
	HSR	.384[a]	.142	−.14, .73	.147	.096
	VHSR	.660[b]	.006	.22, .88	—	—
	LMDEC	−.376[a]	.151	−.44, .53	.141	.951
	MSP	.536[a]	.032	−.05, .88	.286	.066
ΔGNGt	TDC (m)	−.323[a]	.223	−.71, .20	.104	.032
	TDC (m/min)	−.333[a]	.207	−71, 19	.111	.583
	LSR	.402[a]	.123	−.12, .75	.162	.038
	MSR	−.596[a]	.015	−.85, −.15	.319	.141
	LMACC	−.410[b]	.111	−.75, .10	—	—
	LMDEC	−.392[a]	.201	−.73, .16	.154	.016
	70%–79% HR_{max}	−.345[a]	.191	−.18, .72	.119	.038
	>90% HR_{max}	−.338[a]	.064	−.19, .71	.114	.041
ΔGNGe	TDC (m)	−.576[b]	.021	−.84, .10	—	—
	TDC (m/min)	−.631[b]	.009	−71, 19	—	—
	MSR	−.374[b]	.076	−.74, .17	—	—
	HSR	−.456[b]	.076	−.78, .07	—	—
	VHSR	−.370[b]	.159	−.74, .17	—	—
	HDEC	−.353[b]	.180	−.73, .19	—	—
	LMDEC	−.337[b]	.201	−72, .21	—	—
	MSP	−.531[b]	.053	−.82, .03	—	—
ΔPA	HACC	−.764[b]	.002	−.87, −.21	—	—
	LMDEC	.481[a]	.099	.09, .76	.230	.090
ΔRA	<59% HR_{max}	.439[a]	.258	−.44, .55	.193	.078
	VHSR	−.501[b]	.022	−.32, .64	—	—
	MSP	−.524[a]	.037	−.81, −.04	.275	.214

ΔCMJ, countermovement jump height; ΔPA, planned agility time; ΔRA, reactive agility time; ΔGNGt, average Go/No-go task response time to "go" stimuli; Δ GNGe, number of errors in Go/No-go task; TDC (m), total distance covered; TDC (m/min), relative total distance covered; HR_{max} (%), time spent in respective heart rate zone; LSR, low-speed running (0–6.99 km/h); MSR, medium-speed running (7–13.99 km/h); HSR, high-speed running (14–20.99 km/h); VHSR, very high-speed running (>21 km/h); LMACC, low to moderate accelerations (1–2.99 m/s); LMDEC, low to moderate decelerations (1–2.99 m/s^2); HACC, high-intensity accelerations (>3 m/s); HDEC, high-intensity decelerations (>3 m/s); MSP, maximal speed achieved during SSG (km/h); r, correlation coefficient (a, Pearson's correlation coefficient; b, Spearman's correlation coefficient); p, level of significance; CI (90%), lower and upper confidence intervals; R^2, the amount of variance explained; SE, standard error of regression coefficient.

remains whether declines in reactive agility and perceptual-cognitive performance can be compensated as well.

4.2 Effects of SSG on perceptual-cognitive performance

A slight decline in players' response time (−3.36%, n.s.) but a significant increase in errors of commission (87.1%) was observed in the response inhibition task. SSGs engage players' physical and mental effort in an open-skill and dynamic environment (Owen et al., 2012; Mitrotasios et al., 2021). Therefore, some aspects of cognition are affected by sport-specific exercises as well. Previously, an improved inhibitory control was found in primary school children after the high-intensity SSG (Lind et al., 2019). Exercise-induced arousal improves a choice reaction time (Kashihara and Nakahara, 2005), but it can simultaneously affect object detection in sport-specific tasks (Klatt and Smeeton, 2021). These findings support our results, as youth soccer players react to visual stimuli slightly faster but less accurately after the SSG.

Intermittent exercise induces changes in perceptual-cognitive processes in both high- and low-level soccer players (Casanova et al., 2013). These temporal cognitive declines are often ascribed to the hypothesis of hypofrontality. For the maintenance of motor functions, the brain is limiting its resources to movement centers, causing less activation in centers responsible for higher-order cognitive functions (Dietrich, 2006). However, the lack of advanced neuroimaging tools available for use in sport-specific conditions does not allow us to reveal these changes. More evident is the role of mental fatigue and its impairment of decision-making, the tactical aspect of performance, and the skill execution in elite athletes (Russell et al., 2019). It has been shown that even a 20-min intermittent soccer-specific exercise produces mental fatigue in well-trained soccer players (Bian et al., 2022). However, research needs to shed light on the inducement of mental fatigue by SSGs.

Cognition also plays an important role in reactive agility performance (Young et al., 2015). It is suggested that reactive and planned agility differentiate under fatigue conditions (Ciocca et al., 2022). This may be corroborated by our results with the largest effect size for ΔRA time (6.45%, g = 1.16). Both the Y-shaped reactive agility test and the go/no-go task partly focus on the assessment of decision-making ability. This ability is often evaluated in soccer by the analysis of in-game successful passing (i.e., decision-making index) which tends to decrease with an increasing volume of exercise (Mitrotasios et al., 2021) and additional inducement of mental fatigue before SSG (Fortes et al., 2019; Gantois et al., 2020). Our results confirm that changes in perceptual-cognitive performance occur in response to sport-specific exercise load. However, the current literature deals with the lack of information about the effects of exercise on reactive agility while preferring more conventional methods of planned agility assessments (Marqués-Jiménez et al., 2022; Bilić et al., 2023).

4.3 Relationship between load variables and performance changes

No single robust variable of SSG load was related to neuromuscular nor perceptual-cognitive performance declines in youth soccer players. In the case of external load, only a ΔPA time was moderately correlated with the amount of LMDEC. This resulted in a 23% proportion of variance in ΔPA time increase. It can be assumed that players in our study were not able to cover enough high-intensity distance and perform high-intensity accelerations or decelerations, which would point to these variables as the most contributing to respective performance declines. From the perspective of internal load, time spent in <59% HR_{max} moderately correlated with ΔRA time by a 19% proportion of variance. The discovered relationships did not fully reveal the contribution of exercise load to the observed declines in neuromuscular and perceptual-cognitive performance.

Previously, a significant association was found between CMJ height decline and high-intensity activities in SSG 4v4 (Rebelo et al., 2016). Similar associations were presented in relation to the amount of external load in soccer matches (Rampinini et al., 2011; Silva et al., 2013; Rowell et al., 2017). Since SSGs 4v4 can relatively overload the mechanical work accumulated in a soccer match (Lacome et al., 2018), similar associations were expected to be found in our case. As mentioned above, we did not confirm these presumptions. Soccer games also include barely detectable high-power actions without a change in the location of players, such as jumping or duels (Dalen et al., 2016). However, our findings can be related to the fact that amateur and professional players' kinematic profiles in SSGs differ in the amount of high-intensity actions (Dellal et al., 2011). Additionally, no correlation was reported between changes in linear sprint performances and the rate of perceived exertion registered during the four different 5v5 SSG protocols (Castillo et al., 2019). It is also suggested that interindividual differences exist between the perceived effort and the lactate responses of players during SSGs (Köklü et al., 2015). In accordance with our results, the evaluation of youth players' level of fatigue or the response to exercise should incorporate more than subjective assessment methods.

From the perspective of external load, players who achieved a higher VHSR distance and MSP in SSG tend to show a lesser drop in the ΔCMJ height. Similarly, a correlation of HACC with ΔPA time, and ΔRA time with VHSR was found. A slight compensatory effect occurred in players who were able to achieve very high-speed running and high-intensity accelerations. The same was true for the total distance covered in SSG and the errors in the response inhibition task. In fact, the usage of SSG, usually in warp-ups, can also have positive effects on CMJ and reactive agility performance (Zois et al., 2011). Temporally enhanced performance can be explained by athletes' physiological response to physical exercise in terms of increased muscle temperature and blood flow, increased neural activation, and improved force-velocity relationship (Binkhorst et al., 1977; Sale, 2002). The lack of correlation in the case of perceptual-cognitive and reactive agility performance with load variables would be attributed to the complexity of SSGs as they engage humans' motor, sensory, and cognitive systems (Owen et al., 2012; Figueira et al., 2019). Therefore, it seems unlikely to reveal a single variable that would interfere with cognitive performance declines solely from load tracking data or subjective assessment of players.

Nevertheless, this study has some limitations. Heterogeneity in study protocols, the performance level or age of participants makes it difficult to compare our results with the findings of other authors. In addition, there is a variance in the assessment procedures regarding to agility and perceptual-cognitive performance testing. Larger sample sizes and consideration of the growth and maturity levels of players should bring a more profound understanding of the acute effects of SSGs on reactive agility and perceptual-cognitive performance. The novel objective cognitive function evaluation methods could provide evidence to support temporal cognitive changes in response to acute bouts of sport-specific exercises. Since the mental effort of sport-specific tasks is often neglected, research would develop a method that counts physical and psychological exertion of players in these tasks. Practitioners could better estimate the load of sport-specific exercises, players' level of fatigue, and thereby optimize the exercise load in training microcycles.

5 Conclusion

Fatigue induced by SSG has the most negative effect on reactive agility, followed by planned agility, and explosive strength in youth soccer players. It also affects decision-making in response inhibition task rather than speed of response to visual stimuli. There are no significant relationships between the external load variables and neuromuscular performance declines. The accuracy of decision-making is not affected by the internal load. Interestingly, high-intensity actions performed during SSG (i.e., very high-speed running, high-intensity accelerations) partially compensate for fatigue-induced declines in agility and explosive strength. Since load variables and the visual analog scale of fatigue were not able to fully reveal changes in players' performance, further research should aim to develop a method for assessing both the physical and cognitive components of exercise load in sport-specific tasks, which would also reflect players' level of fatigue. Consequently, besides the acute neuromuscular performance declines, less accurate decision-making and slower change of direction speed in response to visual stimuli can be expected after the application of SSG 4v4 in training.

5.1 Practical applications

We suggest using the SSG 4v4 and its numerous modifications to target players' agility and decision-making ability. However, practitioners should be aware of subsequent acute performance declines in the planning of the training structure. These declines are hardly detectable by the available load tracking systems and subjective methods. The application of SSGs with a relatively high work-to-rest ratio must be manipulated with caution for youth soccer players.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Ethics committee of the Faculty of Physical Education and Sport, Comenius University in Bratislava (no. 3/2022, date: 22. September 2022). 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

FS: Writing–original draft, Writing–review and editing. EZ: 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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References

Abbasi, A. M., Motamedzade, M., Aliabadi, M., Golmohammadi, R., and Tapak, L. (2018). Study of the physiological and mental health effects caused by exposure to low-frequency noise in a simulated control room. *Build. Acoust.* 25, 233–248. doi:10.1177/1351010X18779518

Akyildiz, Z., Yildiz, M., and Clemente, F. M. (2022). The reliability and accuracy of Polar Team Pro GPS units. *Proc. Inst. Mech. Eng. Part P J. Sport. Eng. Technol.* 236, 83–89. doi:10.1177/1754337120976660

Almonroeder, T. G., Tighe, S. M., Miller, T. M., and Lanning, C. R. (2020). The influence of fatigue on decision-making in athletes: a systematic review. *Sport. Biomech.* 19, 76–89. doi:10.1080/14763141.2018.1472798

Bian, C., Ali, A., Nassis, G. P., and Li, Y. (2022). Repeated interval loughborough soccer passing tests: an ecologically valid motor task to induce mental fatigue in soccer. *Front. Physiol.* 12, 803528. doi:10.3389/fphys.2021.803528

Bilić, Z., Sinković, F., Barbaros, P., Novak, D., and Zemkova, E. (2023). Exercise-induced fatigue impairs change of direction performance and serve precision among young male tennis players. *Sports* 11, 111. doi:10.3390/sports11060111

Binkhorst, R. A., Hoofd, L., and Vissers, A. C. A. (1977). Temperature and force velocity relationship of human muscles. *J.Appl.Physiol.Respir.Environ.Exercise Physiol.* 42, 471–475. doi:10.1152/jappl.1977.42.4.471

Bosco, C., Luhtanen, P., and Komi, P. V. (1983). A simple method for measurement of mechanical power in jumping. *Eur. J. Appl. Physiol. Occup. Physiol.* 50, 273–282. doi:10.1007/BF00422166

Branquinho, L., Ferraz, R., and Marques, M. C. (2021b). 5-a-Side game as a tool for the coach in soccer training. *Strength Cond. J.* 43, 96–108. doi:10.1519/SSC.0000000000000629

Branquinho, L., Ferraz, R., Travassos, B., Marinho, D. A., and Marques, M. C. (2021a). Effects of different recovery times on internal and external load during small-sided games in soccer. *Sports Health* 13, 324–331. doi:10.1177/1941738121995469

Bujalance-Moreno, P., Latorre-Román, P. A., Ramírez-Campillo, R., Martínez-Amat, A., and García-Pinillos, F. (2020). Acute responses to 4 vs. 4 small-sided games in football players. *Kinesiology* 52, 46–53. doi:10.26582/k.52.1.7

Calderón Pellegrino, G., Paredes-Hernández, V., Sánchez-Sánchez, J., García-Unanue, J., and Gallardo, L. (2020). Effect of the fatigue on the physical performance in different small-sided games in elite football players. *J. Strength Cond. Res.* 34, 2338–2346. doi:10.1519/JSC.0000000000002858

Casanova, F., Garganta, J., Silva, G., Alves, A., Oliveira, J., and Williams, A. M. (2013). Effects of prolonged intermittent exercise on perceptual-cognitive processes. *Med. Sci. Sports Exerc.* 45, 1610–1617. doi:10.1249/MSS.0b013e31828b2ce9

Castillo, D., Yanci, J., Sánchez-Díaz, S., and Raya-González, J. (2019). An approach to the fatigue in young soccer players resulting from sided games. *Sports* 7, 174. doi:10.3390/sports7070174

Ciocca, G., Tessitore, A., and Tschan, H. (2022). Agility and change-of-direction speed are two different abilities also during the execution of repeated trials and in fatigued conditions. *PLoS One* 17, e0269810. doi:10.1371/journal.pone.0269810

Clemente, F. M., Nikolaidis, P. T., Van Der Linden, C. M. I. N., and Silva, B. (2017). Effects of small-sided soccer games on internal and external load and lower limb power: a pilot study in collegiate players. *Hum. Mov.* 18, 50–57. doi:10.1515/humo-2017-0007

Cortes, N., Quammen, D., Lucci, S., Greska, E., and Onate, J. (2012). A functional agility short-term fatigue protocol changes lower extremity mechanics. *J. Sports Sci.* 30, 797–805. doi:10.1080/02640414.2012.671528

Dalen, T., Jørgen, I., Gertjan, E., Havard, H. G., and Ulrik, W. (2016). Player load, acceleration, and deceleration during forty-five competitive matches of elite soccer. *J. Strength Cond. Res.* 30, 351–359. doi:10.1519/JSC.0000000000001063

Del Giorno, J. M., Hall, E. E., O'Leary, K. C., Bixby, W. R., and Miller, P. C. (2010). Cognitive function during acute exercise: a test of the transient hypofrontality theory. *J. Sport Exerc. Psychol.* 32, 312–323. doi:10.1123/jsep.32.3.312

Dellal, A., Hill-Haas, S., Lago-Penas, C., and Chamari, K. (2011). Small-sided games in soccer: amateur vs. professional players' physiological responses, physical, and technical activities. *J. Strength Cond. Res.* 25, 2371–2381. doi:10.1519/JSC.0b013e3181fb4296

Dietrich, A. (2006). Transient hypofrontality as a mechanism for the psychological effects of exercise. *Psychiatry Res.* 145, 79–83. doi:10.1016/j.psychres.2005.07.033

Donnan, K. J., Williams, E. L., and Stanger, N. (2022). The effect of exercise-induced fatigue and heat exposure on soccer-specific decisionmaking during high-intensity intermittent exercise. *PLoS One* 17, e0279109. doi:10.1371/journal.pone.0279109

Dupuy, O., Billaut, F., Raymond, F., Benraiss, A., Theurot, D., Bosquet, L., et al. (2018). Effect of acute intermittent exercise on cognitive flexibility: the role of exercise intensity. *J. Cogn. Enhanc.* 2, 146–156. doi:10.1007/s41465-018-0078-z

Edouard, P., Mendiguchia, J., Lahti, J., Arnal, P. J., Gimenez, P., Jiménez-Reyes, P., et al. (2018). Sprint acceleration mechanics in fatigue conditions: compensatory role of gluteal muscles in horizontal force production and potential protection of hamstring muscles. *Front. Physiol.* 9, 1706. doi:10.3389/fphys.2018.01706

Falk, B., and Dotan, R. (2006). Child-adult differences in the recovery from high-intensity exercise. *Exerc. Sport Sci. Rev.* 34, 107–112. doi:10.1249/00003677-200607000-00004

Faude, O., Steffen, A., Kellmann, M., and Meyer, T. (2014). The effect of short-term interval training during the competitive season on physical fitness and signs of fatigue: a crossover trial in high-level youth football players. *Int. J. Sports Physiol. Perform.* 9, 936–944. doi:10.1123/ijspp.2013-0429

Figueira, B., Exel, J., Gonçalves, B., Masiulis, N., and Sampaio, J. (2019). Exploring new approaches to access cognitive demands in football small-sided games. *Mot. Suppl.* 15, 183.

Fortes, L. S., Lima-Junior, D., Nascimento-Júnior, J. R. A., Costa, E. C., Matta, M. O., and Ferreira, M. E. C. (2019). Effect of exposure time to smartphone apps on passing decision-making in male soccer athletes. *Psychol. Sport Exerc.* 44, 35–41. doi:10.1016/j.psychsport.2019.05.001

Frýbort, P., Kokštejn, J., Musálek, M., and Süss, V. (2016). Does physical loading affect the speed and accuracy of tactical decision-making in elite junior soccer players? *J. Sports Sci. Med.* 15, 320–326.

Gabbett, T. J. (2006). Skill-based conditioning games as an alternative to traditional conditioning for rugby league players. *J. Strength Cond. Res.* 20, 309–315. doi:10.1519/r-17655.1

Gaitanos, G. C., Williams, C., Boobis, L. H., and Brooks, S. (1993). Human muscle metabolism during intermittent maximal exercise. *J. Appl. Physiol.* 75, 712–719. doi:10.1152/jappl.1993.75.2.712

Gantois, P., Caputo Ferreira, M. E., Lima-Junior, D. de, Nakamura, F. Y., Batista, G. R., Fonseca, F. S., et al. (2020). Effects of mental fatigue on passing decision-making performance in professional soccer athletes. *Eur. J. Sport Sci.* 20, 534–543. doi:10.1080/17461391.2019.1656781

Gaudino, P., Alberti, G., and Iaia, F. M. (2014). Estimated metabolic and mechanical demands during different small-sided games in elite soccer players. *Hum. Mov. Sci.* 36, 123–133. doi:10.1016/j.humov.2014.05.006

Gollhofer, A., Komi, P. V., Miyashita, M., and Aura, O. (1987). Fatigue during stretch-shortening cycle exercises: changes in mechanical performance of human skeletal muscle. *Int. J. Sports Med.* 8, 71–78. doi:10.1055/s-2008-1025644

Greig, M., and Siegler, J. C. (2009). Soccer-specific fatigue and eccentric hamstrings muscle strength. *J. Athl. Train.* 44, 180–184. doi:10.4085/1062-6050-44.2.180

Hill-Haas, S., Rowsell, G., Coutts, A., and Dawson, B. (2008). The reproducibility of physiological responses and performance profiles of youth soccer players in small-sided games. *Int. J. Sports Physiol. Perform.* 3, 393–396. doi:10.1123/ijspp.3.3.393

Hill-Haas, S. V., Dawson, B., Impellizzeri, F. M., and Coutts, A. J. (2011). Physiology of small-sided games training in football: a systematic review. *Sport. Med.* 41, 199–220. doi:10.2165/11539740-000000000-00000

Hopkins, W. G. (2007). A spreadsheet for deriving a confidence interval, mechanistic inference and clinical inference from a p value. *Sportscience* 11, 16–20.

Hopkins, W. G., Marshall, S. W., Batterham, A. M., and Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med. Sci. Sports Exerc.* 41, 3–13. doi:10.1249/MSS.0b013e31818cb278

Horníková, H., Jeleň, M., and Zemková, E. (2021). Determinants of reactive agility in tests with different demands on sensory and motor components in handball players. *Appl. Sci.* 11, 6531. doi:10.3390/app11146531

Jones, P., Bampouras, T. M., and Marrin, K. (2009). An investigation into the physical determinants of change of direction speed. *J. Sports Med. Phys. Fit.* 49, 97–104.

Kashihara, K., and Nakahara, Y. (2005). Short-term effect of physical exercise at lactate threshold on choice reaction time. *Percept. Mot. Ski.* 100, 275–291. doi:10.2466/PMS.100.2.275-291

Katis, A., and Kellis, E. (2009). Effects of small-sided games on physical conditioning and performance in young soccer players. *J. Sport. Sci. Med.* 8, 374–380.

Klatt, S., and Smeeton, N. J. (2021). Attentional and perceptual capabilities are affected by high physical load in a simulated soccer decision-making task. *Sport. exerc. Perform. Psychol.* 10, 205–216. doi:10.1037/spy0000228

Klatt, S., and Smeeton, N. J. (2022). Processing visual information in elite junior soccer players: effects of chronological age and training experience on visual perception, attention, and decision making. *Eur. J. Sport Sci.* 22, 600–609. doi:10.1080/17461391.2021.1887366

Köklü, Y., Sert, Ö., Alemdaroılu, U., and Arslan, Y. (2015). Comparison of the physiological responses and time-motion characteristics of young soccer players in small-sided games: the effect of goalkeeper. *J. Strength Cond. Res.* 29, 964–971. doi:10.1519/JSC.0b013e3182a744a1

Krzysztofik, M., Kalinowski, R., Trybulski, R., Filip-Stachnik, A., and Stastny, P. (2021). Enhancement of countermovement jump performance using a heavy load with velocity-loss repetition control in female volleyball players. *Int. J. Environ. Res. Public Health* 18, 11530. doi:10.3390/ijerph182111530

Lacome, M., Simpson, B. M., Cholley, Y., Lambert, P., and Buchheit, M. (2018). Small-sided games in elite soccer: does one size fit all? *Int. J. Sports Physiol. Perform.* 13, 568–576. doi:10.1123/ijspp.2017-0214

Lee, K. A., Hicks, G., and Nino-Murcia, G. (1991). Validity and reliability of a scale to assess fatigue. *Psychiatry Res.* 36, 291–298. doi:10.1016/0165-1781(91)90027-M

Lind, R. R., Beck, M. M., Wikman, J., Malarski, K., Krustrup, P., Lundbye-Jensen, J., et al. (2019). Acute high-intensity football games can improve children's inhibitory control and neurophysiological measures of attention. *Scand. J. Med. Sci. Sport.* 29, 1546–1562. doi:10.1111/sms.13485

Marqués-Jiménez, D., Calleja-González, J., Arratibel-Imaz, I., and Terrados, N. (2022). Match loads may predict neuromuscular fatigue and intermittent-running endurance capacity decrement after a soccer match. *Int. J. Environ. Res. Public Health* 19, 15390. doi:10.3390/ijerph192215390

Martínez-Serrano, A., Freitas, T. T., Franquesa, X., Enrich, E., Mallol, M., and Alcaraz, P. E. (2023). Does external load reflect acute neuromuscular fatigue and rating of perceived exertion in elite young soccer players? *J. Strength Cond. Res.* 37, E1–e7. doi:10.1519/JSC.0000000000004296

McMorris, T., Collard, K., Corbett, J., Dicks, M., and Swain, J. P. (2008). A test of the catecholamines hypothesis for an acute exercise-cognition interaction. *Pharmacol. Biochem. Behav.* 89, 106–115. doi:10.1016/j.pbb.2007.11.007

Mitrotasios, M., Christofilakis, O., Armatas, V., and Apostolidis, N. (2021). The impact of small-sided games on cognitive fatigue and decision-making ability of elite youth soccer players. *Facta Univ. Ser. Phys. Educ. Sport* 19, 139–153. doi:10.22190/FUPES210216018M

Mohr, M., Krustrup, P., and Bangsbo, J. (2005). Fatigue in soccer: a brief review. *J. Sports Sci.* 23, 593–599. doi:10.1080/02640410400021286

Moore, R. D., Romine, M. W., O'connor, P. J., and Tomporowski, P. D. (2012). The influence of exercise-induced fatigue on cognitive function. *J. Sports Sci.* 30, 841–850. doi:10.1080/02640414.2012.675083

Nicol, C., Avela, J., and Komi, P. V. (2006). The stretch-shortening cycle: a model to study naturally occurring neuromuscular fatigue. *Sport. Med.* 36, 977–999. doi:10.2165/00007256-200636110-00004

Nikolaidis, P. (2014). Age-predicted vs. measured maximal heart rate in young team sport athletes. *Niger. Med. J.* 55, 314–320. doi:10.4103/0300-1652.137192

Nygaard Falch, H., Guldteig Rædergård, H., and van den Tillaar, R. (2019). Effect of different physical training forms on change of direction ability: a systematic review and meta-analysis. *Sport. Med. - Open* 5, 53. doi:10.1186/s40798-019-0223-y

Oliver, J. L., and Meyers, R. W. (2009). Reliability and generality of measures of acceleration, planned agility, and reactive agility. *Int. J. Sports Physiol. Perform.* 4, 345–354. doi:10.1123/ijspp.4.3.345

Owen, A. L., Wong, D. P., Paul, D., and Dellal, A. (2012). Effects of a periodized small-sided game training intervention on physical performance in elite professional soccer. *J. Strength Cond. Res.* 26, 2748–2754. doi:10.1519/JSC.0b013e318242d2d1

Rampinini, E., Bishop, D., Marcora, S. M., Ferrari Bravo, D., Sassi, R., and Impellizzeri, F. M. (2007). Validity of simple field tests as indicators of match-related physical performance in top-level professional soccer players. *Int. J. Sports Med.* 28, 228–235. doi:10.1055/s-2006-924340

Rampinini, E., Bosio, A., Ferraresi, I., Petruolo, A., Morelli, A., and Sassi, A. (2011). Match-related fatigue in soccer players. *Med. Sci. Sports Exerc.* 43, 2161–2170. doi:10.1249/MSS.0b013e31821e9c5c

Ratel, S., Duché, P., and Williams, C. A. (2006). Muscle fatigue during high-intensity exercise in children. *Sport. Med.* 36, 1031–1065. doi:10.2165/00007256-200636120-00004

Rebelo, A. N. C., Silva, P., Rago, V., Barreira, D., and Krustrup, P. (2016). Differences in strength and speed demands between 4v4 and 8v8 small-sided football games. *J. Sports Sci.* 34, 2246–2254. doi:10.1080/02640414.2016.1194527

Reilly, T., Drust, B., and Clarke, N. (2008). Muscle fatigue during football match-play. *Sport. Med.* 38, 357–367. doi:10.2165/00007256-200838050-00001

Rodrigues, M. C. J., Figueiredo, L. S., De Lira, C. A. B., Laporta, L., and Costa, G. D. C. T. (2022). Cognitive processes in small-sided games (Procesos cognitivos en pequeños juegos). *Retos* 44, 897–906. doi:10.47197/retos.v44i0.90369

Rowell, A. E., Aughey, R. J., Hopkins, W. G., Stewart, A. M., and Cormack, S. J. (2017). Identification of sensitive measures of recovery after external load from football match play. *Int. J. Sports Physiol. Perform.* 12, 969–976. doi:10.1123/ijspp.2016-0522

Russell, S., Jenkins, D., Rynne, S., Halson, S. L., and Kelly, V. (2019). What is mental fatigue in elite sport? Perceptions from athletes and staff. *Eur. J. Sport Sci.* 19, 1367–1376. doi:10.1080/17461391.2019.1618397

Sale, D. G. (2002). Postactivation potentiation: role in human performance. *Exerc. Sport Sci. Rev.* 30, 138–143. doi:10.1097/00003677-200207000-00008

Sarmento, H., Clemente, F. M., Harper, L. D., Costa, I. T. da, Owen, A., and Figueiredo, A. J. (2018). Small sided games in soccer–a systematic review. *Int. J. Perform. Anal. Sport* 18, 693–749. doi:10.1080/24748668.2018.1517288

Scott, M. T. U., Scott, T. J., and Kelly, V. G. (2016). The validity and reliability of global positioning systems in team sport: a brief review. *J. Strength Cond. Res.* 30, 1470–1490. doi:10.1519/JSC.0000000000001221

Silva, J. R., Ascensão, A., Marques, F., Seabra, A., Rebelo, A., and Magalhães, J. (2013). Neuromuscular function, hormonal and redox status and muscle damage of professional soccer players after a high-level competitive match. *Eur. J. Appl. Physiol.* 113, 2193–2201. doi:10.1007/s00421-013-2633-8

Silva, J. R., Rumpf, M. C., Hertzog, M., Castagna, C., Farooq, A., Girard, O., et al. (2018). Acute and residual soccer match-related fatigue: a systematic review and meta-analysis. *Sport. Med.* 48, 539–583. doi:10.1007/s40279-017-0798-8

Skala, F., and Zemková, E. (2022). Effects of acute fatigue on cognitive performance in team sport players: does it change the way they perform? A scoping review. *Appl. Sci.* 12, 1736. doi:10.3390/app12031736

Small, K., McNaughton, L., Greig, M., and Lovell, R. (2010). The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. *J. Sci. Med. Sport* 13, 120–125. doi:10.1016/j.jsams.2008.08.005

Stoet, G. (2010). PsyToolkit: a software package for programming psychological experiments using Linux. *Behav. Res. Methods* 42, 1096–1104. doi:10.3758/BRM.42.4.1096

Stoet, G. (2017). PsyToolkit: a novel web-based method for running online questionnaires and reaction-time experiments. *Teach. Psychol.* 44, 24–31. doi:10.1177/0098628316677643

Tanaka, H., Monahan, K. D., and Seals, D. R. (2001). Age-predicted maximal heart rate revisited. *J. Am. Coll. Cardiol.* 37, 153–156. doi:10.1016/S0735-1097(00)01054-8

Teoldo, I., Dambroz, F., and González-Víllora, S. (2022). Exploring the effects of physical fatigue on cognitive performance of youth soccer players. *Int. J. Sport Exerc. Psychol.* 2022, 1–16. doi:10.1080/1612197X.2022.2134437

Thorlund, J. B., Aagaard, P., and Madsen, K. (2009). Rapid muscle force capacity changes after soccer match play. *Int. J. Sports Med.* 30, 273–278. doi:10.1055/s-0028-1104587

Tomczak, M., and Tomczak, E. (2014). The need to report effect size estimates revisited. An overview of some recommended measures of effect size. *Trends Sport Sci.* 1, 19–25.

Tomporowski, P. D. (2003). Effects of acute bouts of exercise on cognition. *Acta Psychol. (Amst).* 112, 297–324. doi:10.1016/s0001-6918(02)00134-8

Torrents, C., Ric, A., Hristovski, R., Torres-Ronda, L., Vicente, E., and Sampaio, J. (2016). Emergence of exploratory, technical and tactical behavior in small-sided soccer games when manipulating the number of teammates and opponents. *PLoS One* 11, e0168866. doi:10.1371/journal.pone.0168866

Young, W. B., Dawson, B., and Henry, G. J. (2015). Agility and change-of-direction speed are independent skills: implications for training for agility in invasion sports. *Int. J. Sport. Sci. Coach.* 10, 159–169. doi:10.1260/1747-9541.10.1.159

Zhao, X., Chen, L., Fu, L., and Maes, J. H. R. (2015). Wesley says: a children's response inhibition playground training game yields preliminary evidence of transfer effects. *Front. Psychol.* 6, 207. doi:10.3389/fpsyg.2015.00207

Zois, J., Bishop, D. J., Ball, K., and Aughey, R. J. (2011). High-intensity warm-ups elicit superior performance to a current soccer warm-up routine. *J. Sci. Med. Sport* 14, 522–528. doi:10.1016/j.jsams.2011.03.012

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A 10-week FIFA 11+ program improves the short-sprint and modified agility T-test performance in elite seven-a-side soccer players

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Objective: The primary objective of this study was to assess the effects of 10 weeks of FIFA 11+ training on the physical performance of elite seven-a-side soccer players.

Methods: Twenty-five seven-a-side soccer players were recruited from two senior national teams. The players completed the following protocols during 10 weeks of training: a) FIFA 11+: The FIFA group (*n* = 13) underwent the FIFA 11+ program combined with regular soccer training; b) Dynamic conventional warm-up: The control group (*n* = 12) underwent regular soccer training. Their ability was validated using a pre-test followed by a post-test to measure the sprint performance (5-, 10-, and 20-m sprints), a modified agility T-test (MAT), and a five-jump test (FJT).

Results: A comparison of pre- and post-tests for physical performance in each group demonstrated that the FIFA 11+ warm-up significantly improved the 10-m sprinting performance ($p = 0.034$; $F = 5.04$; $\eta_p^2 = 0.17$) and reduced the time spent to perform the MAT ($p = 0.000$; $F = 23.16$; $\eta_p^2 = 0.52$) in the FIFA group compared with the control group; however, no significant changes were observed in the 5- and 20-m sprints and FJT.

Conclusion: The main findings of this research showed that the 10-week FIFA 11+ program led to significant improvements in the 10-m sprint and MAT compared to regular training among elite seven-a-side soccer players. Given these positive outcomes, further studies on the practical implementation and optimization of the FIFA 11+ program are warranted to provide valuable guidance for coaches and athletes, seeking to maximize its benefits in real-world settings.

KEYWORDS

physical performance, warm-up, sprint times, soccer, training program, horizontal jump

1 Introduction

Soccer is a team sport that encompasses a wide range of physical demands, including short and long sprints, agility, rapid changes in direction, tackling, jumping, and kicking the ball (Haycraft et al., 2017; Seyedi et al., 2023). Consequently, it garners significant attention from researchers and practitioners, aiming to optimize training methods and techniques for enhanced physical performance (Miguel et al., 2021; Torres-Ronda et al., 2022; Ammann et al., 2023). In this context, the development of effective warm-up programs, which prepare soccer players for these challenges, holds paramount importance (Fort-Vanmeerhaeghe et al., 2016).

The FIFA 11+ program has emerged as one such preparatory training program designed specifically for soccer players (Franchina et al., 2023). Endorsed by the International Federation of Football Association (FIFA), it incorporates various cardiovascular and neuromuscular activities aimed at promoting body control, neuromuscular coordination, and postural stability during physical and athletic exercises (Steffen et al., 2013; Franchina et al., 2023). The program comprises 15 exercises grouped into three sections: 1) running exercises with stretching and co-worker contacts; 2) exercises that focus on core and leg strength, agility, and plyometric training; and 3) advanced running exercises and change-of-direction speed (Seyedi et al., 2023).

Compared to other warm-up approaches, the FIFA 11+ program offers several distinct advantages. First, it does not require any additional or specific equipment, making it easily accessible for coaches and players (Bizzini et al., 2013). Additionally, studies have demonstrated that the FIFA 11+ program can elicit acute improvements in performance, including a reduction in 20-m sprint time, an increase in jump height, and improved agility compared to dynamic warm-ups (Bizzini et al., 2013; Pomares-Noguera et al., 2018). Moreover, in addition to its potential benefits for neuromuscular control (Impellizzeri et al., 2013), the FIFA 11+ program also leads to similar improvements in resting oxygen uptake, core temperature, and lactate levels when used as conventional warm-ups, indicating its effectiveness in preparing players for the physical demands of the game (Pomares-Noguera et al., 2018).

An essential benefit of the FIFA 11+ program lies in its established effectiveness in mitigating the incidence of sports-related injuries, notably those affecting the lower extremities, including knee injuries (Owoeye et al., 2014; Silvers-Granelli et al., 2015; Al Attar et al., 2021; Miguel et al., 2021). This reduction in injury incidence is attributed to improvements in the neuromuscular control of the trunk and lower limb achieved through the regular implementation of the FIFA 11+ program (Daneshjoo et al., 2012). It has been suggested that the high neural demand of plyometric training (e.g., countermovement jump for maximum height and double-leg hops in different directions) included in FIFA 11+ can provide a stimulus that aligns with proliferation in neural coordination and central nervous system maturation, notably observed during pre-pubescence (Lloyd et al., 2016). Additionally, athletes who participate in FIFA 11+ benefit not only from neurophysiological adaptations but also from dynamic correspondence, specifically in terms of horizontal force production vectors, which contribute to improved performance (Arede et al., 2022).

However, no studies have investigated the effectiveness of the "FIFA 11+" warm-up. It is well known that a sufficient warm-up is able to improve the performance and reduce the injury risk (Bizzini et al., 2013). With this background and in detail, we consider the following main targeted physiological factors: an increase in muscle and core temperature, anaerobic metabolism, nerve conduction rate, blood flow, and oxygen delivery to muscles (Bishop, 2003). The dynamic exercises that are covered by "FIFA 11+" are potentially enough to induce physiological modifications suitable for an appropriate warm-up. This warm-up protocol has been the subject of several studies in numerous age groups (Neto et al., 2017). Some encouraging findings from a randomized controlled trial suggested that the FIFA 11+ program may be helpful in producing a significant improvement in vertical jump and change-of-direction speed among 9–11-year-old female soccer players (Parsons et al., 2019). However, despite the number of studies exploring the chronic effects of FIFA 11+ on some measures of physical performance (Daneshjoo et al., 2012; Impellizzeri et al., 2013; Steffen et al., 2013), postural stability, sprinting, and jumping ability (Daneshjoo et al., 2013; Impellizzeri et al., 2013), the findings of the literature are conflicting and hence not conclusive (Robles-Palazón et al., 2016). In addition, its short- or long-term effects on physical performance, especially in elite seven-a-side soccer players, remain relatively unexplored.

Therefore, the first aim of this present study was to evaluate the effects of 10-week FIFA 11+ on several physical performance measures (sprinting, jumping, and change-of-direction speed) in elite seven-a-side soccer players, in order to find out whether this program can be considered an appropriate warm-up routine for soccer players. The second aim was to compare the effects of the 10-week FIFA 11+ warm-up in an experimental group and a regular warm-up in a control group on short sprint, change of direction, and horizontal jump performances in elite senior seven-a-side soccer players. Due to the lack of comparable reports, we propose the null hypothesis that there will be no difference in the physical performance tests between FIFA 11+ and regular warm-up programs.

2 Materials and methods

2.1 Sample of subjects

In this study, we conducted *a priori* power calculations using G*power software to determine the necessary sample size. The purpose of these calculations was to ensure that our study has a high probability (80%) of detecting a significant effect, given a 5% level of significance (alpha). In other words, we aimed to have a strong likelihood of identifying meaningful results if they exist in our data. The estimated effect size of 0.50 represents the magnitude of the difference we expect to observe between conditions. This value is crucial as it helps us gauge the practical significance of our findings. By performing these power calculations, we aimed to optimize the study's design and sample size, ensuring that our research can provide meaningful and statistically sound conclusions. Based on

TABLE 1 Characteristics of both groups (mean ± SEM, n = 25).

Group	Age (years)	Height (cm)	Body mass (kg)
Control	25.6 ± 1.25	179 ± 1.35	71.9 ± 2.07
FIFA	28.1 ± 0.79	178 ± 1.21	77.9 ± 2.30

G*Power, 12 participants per group for a total of 24 participants were needed. Participants included 25 soccer male athletes (FIFA group, n = 13; control group, n = 12) from two teams. The two teams were randomly allocated to the FIFA group and control group using the simple random sampling technique between the two teams using a coin flip (Melnyk and Morrison-Beedy, 2020). A unique identifier was assigned to each team (the two teams were labeled as the control group and FIFA group). In order to ensure the confidentiality of the randomization sequence, this process was conducted by another independent assessor researcher external to the study.

Based on the players' baseline characteristics including anthropometric data and the history of previous injuries, which were given by the medical staff (team physician and physiotherapist) for each individual player, none of the players suffered from any musculoskeletal disorders, and they were required not have been dependent on a medical procedure on the lower limb during 3 months prior to the study. The study involved participants from the first national championship soccer (Division-I), and it is important to clarify that the participants were seven-a-side professional soccer players. They underwent training sessions for 4–5 days a week (~90 min per session) and played one match over the weekend. All participants possessed more than 8 years of experience in soccer training and competition and took part in national championship at the time of investigation. The age and anthropometric characteristics (height and body mass) of the groups are listed in Table 1.

After randomization of the groups and before beginning the FIFA 11+ program, two soccer players were excluded because of leg injury.

The study adopts a pre-test–post-test control group character design with an intervention period of 12 weeks. Two teams were used (Figure 1): the FIFA group (n = 18), which is considered the experimental group, and the control group (CG; n = 14).

After randomization of the groups and during the intervention, five soccer players from the FIFA group and two players from the control group were injured. The FIFA group was then reduced to thirteen players, while the CG was reduced to twelve players.

2.2 Experimental design

Two weeks before the pre-test measurements, all subjects completed two familiarization trials of all procedures except the anthropometric characteristics. Subjects of the two groups (control and FIFA groups) performed measurements of speed (i.e., 5-, 10-, and 20-m sprints), modified agility T-test (MAT), and five-jump test (FJT) before and after training.

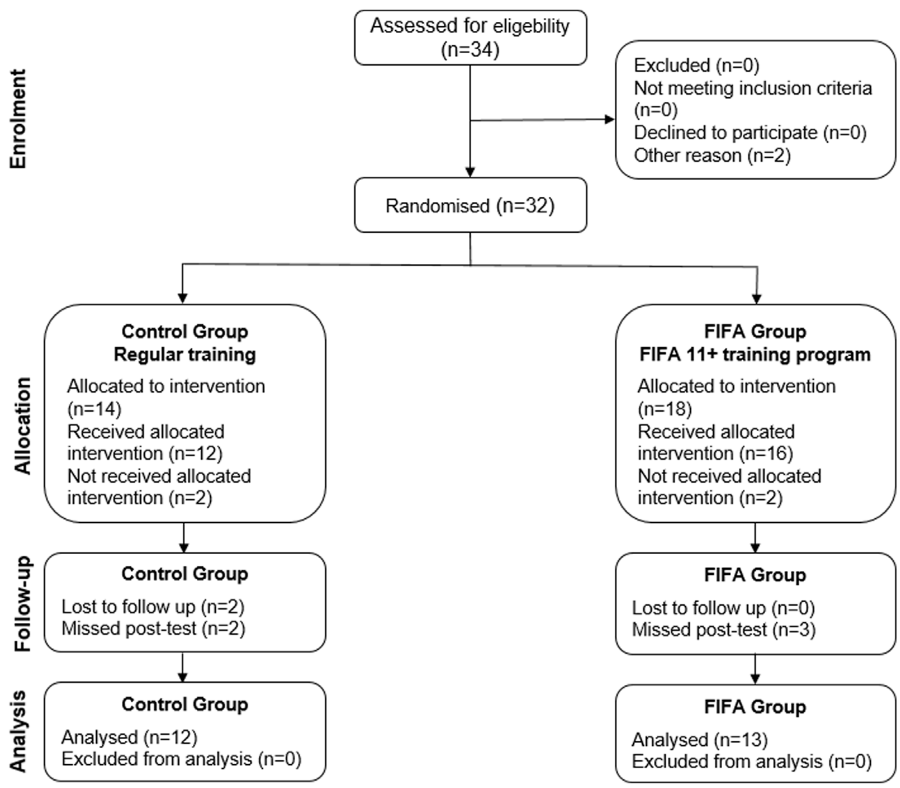

FIGURE 1
Consort diagram includes detailed information about the interventions received and the number of participants through each stage.

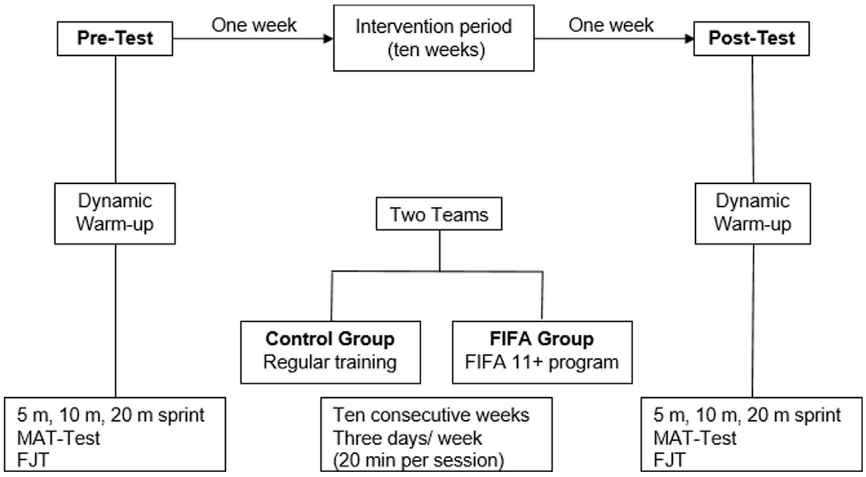

FIGURE 2
Schematic representation of the study design. R, randomization; FJT, five-jump test; MAT, modified agility T-test.

Pre- and post-tests were conducted over 2 days with an interval of 72 h between each session. The test measurements were completed using the same testing order for all performance tests on the same soccer field. The details of the study were explained to the participants by the researchers. All procedures were approved by the Manouba University Institutional Review Committee (Tunisia) for the ethical use of human participants and were conducted in accordance with the Declaration of Helsinki. The participants were informed that they were free to withdraw from the study at any time without penalty. Individual written consent was obtained from all participants after they had received both oral and written explanations of the experimental procedure and its possible risks and benefits.

The study was realized over a period of 12 weeks during January, February, and March as part of an official competitive season. To minimize the effects of circadian rhythms on performance, all sessions were conducted at the same time of the subjects' regular training session time (in the evenings) and at same temperature and humidity ranges (22°C–24°C and 38%–42%, respectively). After the completion of the pre-test, the control group participants were asked to continue their regular training (which consists of standard jogging, ball exercises, and whole-body stretching). In addition to regular training, the FIFA group performed the FIFA 11+ program three times a week, with a mean of 20 min per session. Three training sessions per week (~90 min per session) on different days (non-consecutive days) were performed. In addition, the participants played an official match per week.

The data collection involved a baseline phase followed by 10 weeks of the FIFA 11+ program and a final phase at the end of the FIFA 11+ program (Figure 2).

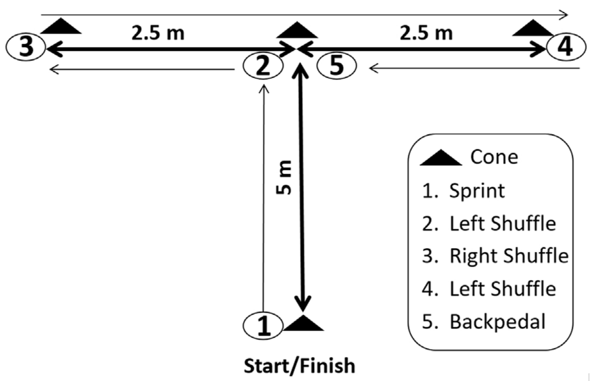

FIGURE 3
Modified agility T-test (MAT) showing the movement patterns which should be performed.

2.3 Testing procedures

2.3.1 Modified agility T-test (MAT)

The MAT was determined to examine the change-of-direction speed during forward sprinting, lateral leftward and lateral rightward shuffling, and back-pedaling (Sassi et al., 2009). A photocell system (Microgate, Bolzano, Italy) was used to measure the time. Each player performed two trials with at least 2-min rest between trials, and the best MAT time was used for the analysis. Subjects were instructed to begin the test with both feet placed on a marked line of 30 cm behind the starting gate (Mathisen and Danielsen, 2014) and 1) run as quickly as possible forward linear (5 m) to cone 2 and then touch its base with their right hand (Figure 3). 2) Next, facing forward and without crossing feet, they should sidestep to the left 2.5 m to cone 3 and touch its base with the left hand. Afterward, they must 3) sidestep to the right 5 m to cone 4, and touch its base with the right hand. Then, they should sidestep back 2.5 m to cone 2, touching its base and run back as quickly as possible toward the finish line (Figure 3; Sassi et al., 2009).

2.3.2 Sprint test

The 20-m sprint test was preceded by a standardized warm-up with two sub-maximal 20-m sprints. Four paired photocells

TABLE 2 "FIFA 11+": Exercises, duration, and intensities of the structured warm-up program used (F-MARC).

Exercise	Duration (min)
Part 1: Running Straight ahead, hip out, hip in, circling partner, shoulder contact, and quick forward and backward (six running items, each item performed in two sets)	8
Part 2: Strength and plyometric and postural stability The bench Static, alternate legs, and one leg lift and hold (three items, each item performed in three sets) Sideways bench Static, raise, and lower hip, with leg lift (three items, performed in three sets on each sides) Hamstring Beginner (3–5 repetitions, one set), intermediate (7–10 repetitions, one set), and advanced (12–15 repetitions, one set) (three items) Single-leg stance Hold the ball, throwing the ball to the partner, and test your partner (three items, each item performed in two sets) Squats With toe raise, walking lunges, and one-leg squats (three items, each item performed in two sets) Jumping Vertical jumps, lateral jumps, and box jumps (three items, each item performed in two sets)	10
Part 3: Running exercise Across the pitch, bounding, plant, and cut (three items, each item performed in two sets)	2

(Microgate, Bolzano, Italy) were used and positioned in a straight line at distances of 0, 5, 10, and 20 m along the course. The paired photocells, separated by a distance of 1.5 m (Yeadon et al., 1999), were located 1 m above the ground at the starting and finishing lines. The first sprint was started 30 cm behind the starting photocell gate, and time measurement started when the subject traversed the first gate. Players performed two maximal 20-m sprints, and the best performance was used for the statistical analysis. Times over 5, 10, and 20 m were recorded. A 5–8-min rest interval of recovery was allowed between the two trials, and the fastest time for each distance was retained to be analyzed.

2.3.3 Five-jump test (FJT)

This test was used to evaluate player's lower limb explosive power. For the FJT, each player should perform, from an upright standing position, five forward jumps by alternating left- and right-leg ground contacts and tried to cover a maximal distance. At the start of the FJT, each player with joined feet had the choice to select which foot to put first. Distances covered when performing the five-jump test were measured using a tape measure (Ayed et al., 2020).

2.4 Training program

The weekly soccer training regimen was followed by both teams (three 90-min sessions per week and one match per week). The study assistants paid both teams a visit at least once per week to verify whether the groups did the suggested soccer training with a regular warm-up. The same weekly soccer training regimen was followed by both teams with three 90-min sessions per week and one match per week. The training including FIFA 11+ was conducted by the habitual coach of the FIFA group (i.e., the same coach of the team) after identifying and presenting the FIFA 11+ program and completing two familiarization trials of all procedures. The FIFA 11+ warm-up comprised a program with a total duration of 20 min and included three levels of difficulty, which depends on the athletes' age and their physical aptitude. Therefore, level II of difficulty, which was completed during the familiarization sessions, was chosen for this study. It consists of three parts (Impellizzeri et al., 2013). The first part consists of running exercises; the second part focuses on core and leg strength, balance, and plyometric/agility; and the third part includes running exercise combined with direction changes (cutting movements). In this research, during the experimental period, the FIFA group followed the third and the hardest level, while the control group performed their usual soccer training, as applied by Trajković et al. (2020) (Table 2).

2.5 Data analysis

Data are presented as the mean ± standard error of the mean (SEM). SPSS version 28.0 for Windows (IBM, Armonk, NY, United States) was used for all statistical analyses. Normality distribution was determined using the Shapiro–Wilk test ($p < 0.05$). Moreover, the sphericity and homogeneity were checked using Mauchly's and Levene's tests, respectively. The effects of the interventions on the physical parameters were analyzed using a 2 × 2 (control and FIFA groups x pre- and post-test) two-way repeated measures analysis of variance (ANOVA). Test–retest reliability was established using the intraclass correlation coefficient (ICC). The absolute reliability, measured by the coefficient of variation (CV%), was calculated by dividing the SEM and the sum of the average attempts and multiplied by 100 (Macadam et al., 2017). The interpretation of the ICC values was based on Shrout and Fleiss (1979). The ICC was considered to show excellent relative reliability (inter-subject variability) when >0.75, fair to good when 0.40–0.75, and poor when <0.40. The CV can be

TABLE 3 Descriptive statistics (mean ± SEM) for sprint (5, 10, 20 m), modified agility T-test (MAT), and five-jump test (FJT) performance. Relevant mean differences ($\eta_p^2 \geq 0.14$) marked in bold.

Test	Control group mean ± SEM (s)		FIFA group mean ± SEM (s)		Group			Time			time * group		
	Pre-test	Post-test	Pre-test	Post-test	F	p	η_p^2	F	p	η_p^2	F	p	η_p^2
5-m sprint	1.08 ± 0.02	1.09 ± 0.01	1.14 ± 0.02	1.10 ± 0.02	0.40	0.53	0.02	0.68	0.42	0.03	0.09	0.77	0.01
10-m sprint	1.81 ± 0.03	1.87 ± 0.02	1.95 ± 0.18	1.88 ± 0.06	5.04	0.03	0.17	4.02	0.06	0.14	1.40	0.25	0.05
20-m sprint	3.13 ± 0.03	3.18 ± 0.03	3.22 ± 0.04	3.24 ± 0.03	4.23	0.05	0.15	3.21	0.09	0.12	0.01	0.92	0.00
MAT	6.57 ± 0.07	6.22 ± 0.13	6.43 ± 0.13	5.51 ± 0.08	23.2	<0.001	0.52	20.1	<0.001	0.49	1.01	0.33	0.05
FJT	11.6 ± 0.10	11.6 ± 0.12	11.3 ± 0.20	11.5 ± 0.22	0.89	0.46	0.02	0.88	0.36	0.03	0.45	0.51	0.02

SEM: standard error of measurement; η_p^2: partial eta-squared.
Time: This is an independent variable, and it represents two different time points—pre-test and post-test. These time points were used to measure changes over time in the study.

defined as good with values <10% (Brughelli and Van Leemputte, 2013). The statistical significance was set at $p < 0.05$. Effect size, presented by partial eta-squared (η_p^2), was determined to assess the magnitude of the effects (Macadam et al., 2017). Partial eta-squared (η_p^2) was chosen because it is particularly suitable for assessing the proportion of variance explained by each factor while accounting for the interactions among factors and the impact of covariates. The more independent the variables included in the model, the less accurate the use of the eta-squared compared to the partial eta-squared. The use of this effect size aligns with the classification provided by Cohen (1988): $0.01 < \eta_p^2 < 0.06$ (small effect), $0.06 < \eta_p^2 < 0.14$ (medium effect), and $\eta_p^2 \geq 0.14$ (large effect).

3 Results

At baseline, there were no significant differences in the anthropometric characteristics and physical performance parameters between the groups ($p \geq 0.05$). Mean repeated measure indices displayed strong inter-trial (ICC = 0.86–0.94; CV %: 4.5–7.0) and intersession reliability (ICC = 0.89–0.95; CV%: 2–14). A coefficient of variation (CV%) ranging between 4.5% and 7% is generally considered quite favorable when assessing reliability. The goal of having a CV of less than 10% to denote reliability is widely accepted within the scientific community (Turner et al., 2015), which suggests that our study exhibits relatively low variability in relation to the mean. This means that the measurements are relatively consistent and precise. The differences between pre- and post-tests in the FIFA 11+ warm-up were determined for different performance variables in each group. The results demonstrated that the FIFA 11+ warm-up significantly improves the 10-m sprinting performance in the FIFA group. In fact, the time performance was significantly reduced from 1.95 ± 0.05 s to 1.88 ± 0.08 s for the 10-m sprint ($p = 0.034$; F = 5.04; $\eta_p^2 = 0.17$). However, no significant changes were observed for the 5-m ($p = 0.531$; F = 0.68; $\eta_p^2 = 0.03$) and 20-m sprints ($p = 0.051$; F = 4.23; $\eta_p^2 = 0.15$).

Furthermore, the time spent to perform the MAT was significantly reduced in the FIFA group from 6.43 ± 0.47 s to 5.51 ± 0.27 s ($p < 0.001$; F = 23.16; $\eta_p^2 = 0.52$) in the post-test compared to that observed in the pre-test (Table 3). The differences observed in the pre- and post-tests for the remaining studied physical performance parameters for the FIFA 11+ program (5- and 20-m sprints and FJT) were not significant. However, no significant effect was observed between the values of pre- and post-tests in the control group who underwent the habitual training program (Table 3).

4 Discussion

The aim of this study was to investigate the effects of the FIFA 11+ warm-up program over a 10-week period on the physical performance of elite seven-a-side soccer players. The results of our study indicated that after completing the program for 10 weeks, certain physical performance parameters, such as the 10-m sprints and the MAT, showed significant improvements as a result of the training stimuli provided by the FIFA 11+ program.

The observed effects of the FIFA 11+ program on physical performance were generally in the range of moderate to substantial, and they align with findings commonly reported in the existing literature. Numerous studies have reported improvements in various physical performance variables in soccer players following the implementation of the FIFA 11+ program. These improvements encompass a wide range of aspects. In particular, Daneshjoo et al. (2013) and Kilding et al. (2008) reported benefits in jumping height, 20-m sprint time, and Illinois agility tests compared to traditional warm-up routines. These improvements were observed in young male professional football players aged between 17 and 20 years (Daneshjoo et al., 2013) and preadolescent football players with an average age of 10.4 ± 1.4 years (Kilding et al., 2008). Both groups experienced these positive effects after participating in the FIFA 11+ program three times per week for 2 months.

Similarly, Ayala et al. (2017) noted significant improvements in sprinting speed, both in 10- and 20-m sprints, among young male amateur soccer players with an average age of 16.8 ± 0.7 years. These improvements were observed after the participants engaged in the FIFA 11+ program for 4 weeks, with three sessions per week. Furthermore, Arede et al. (2022) reported a significant decrease in 0–20-m sprint times and change-of-direction times in young male soccer players with an average age of 11.2 ± 0.7 years. These findings collectively suggest the positive impact of the FIFA 11+ program on various aspects of physical performance in different age groups of soccer players.

For a field sport athlete, the distance from 5 to 10 m in a sprint could be viewed as a transitionary period between initial acceleration and peak velocity. Training protocols that encourage high force production (i.e., weights or plyometric training) may be required to enhance performance in the transition from acceleration to maximum velocity in field sports (Lockie et al., 2012). Regarding our results, the significant improvement in the 10-m sprint performance after the FIFA 11+ program, without a corresponding significant improvement in the 5-m sprint, can be explained by the unique demands of these two sprint distances and the specific nature of the training protocols involved. In a sprint, the first 5 m typically involves initial acceleration (Lockie et al., 2012), where athletes need to generate quick bursts of speed from a stationary position. This phase relies heavily on explosive power and rapid acceleration, and it can be influenced by factors such as the strength of the leg muscles, coordination, and technique. It is during this phase that a high ground reaction force is critical. Therefore, it is possible that the FIFA 11+ program, while beneficial for the transition phase and peak velocity, may not specifically target the requirements of the 5-m sprint phase, which demands rapid acceleration. This could explain the absence of a significant improvement in the 5-m sprint, despite the improvements observed in the 10-m sprint.

The FIFA 11+ program, while effective in enhancing aspects of performance, may primarily focus on elements that benefit the transition from acceleration to maximum velocity, which often occurs in the 10-m phase of a sprint. This transition phase is different from the initial acceleration phase and places different demands on the athlete. It involves maintaining and increasing the speed, and it may benefit from the development of maximal strength, power, and neuromuscular coordination.

It seems that soccer players who participated in FIFA 11+ have demonstrated neurophysiological adaptations, as indicated by Arede et al. (2022). This study supports previous research suggesting that plyometric training is highly effective in improving short-to-medium sprinting times (under 20 m). Following plyometric training, sprint training emerges as the most effective method for further improving sprint times in participants at the pre-peak height velocity stage (Rumpf et al., 2012). Notably, the FIFA 11+ protocol incorporates sprinting-based activities, including 40-m sprints at 75%–80% of maximum speed, involving movements that utilize the stretch-shortening cycle. These activities have the potential to enhance an individual's rate of force development, impulse generation, and muscle stiffness—neurophysiological adaptations associated with optimized sprint performance (Haff and Triplett, 2016).

However, the lack of improvement in the FJT could be due to various factors, including the duration of the training program, the specific demands of these tests, and the individual responses of the athletes. It is possible that more extended or targeted training may be needed to obtain significant changes in longer sprints and explosive power measured by the FJT.

Additionally, the program has been associated with improvements in dynamic balance (Steffen et al., 2013), jump height (Blazevich and Babault, 2009), and muscle strength and power (Steffen et al., 2013). In direct comparisons to a standard dynamic warm-up, researchers have consistently observed enhancements in agility times and improved endurance of trunk muscles among participants who followed the FIFA 11+ program (Trajković et al., 2020). These findings collectively emphasize that the FIFA 11+ warm-up program effectively enhances various aspects of physical performance among soccer players.

However, in contrast to our findings, some studies have reported no improvements in several specific physical performance aspects relevant to soccer practice. Notably, our results regarding sprint tests contradicted the outcomes of previous studies conducted on male amateur soccer players aged 23.7 ± 3.7 years, specifically in the context of sprints (10 and 20 m) and the agility T-test (Impellizzeri et al., 2013). One potential explanation for these contradictory results could be the differing durations of the intervention phases within the training regimens used by the respective authors. For instance, Impellizzeri et al. (2013) found no significant improvement in sprint performance among professional soccer players following a 2-month FIFA 11+ training program that incorporated soccer-specific content. Similarly, after a 9-week period of implementing the FIFA 11+ program, Impellizzeri et al. (2013) reported comparable results among amateur soccer players. These variations in outcomes may be attributed to differences in the duration of the intervention programs and the specific content of the training, highlighting the importance of considering these factors when evaluating the impact of warm-up programs on physical performance in soccer players.

To assess this, the players substituted their regular warm-up routine with "FIFA 11+" three times a week for a total of 9 weeks. During the first 3 weeks, they followed level 1 of the program. In the following 3 weeks (weeks 4 to 6), they advanced to level 2, and in the last 3 weeks (weeks 7 to 9), they progressed to level 3. The post-test results of agility performance metrics in our study were consistent with the findings from other research studies (Zarei et al., 2018; Trajković et al., 2020). However, it is worth noting that some authors have reported that the Illinois agility test results remained unaffected by FIFA 11+ exercises, as demonstrated by Impellizzeri et al. (2013) and Lopes et al. (2019). It is important to recognize that while there is a relationship between the Illinois agility test and the modified T-test, there are key distinctions between the two tests. The MAT is not a continuous running test; instead, it involves multiple stopping and re-activation phases. This fundamental difference sets the T-test apart from the Illinois tests, as highlighted by Muniroglu and Subak, (2018).

An important argument to consider is that exercise-based injury prevention programs have the potential to improve relevant performance measures, as demonstrated by Maffulli et al. (2011). Existing evidence suggests that injury prevention programs can have beneficial effects on various performance parameters among soccer players. These effects encompass improvements in anaerobic power (Kilding et al., 2008; Daneshjoo et al., 2013), sprint performance (Kilding et al., 2008), neuromuscular control (Impellizzeri et al., 2013), and agility performance (Daneshjoo et al., 2013; Rössler et al., 2016).

The FIFA 11+ program has been shown to have potential benefits for neuromuscular control; however, Impellizzeri et al. (2013) noted that its impact on the overall athletic performance of soccer players may be limited. Notably, in their study, even though players undergoing the FIFA 11+ program tended to show improvements in the Illinois agility test and sprint performance only after 9 weeks, these improvements did not reach statistical significance (p for interaction 0.126 and 0.042, respectively). The absence of significant improvements in these performance measures could be attributed to the training stimulus provided by the FIFA 11+ program, which may have been insufficient in terms of both intensity and duration to elicit a notable response in the measured soccer performance parameters. Impellizzeri et al. (2013) suggested that while the amount of plyometric and agility training in the FIFA 11+ program might be adequate for enhancing neuromuscular control, it may fall short of the intensity typically employed to improve these aspects in soccer players, particularly through dedicated plyometric training. It is important to note that direct comparisons of the results of these studies with those of our current study should be done cautiously due to differences in study populations and the presence of various uncontrolled confounders, both experimentally and statistically, which may have influenced the outcomes.

Steffen et al. (2013) indicated that the lack of significant improvement in physical performance following the FIFA 11+ program could be attributed to several factors. One key factor is the relatively low intensity of the FIFA 11+ program itself compared to the high-intensity demands of soccer practice. In our study, we specifically used the second level of the FIFA 11+ program, which is designed to be more intensive than the first level but less intensive than the third level. While the second level represents an intermediate intensity option within the program, it is essential to note that the FIFA 11+ program offers a progression through three distinct levels to cater to various fitness levels and demands. This allows for flexibility in tailoring the warm-up to suit the needs of different groups of soccer players. The primary objective of the FIFA 11+ program is not necessarily to enhance physical performance but rather to familiarize players with proper movement techniques, methods, and body alignments to reduce the risk of injuries. In contrast, soccer practice typically involves intense physical activities that demand a high level of effort and performance from the players. As such, the FIFA 11+ program may not provide the same level of intensity and specificity required to significantly enhance athletic performance, especially in areas such as sprinting, agility, and explosive power. Therefore, it is important to recognize that the FIFA 11+ program primarily serves as a warm-up strategy. While it may have some positive effects on physical performance, its main focus is on reducing injury risk by promoting proper movement patterns and body alignments.

It is interesting to note that the sprint test results of amateur soccer players showed significant improvements only after 4 weeks of following the FIFA 11+ program, as reported by Ayala et al. (2017). This finding aligns with the outcomes of previous studies (Rössler et al., 2016; Panagoulis et al., 2020). In particular, Ayala et al. (2017) highlighted that amateur soccer players experienced notable enhancements in sprinting speed after engaging in the FIFA 11+ program for 4 weeks, with three sessions per week. This improvement in sprint performance is consistent with previous research that suggested the effectiveness of plyometric training in reducing short sprint times (typically less than 20 m), especially among athletes in the pre-peak height velocity stage (Wang and Zhang, 2016; Beato et al., 2018). Lloyd et al. (2016) previously found that plyometric training, which includes exercises such as double-leg hops in various directions and countermovement jumps for maximum height (similar to components of the FIFA 11+ program), can stimulate neural coordination and central nervous system maturation during the prepubescent stage. This neural demand and training stimulus may contribute to the observed improvements in sprinting performance among soccer players who undergo programs like the FIFA 11+ program.

The observed improvement in physical performance can be attributed to the specific characteristics of the FIFA 11+ program, which includes a range of exercises such as balancing, jumping, squatting, bounding, cutting, and muscle strength training. These exercises have the potential to improve various aspects of physical performance, including strength, neuromuscular recruitment, and muscle coordination (Chimera et al., 2004). These aspects of physical performance can play a significant role in improving leg power, speed, and agility.

The effectiveness of the FIFA 11+ program in enhancing athletic performance (particularly the 10-m sprint and the MAT) can be further understood in the context of plyometric exercises. As a rule, the more specific a plyometric exercise is to the stretch rate and load characteristics of the sport movement, the greater the transfer of the training effect to performance (Cormie et al., 2011; Sáez de Villarrea et al., 2012). Equally, in the FIFA 11+ program, there are some dynamic exercises, particularly in part 2, which may adequately optimize the neuromuscular system and improve proprioception, muscular activity, and joint stability (Hübscher et al., 2010). These underlying mechanisms are theorized to elicit specific adaptations in the neural drive, rate of neural activation, and inter-muscular control, which results in an improved rate of force development (Cormie et al., 2011). Additionally, the inclusion of sprinting, agility, and plyometric exercises alongside neuromuscular exercises in the FIFA 11+ program, which also emphasizes the importance of correct techniques in various movements (Impellizzeri et al., 2013; Akbari et al., 2019), aligns well with this principle.

The observed increase in core temperature following the FIFA 11+ warm-up, as reported by Zois et al. (2011), is indeed consistent with the improvements in various performance measures such as 20-m sprints, agility, vertical jump, and stiffness. However, we acknowledge that there are also adaptations not associated with temperature, such as post-activation potentiation (PAP), which can contribute to performance improvements. These findings are in line with similar studies (Mohr et al., 2004; Brown et al., 2008), which also indicated that warm-up routines can lead to enhanced performance. Another notable benefit of the FIFA 11+ warm-up is the increase in baseline VO_{2max}, as suggested by Bizzini et al. (2013). This increase in aerobic capacity may reduce the anaerobic contribution during the initial stages of subsequent exercises. By focusing on oxidative mechanisms at the beginning of the task, there is a potential reduction in the oxygen deficit and a decrease in the contribution of anaerobic energy sources necessary for subsequent anaerobic activities. These effects can contribute to an improved endurance related to the ability to recover during and after high-intensity efforts.

While our study identified a significant improvement within the FIFA group compared to baseline measurements, it is important to acknowledge the absence of a statistically significant difference between the FIFA group and the control group. This apparent lack of difference may be attributed to several factors that warrant consideration.

- **Small sample sizes:** Both groups had relatively small sample sizes (FIFA group, $n = 13$; control group, $n = 12$). This limited sample size may have reduced the statistical power to detect differences between the groups, even if true differences exist.
- **Baseline characteristics:** The participants in both groups had similar baseline characteristics, such as age, fitness level, and physical performance. The initial similarity between the two groups may have posed a challenge in detecting significant differences resulting from the intervention.
- **Variability within groups:** Despite significant improvements within the FIFA group, there may have been substantial variability or individual responses to the intervention. This within-group variability could have obscured the between-group differences. Some participants within the control group may naturally show improvements over time, and some within the intervention group may not respond as expected. This individual variability can make it challenging to observe significant differences at the group level.
- **Duration of intervention:** The duration and intensity of the FIFA group's intervention may not have been sufficient to generate significant differences between the groups during the study's timeframe. Longer or more intensive interventions might be required to observe notable effects.

While our study did not reveal statistically significant differences between the FIFA and control groups, the observed significant improvement within the FIFA group indicates that further investigation is warranted. Future research should aim to investigate the effects of longer-term applications of the FIFA 11+ program on a wide range of physical performance variables and soccer-related skills. These studies should employ randomized control trial designs to ensure rigorous scientific investigation. Additionally, it would be valuable to examine the impact of the FIFA 11+ program on the performance of young athletes, specifically considering their maturity status. Young athletes may respond differently to training interventions due to their developmental stage, and understanding these effects is crucial. Furthermore, future studies should seek to uncover the mechanisms underlying the observed reduction in injury incidence associated with the FIFA 11+ program. This could involve investigating the influences of the program on neuromuscular control, biomechanics, and other factors related to injury risk in various team sports, as suggested by Gomes Neto et al. (2017). By conducting well-designed and comprehensive research in these areas, we can further validate the improvements in physical performance associated with the FIFA 11+ program and gain a deeper understanding of the contribution of the program to reducing injuries in collective sports.

4.1 Strengths and limitations of the study

Despite this study being the first to be realized in elite seven-a-side soccer players, it remains unclear whether the current findings can reflect general data also for elite eleven-a-side soccer players or rather represent only a team of elite seven-a-side soccer players. This is why prudence must be taken when generalizing these results. Another important limitation was the small sample size used in both the control and experimental groups. In our study, a significant number of dropouts occurred primarily due to injuries that occurred during the intervention, particularly during weekend matches and training sessions. Participants were engaged in intensive training 4–5 days a week, in addition to participating in competitive weekend matches. The nature and frequency of these activities increased the likelihood of injuries. Consequently, five participants from the FIFA group and two from the control group were injured, leading to an imbalance in group sizes. This high dropout rate affected the statistical power of our study and may impact the findings. To address this limitation, we recommend that future research should explore strategies for mitigating injuries and dropouts, including more extensive injury prevention protocols and modified interventions. These recommendations are intended to enhance the quality and practicality of future studies. However, although the sample size that was recruited for this experiment was small, significant main effects were observed. The nature of the study is based on examining these variables at a specific point in time. However, further profiling studies of elite male and female youth soccer players are necessary in order to establish reference data about the long-term FIFA 11+ program. Future research studies should take this into account and attempt to follow changes in a reproducible manner over a long-term period.

5 Conclusion

The experimental research presented in this study has confirmed that the 10-week FIFA 11+ program led to notable improvements in the 10-m sprinting performance and reduced the time spent to perform the MAT, particularly among elite seven-a-side soccer players, when compared to regular training. These findings align with previous research studies, indicating the FIFA 11+ program as an effective training protocol for enhancing physical performance in soccer players. However, it is worth noting that some parameters, like the 5-m sprint and FJT (between-group analysis), did not show significant improvements, highlighting the complexity of performance enhancement.

In light of these outcomes, there is a compelling case for further studies that delve deeper into the practical implementation of the FIFA 11+ program in real-world soccer settings. These investigations should address various factors, including training frequency, duration, and adherence. Such research will provide valuable insights into how to maximize the benefits of this protocol while considering the multifaceted nature of physical performance in soccer. This balanced approach, addressing both its strengths and areas of non-improvement, will guide coaches and athletes in optimizing their training regimens for comprehensive performance enhancement.

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

All procedures were approved by the Manouba University Institutional Review Committee (Tunisia) for the ethical use of human participants and were conducted in accordance with the Declaration of Helsinki. 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

Conceptualization: BF and RA; methodology: BF; software: RA; validation: ML, RA, and BF; formal analysis: RA; investigation: ML; resources: ML; data curation: RA; writing–original draft preparation: RA; writing–review and editing: SH, RS, and TB; visualization: RS; supervision: RA; project administration: BF; funding acquisition: RS. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author TB was employed by MVZ Sports Clinic Halle GmbH.

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

Publisher's note

References

Akbari, H., Sahebozamani, M., Daneshjoo, A., Amiri-Khorasani, M., and Shimokochi, Y. (2019). Effect of the FIFA 11+ on landing patterns and baseline movement errors in elite male youth soccer players. *J. Sport Rehabil.* 29, 730–737. doi:10.1123/jsr.2018-0374

Al Attar, W. S. A., Faude, O., Bizzini, M., Alarifi, S., Alzahrani, H., Almalki, R. S., et al. (2021). The FIFA 11+ shoulder injury prevention program was effective in reducing upper extremity injuries among soccer goalkeepers: a randomized controlled trial. *Am. J. Sports Med.* 49, 2293–2300. doi:10.1177/03635465211021828

Ammann, L., Altmann, S., Ruf, L., and Sperlich, B. (2023). Seasonal analysis of match load in professional soccer players: an observational cohort study of a Swiss U18, U21 and first team. *Front. Physiol.* 13, 1023378. eCollection 2022. doi:10.3389/fphys.2022.1023378

Arede, J., Fernandes, J., Moran, J., Leite, N., Romero-Rodriguez, D., and Madruga-Parera, M. (2022). Effects of an integrative neuromuscular training protocol vs. FIFA 11+ on sprint, change of direction performance and inter-limb asymmetries in young soccer players. *Int. J. Sports Sci Coach.* 17, 54–62. doi:10.1177/17479541211011438

Ayala, F., Pomares-Noguera, C., Robles-Palazón, F. J., del Pilar García-Vaquero, M., Ruiz-Pérez, I., Hernández-Sánchez, S., et al. (2017). Training effects of the FIFA 11+ and harmoknee on several neuromuscular parameters of physical performance measures. *Int. J. Sports Med.* 38, 278–289. doi:10.1055/s-0042-121260

Ayed, K. B., Saad, H. B., Hammami, M. A., and Latiri, I. (2020). Relationships of the 5-jump test (5JT) performance of youth players with volleyball specific' laboratory tests for explosive power. *Am. J. Mens. Health* 14, 1557988320977686. doi:10.1177/1557988320977686

Beato, M., Bianchi, M., Coratella, G., Merlini, M., and Drust, B. (2018). Effects of plyometric and directional training on speed and jump performance in elite youth soccer players. *J. Strength Cond. Res.* 32, 289–296. doi:10.1519/JSC.0000000000002371

Bishop, D. (2003). Warm up I: potential mechanisms and the effects of passive warm up on exercise performance. *Sports Med.* 33, 439–454. doi:10.2165/00007256-200333060-00005

Bizzini, M., Junge, A., and Dvorak, J. (2013). Implementation of the FIFA 11+ football warm up program: how to approach and convince the Football associations to invest in prevention. *Br. J. Sports Med.* 47, 803–806. doi:10.1136/bjsports-2012-092124

Blazevich, A. J., and Babault, N. (2009). Post-activation potentiation versus post-activation performance enhancement in humans: historical perspective, underlying mechanisms, and current issues. *Front. Physiol.* 10, 1359. doi:10.3389/fphys.2019.01359

Brown, P. I., Hughes, M. G., and Tong, R. J. (2008). The effect of warm-up on high-intensity, intermittent running using nonmotorized treadmill ergometry. *J. Strength Cond. Res.* 22, 801–808. doi:10.1519/JSC.0b013e31816a5775

Brughelli, M., and Van Leemputte, M. (2013). Reliability of power output during eccentric sprint cycling. *J. Strength Cond. Res.* 27, 76–82. doi:10.1519/JSC.0b013e31824f2055

Chimera, N. J., Swanik, K. A., Swanik, C. B., and Straub, S. J. (2004). Effects of plyometric training on muscle-activation strategies and performance in female athletes. *J. Athl. Train.* 39, 24–31.

Cohen, J. (1988). "The effect size," in *Statistical power analysis for the behavioural sciences* (Abingdon, UK: Taylor & Francis), 77–83.

Cormie, P., McGuigan, M. R., and Newton, R. U. (2011). Developing maximal neuromuscular power: part 2 - training considerations for improving maximal power production. *Sports Med.* 41, 125–146. doi:10.2165/11538500-000000000-00000

Daneshjoo, A., Mokhtar, A. H., Rahnama, N., and Yusof, A. (2012). The effects of injury preventive warm-up programs on knee strength ratio 260 in young male professional soccer players. *PloS One* 261, e50979. doi:10.1371/journal.pone.0050979

Daneshjoo, A., Mokhtar, A. H., Rahnama, N., and Yusof, A. (2013). Effects of the11+and harmoknee warm-up programs on physical performance measures in professional soccer players. *J. Sports Sci. Med.* 12, 489–496.

Fort-Vanmeerhaeghe, A., Romero-Rodriguez, D., Kushner, A. M., Lloyd, R., and Myer, G. D. (2016). Integrative neuromuscular training in youth athletes. Part II: strategies to prevent injuries and improve performance. *Strength Cond. J.* 38, 9–27. doi:10.1519/SSC.0000000000000234

Franchina, M., Turati, M., Tercier, S., and Kwiatkowski, B. (2023). FIFA 11+ Kids: challenges in implementing a prevention program. *J.* Child. Orthop. 17, 22–27. doi:10.1177/18632521221149057

Gomes Neto, M., Conceicao, C. S., de Lima Brasileiro, A. J., de Sousa, C. S., Carvalho, V. O., and de Jesus, F. L. (2017). Effects of the FIFA 11 training program on injury prevention and performance in football players: a systematic review and meta-analysis. *Clin. Rehabil.* 31, 651–659. doi:10.1177/0269215516675906

Haff, G. G., and Triplett, T. (2016). *Essentials of strength training and conditioning.* 4th ed. Champaign. Illinois Illinois: Human Kinetics Publishers Inc. Country of Publication: United States.

Haycraft, J. A. Z., Kovalchik, S., Pyne, D. B., and Robertson, S. (2017). Physical characteristics of players within the Australian Football League participation pathways: a systematic review. *Sports Med. - Open* 3, 46. doi:10.1186/s40798-017-0109-9

Hill, A. V. (1927). *Living machinery.* New York: Harcourt, Brace and World Inc.

Hübscher, M., Zech, A., Pfeifer, K., Hänsel, F., Vogt, L., and Banzer, W. (2010). Neuromuscular training for sports injury prevention: a systematic review. *Med. Sci. Sports Exerc.* 42, 413–421. doi:10.1249/MSS.0b013e3181b88d37

Impellizzeri, F. M., Bizzini, M., Dvorak, J., Pellegrini, B., Schena, F., and Junge, A. (2013). Physiological and performance responses to the FIFA 11+ (part 2): a randomised controlled trial on the training effects. *J. Sports Sci.* 31, 1491–1502. doi:10.1080/02640414.2013.802926

Kilding, A. E., Tunstall, H., and Kuzmic, D. (2008). Suitability of FIFA's "the 11" training programme for young football players - impact on physical performance. *J. Sports Sci. Med.* 7, 320–326.

Lloyd, R. S., Radnor, J. M., De Ste Croix, M. B., Cronin, J. B., and Oliver, J. L. (2016). Changes in sprint and jump performances after traditional, plyometric, and combined resistance training in male youth pre- and post-peak height velocity. *J. Strength Cond. Res.* 30, 1239–1247. doi:10.1519/JSC.0000000000001216

Lockie, R. G., Murphy, A. J., Schultz, A. B., Knight, T. J., Janse, J., and Xanne, A. K. (2012). The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. *J. Strength Cond. Res.* 26, 1539–1550. doi:10.1519/JSC.0b013e318234e8a0

Lopes, M., Simões, D., Rodrigues, J. M., Costa, R., Oliveira, J., and Ribeiro, F. (2019). The FIFA 11+ does not alter physical performance of amateur futsal players. *J. Sports Med. Phys. Fit.* 59, 743–751. doi:10.23736/S0022-4707.18.08532-8

Macadam, P., Simperingham, K. D., Cronin, J. B., Couture, G., and Evison, C. (2017). Acute kinematic and kinetic adaptations to wearable resistance during vertical jumping. *Eur. J. Sport Sci.* 17, 555–562. doi:10.1080/17461391.2017.1298672

Maffulli, N., Giuseppe Longo, U., Spiezia, F., and Denaro, V. (2011). Aetiology and prevention of injuries in elite young athletes. *Med. Sport Sci.* 56, 187–200. doi:10.1159/000321078

Mathisen, G. E., and Danielsen, K. H. (2014). Effects of speed exercises on acceleration and agility performance in 13-year-old female soccer players. *J. Phys. Educ. Sport.* 71, 471–474. doi:10.7752/jpes.2014.04071

Melnyk, B. M., and Morrison-Beedy, D. (2020). Intervention research and evidence-based quality improvement: designing, conducting, analyzing, and funding, 2nd edition. *Med. Sci. Sports Exerc.* 52, 267. doi:10.1249/01.mss.0000615364.41049.bc

Miguel, M., Oliveira, R., Loureiro, N., Gracia-Rubio, J., and Ibanez, S. J. (2021). Load measures in training/match monitoring in soccer: a systematic review. *Int. J. Environ. Res. Public Health* 18, 2721. doi:10.3390/ijerph18052721

Mohr, M., Krustrup, P., Nybo, L., Nielsen, J. J., and Bangsbo, J. (2004). Muscle temperature and sprint performance during soccer matches-beneficial effect of rewarm-up at half-time. *Scand. J. Med. Sci. Sports* 14, 156–162. doi:10.1111/j.1600-0838.2004.00349.x

Muniroglu, S., and Subak, E. (2018). A comparison of 5, 10, 30 meters sprint, modified T-test, arrowhead and Illinois agility tests on football referees. *J. Educ. Train. Stud.* 6, 70. doi:10.11114/jets.v6i8.3360

Neto, G. M., Conceicao, C. S., de Lima Brasileira, A. J. A., de Sousa, C. S., Carvalho, V. O., and de Jesus, F. L. A. (2017). Effects of the FIFA 11 training program on injury prevention and performance in football players: a systematic review and meta-analysis. *Clin. Rehabil.* 31, 651–659. doi:10.1177/0269215516675906

Owoeye, O. B., Akinbo, S. R., Tella, B. A., and Olawale, O. A. (2014). Efficacy of the FIFA 11+ warm-up programme in male youth football: a cluster randomised controlled trial. *J. Sports Sci. Med.* 13, 321–328.

Panagoulis, C., Chatzinikolaou, A., Avloniti, A., Leontsini, D., Deli, C. K., Draganidis, D., et al. (2020). In-season integrative neuromuscular strength training improves performance of early-adolescent soccer athletes. *J. Strength Cond. Res.* 34, 516–526. doi:10.1519/JSC.0000000000002938

Parsons, J. L., Carswell, J., Nwoba, I. M., and Stenberg, H. (2019). Athlete perceptions and physical performance effects of the Fifa 11+ program in 9-11 year-old female soccer players: a cluster randomized trial. *Int. J. Sports Phys. Ther.* 14, 740–752. doi:10.26603/ijspt20190740

Pomares-Noguera, C., Ayala, F., Robles-Palazón, F. J., Alomoto-Burneo, J. F., López-Valenciano, A., Elvira, J., et al. (2018). Training effects of the FIFA 11+ kids on physical performance in youth football players: a randomized control trial. *Front. Pediatr.* 6, 40. doi:10.3389/fped.2018.00040

Robles-Palazón, F. J., Pomares-Noguera, C., Ayala, F., Hernández-Sánchez, S., Martínez-Romero, M. T., de Baranda, P. S., et al. (2016). Acute and chronic effects of the FIFA 11+ on several physical performance measures in adolescent football players. *Eur. J. Hum. Mov.* 36, 116–136.

Rössler, R., Donath, L., Bizzini, M., and Faude, O. (2016). A new injury prevention programme for children's football - FIFA 11+ Kids - can improve motor performance: a cluster-randomised controlled trial. *J. Sports Sci.* 34, 549–556. doi:10.1080/02640414.2015.1099715

Rumpf, M. C., Cronin, J. B., Pinder, S. D., Oliver, J., and Hughes, M. (2012). Effect of different training methods on running sprint times in male youth. *Pediatr. Exerc. Sci.* 24, 170–186. doi:10.1123/pes.24.2.170

Sáez de Villarreal, E., Requena, B., and Cronin, J. B. (2012). The effects of plyometric training on sprint performance: a meta-analysis. *J. Strength Cond. Res.* 26, 575–584. doi:10.1519/JSC.0b013e318220fd03

Sassi, R. H., Dardouri, W., Yahmed, M. H., Gmada, N., Mahfoudhi, M. E., and Gharbi, Z. (2009). Relative and absolute reliability of a modified agility T-test and its relationship with vertical jump and straight sprint. *J. Strength Cond. Res.* 23, 1644–1651. doi:10.1519/JSC.0b013e3181b425d2

Seyedi, M., Zarei, M., Daneshjoo, A., Rajabi, R., Shirzad, E., Mozafaripour, E., et al. (2023). Effects of FIFA 11 + warm-up program on kinematics and proprioception in adolescent soccer players: a parallel-group randomized control trial. *Sci. Rep.* 13, 5527. doi:10.1038/s41598-023-32774-3

Shrout, P. E., and Fleiss, J. L. (1979). Intraclass correlations: uses in assessing rater reliability. *Psychol. Bull.* 86, 420–428. doi:10.1037/0033-2909.86.2.420

Silvers-Granelli, H., Mandelbaum, B., Adeniji, O., Insler, S., Bizzini, M., Pohlig, R., et al. (2015). Efficacy of the FIFA 11+ injury prevention program in the collegiate male soccer player. *Am. J. Sports Med.* 43, 2628–2637. doi:10.1177/0363546515602009

Steffen, K., Emery, C. A., Romiti, M., Kang, J., Bizzini, M., Dvorak, J., et al. (2013). High adherence to a neuromuscular injury prevention programme (FIFA 11+) improves functional balance and reduces injury risk in Canadian youth female football players: a cluster randomised trial. *Br. J. Sports Med.* 47, 794–802. doi:10.1136/bjsports-2012-091886

Torres-Ronda, L., Beanland, E., Whitehead, S., Sweeting, A., and Clubb, J. (2022). Tracking systems in team sports: a narrative review of applications of the data and sport specific analysis. *Sports Med. Open* 8, 15. doi:10.1186/s40798-022-00408-z

Trajković, N., Gušić, M., Molnar, S., Mačak, D., Madić, D. M., and Bogataj, S. (2020). Short-term FIFA 11+ improves agility and jump performance in young soccer players. *Int. J. Environ. Res. Public Health.* 17, 2017. doi:10.3390/ijerph17062017

Turner, A., Brazier, J., Bishop, C., Chavda, S., Cree, J., and Read, P. (2015). Data analysis for strength and conditioning coaches using excel to analyze reliability, differences, and relationships. *Strength Cond. J* 37, 76–83. doi:10.1519/SSC.0000000000000113

Wang, Y. C., and Zhang, N. (2016). Effects of plyometric training on soccer players. *Exp. Ther. Med.* 12, 550–554. doi:10.3892/etm.2016.3419

Yeadon, M. R., Kato, T., and Kerwin, D. G. (1999). Measuring running speed using photocells. *J. Sports Sci.* 17, 249–257. doi:10.1080/026404199366154

Zarei, M., Abbasi, H., Daneshjoo, A., Barghi, T. S., Rommers, N., Faude, O., et al. (2018). Long-term effects of the 11+ warm-up injury prevention programme on physical performance in adolescent male football players: a cluster-randomised controlled trial. *J. Sports Sci.* 36, 2447–2454. doi:10.1080/02640414.2018.1462001

Zois, J., Bishop, D. J., Ball, K., and Aughey, R. J. (2011). High-intensity warm-ups elicit superior performance to a current soccer warm-up routine. *J. Sci. Med. Sport* 14, 522–528. doi:10.1016/j.jsams.2011.03.012

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Hamstrings mechanical properties profiling in football players of different competitive levels and positions after a repeated sprint protocol

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Purpose: This study compares the average speed, knee flexor peak torque and shear modulus of the hamstrings after a repeated sprint task, in football players of different competitive levels and playing positions.

Methods: Fifty-four football field players without hamstring strain injury history participated, 15 being categorized as professional (2nd league) and 39 as semi-professional (17 in 3rd and 22 in 4th league). Muscle shear modulus was assessed using ultrasound-based shear wave elastography at rest and at 20% of maximal voluntary isometric effort before and immediately after the repeated sprint protocol.

Results: No significant differences were seen in average sprint speed between competitive levels (p = 0.07; η2p = 0.28) and positions (p = 0.052; η2p = 0.29). Moreover, the sprint fatigue index showed no significant differences between competitive levels (p = 0.14; η2p = 0.08) and playing positions (p = 0.89; η2p = 0.05). No significant differences were observed in hamstring shear modulus changes between competitive levels (p = 0.94; η2p = 0.03) and positions (p = 0.92; η2p = 0.03). Peak torque changes also showed non-significant association with competitive levels (p = 0.46; η2p = 0.03) and positions (p = 0.60; η2p = 0.02).

Conclusion: The results of this study suggest that the average sprint speed performance parameter and mechanical parameters are not able to distinguish football players of different competitive levels and positions.

KEYWORDS

biceps femoris long head, semitendinosus, shear wave elastography, shear modulus, soccer

Introduction

The profiling of athletes of different modalities reveals physiological, anthropometric and physical patterns that are useful for the assessment and monitoring of performance parameters by providing a framework that coaches and sports scientists can use to compare athletes within or between teams (Slimani and Nikolaidis, 2019; Tierney et al., 2021).

Specifically, in football, the physiological, anthropometric and physical profile has been studied in the past years (Abrantes et al., 2004; Sporis et al., 2009; Lago-Peñas et al., 2011) making it possible to describe and compare physical capacities of players of different positions (Schwesig et al., 2017) and competitive levels (Tierney et al., 2021). However, scientific research still reveals a gap in the knowledge of the profiling of football players, especially when it comes to the characterization of the muscular properties of specific muscles that can significantly influence the players' running performance such as the hamstrings muscle group.

The hamstring is a biarticular muscle group that acts simultaneously at two joints by participating in knee flexion and hip extension. Moreover, the hamstrings have an important role for the development of horizontal force components during sprinting in non-fatigued conditions (Edouard et al., 2018). In the context of football matches, players have to sprint also with a change of direction component. This requires stabilization of the knee joint, which is achieved through a distinct contribution of the medial and lateral hamstrings (Zebis et al., 2009). Previous studies demonstrated a decrease in maximal force production of the hamstrings immediately post-match (Bueno et al., 2021); however, as peak torque measurements do not provide information about the mechanical contribution of individual muscles, shear wave elastography has been proposed to quantify mechanical muscle properties (i.e., muscle shear modulus). Indeed, changes in torque production are correlated with changes in muscle shear modulus (Bouillard et al., 2012).

To the best of our knowledge, only two studies have analyzed the behavior of the hamstring mechanical tissue properties after repeated sprints: in healthy individuals (Pimenta et al., 2023c) and football players with and without hamstring strain injury (Pimenta et al., 2023b). The former demonstrated a significant increase in the biceps femoris long head (BFlh) contribution without changes in semitendinosus (ST) (Pimenta et al., 2023c), while the latter showed a significant increase in the contribution of BFlh and semimembranosus (SM) (Pimenta et al., 2023b). Considering the larger muscle volumes of ST and BFlh muscles in sprinters compared to non-sprinters (Handsfield et al., 2017), a higher mechanical contribution by ST and BFlh at higher competitive levels can be expected given the higher sprint volume and intensity. It can also be expected that faster players (e.g., forwards) will show a higher ST contribution due to its considerably higher proportion of fast-twitch fibers (Fournier et al., 2022), whereas players covering long distances (e.g., midfielders) show a higher BFlh contribution due to its higher number of type I/IIa fibers (Dahmane et al., 2005). Therefore, a study comprising the effect of repeated sprints on the hamstring mechanical properties in football players of different competitive levels and positions would be of great interest and utility for the sports science and professional community, adding information to the knowledge framework that already exists comprising other significant components of a football player profile.

The present study aims at comparing the effects of a repeated sprint protocol on the sprint performance and hamstrings shear modulus pattern between players with different competitive levels and positions. The hypothesis was i) a higher sprint performance and a higher mechanical contribution of the ST and BFlh at higher competitive levels; ii) a higher sprint performance and higher mechanical contribution of ST for forwards when compared to midfielders and defenders; iii) a higher mechanical contribution of BFlh for midfielders compared to forwards and defenders.

Methods

Ten clubs were invited to participate in the present study, resulting in 54 football field players (age: 23.5 ± 3.6 years; height: 178.3 ± 6.4 cm; body mass: 73.2 ± 7.1 kg): 15 categorized as professional (2nd league) and 39 as semi-professional (17 on 3rd league and 22 on 4th league) according to the official Portuguese league website. The sample size in relation to the field position was composed by 23 defenders, 15 midfielders and 16 forwards. All participants read and signed an informed consent form prior to participating in the study. The Ethical Committee at the Faculty of Human Kinetics at the University of Lisbon approved the study (#5/2021). Participants were instructed to avoid any strenuous activities 24 h before the test to minimize confounding factors. The exclusion criteria were replicated from previous study (Pimenta et al., 2023b), alongside exclusion of previous hamstring injury.

Dynamometry

The knee flexor torque was measured at a sampling rate of 1,000 Hz using custom-made equipment (Pimenta et al., 2023b). Participants were placed in the prone position, with the hips in neutral anatomical position, knees flexed at 30° (0° = full extension) as previously reported (Pimenta et al., 2023b). Both feet were fixed in a foot holder containing a force transducer (Model STC, Vishay Precision, Malvern, PA, United States) at the heel level to collect the linear force perpendicular to the leg orientation and with the ankle at 90°. Force data were amplified (Model UA73.202, Sensor Techniques, Cowbridge, UK), digitally converted (USB-230 Series, Measurement Computing Corporation Norton, MA, United States), recorded using the DAQami software (v4.1, Measurement Computing Corporation, Norton, MA, United States), and multiplied by the perpendicular distance between the force transducer center and the femoral lateral condyle in order to estimate the knee torque. Visual feedback of force production was provided to individuals during the assessments.

Sprint performance

Sprint performance was evaluated by a 10 × 30 m repeated sprint protocol using a two-point stance, with participants positioned 1 m behind the photocells. The average sprint speed was recorded using four photocells and data was processed by the Chronojump software (version: 2.1.1-16, Chronojump Boscosystem, Barcelona, Spain).

Shear wave elastography

Hamstrings shear modulus was assessed using two similar ultrasound scanners (Aixplorer, v11; Supersonic Imagine, Aix-en-

Provence, France; Aixplorer, v12; Supersonic Imagine, Aix-en-Provence, France) in shear wave elastography (SWE) mode (musculoskeletal preset, penetrate mode, smoothing level 5, opacity 100%, scale: 0–800 kPa for active (i.e., during contraction), coupled with a linear transducer array (SL10-2, 2–10 MHz. Super Linear, Vermon, Tours, France). The SWE procedures were detailed in the previous study with a similar test protocol (Pimenta et al., 2023b). The transducer was placed to align with the muscle fascicles orientation, and to perform minimal pressure during the measurements. To maximize the window of opportunity of the effects in both tasks, both examiners collected data simultaneously in the pairs BFlh + SM and ST + BFsh. The utilization of casts and the measurement with two examiners was previously validated (Pimenta et al., 2023d).

Protocol

Participants visited the Centro de Alto Rendimento Jamor indoors facility, where wind and temperature had no effect on sprint performance and shear modulus assessment, respectively. Testing started by assessing the passive shear modulus for each muscle. For this purpose, two videoclips of 20-s were recorded. Then, individuals were asked to perform 10 submaximal knee flexions at a self-perceived low intensity to prepare and familiarize with the equipment for the maximum voluntary isometric contraction (MVIC) evaluation, which consisted of two 3-s trials with 30-s of recovery between trials. Based on the highest PT on the tested limb, individuals familiarized themselves with the 20% of MVIC through trials using visual feedback. Subsequently, the active shear modulus was then measured twice for each muscle at 20% of MVIC, each trial lasting ~30-s. After active shear modulus measures, a standardized warm-up protocol for sprinting was performed (Pimenta et al., 2023b). Immediately after the warm-up, a 10 × 30-m repeated sprint task with 30-s interval between repetitions was performed. Then, post-task active shear modulus measurements were conducted followed by two MVIC trials. The order of the measurements in each muscle was randomized.

Data processing

Shear wave elastography data were processed using automated MATLAB routines (The Mathworks Inc., Natick, MA, United States) (Mendes et al., 2020). For the shear modulus calculation, each clip exported from Aixplorer's software was sequenced in. jpeg images. Image processing converted each pixel of the color map into a value of the Young's modulus based on the recorded color scale. The largest region of interest in the elastogram window was determined by avoiding aponeuroses and tissue artifacts (e.g., vessels), and the values were averaged to obtain a representative muscle value. Within each trial, the most stable Young's modulus values over ~20-s in the active condition were averaged and divided by 3 to better represent the muscle shear elastic modulus (Bercoff et al., 2004). The shear modulus of each muscle was considered for analysis.

Statistical analysis

Data analysis was performed using IBM SPSS Statistics 27.0 (IBM Corporation, Armonk, NY, United States). To assess the effect of fatigue in each muscle a delta (Δ) active shear modulus (post-pre) was calculated for each muscle (Pimenta et al., 2023a). A one-way between-groups MANOVA was performed to investigate competitive level differences in active shear modulus. A one-way between-groups MANOVA was performed to investigate field positions differences in active shear modulus. For both MANOVA's, a preliminary assumption testing was conducted to check for normality, linearity, univariate and multivariate outliers, homogeneity of variance-covariance matrices, and multicollinearity, with no serious violations noted. The Fatigue index for sprint performance was calculated using the following equation:

$$\text{Fatigue index} = \text{slowest sprint-fastest sprint}/\text{fastest sprint}$$

The fatigue index comparison was examined using a one-way ANOVA for competitive level and playing position. Peak torque changes was calculated using the following equation:

$$\text{Peak Torque changes} = (\text{post} - \text{protocol peak torque}) \text{ - } (\text{pre} - \text{protocol peak torque}) / (\text{pre} - \text{protocol peak torque})$$

A one-way ANOVA was used to analyze the peak torque differences between competitive levels and playing positions. The partial eta square (η2p) values were reported as a measure of the effect size of the MANOVA's and ANOVA findings, classified as small ($\eta 2p$ = 0.01–0.05), medium ($\eta 2p$ = 0.06–0.013), and large ($\eta 2p > 0.14$) effects (Cohen, 2013). Significance was set at $p < 0.05$.

Results

Regarding the sprints performance between competitive levels (Figure 1) no significant differences were seen, F (20, 82) = 1.61; p = 0.07; Wilks' Λ = 0.52; η2p = 0.28. In relation to the sprints performance by position (Figure 2) no significant differences were detected, F (20, 82) = 1.69; p = 0.052; Wilks' Λ = 0.50; η2p = 0.29.

The Δ shear modulus analysis of all hamstring muscles by competition level (Figure 3) showed no significant differences between competitive levels on the combined dependent variables, F (8, 96) = 0.36; p = 0.94; Wilks' Λ = 0.94; η2p = 0.03. Figure 4 presents the Δ shear modulus of all hamstring muscles by position on the field with no significant differences on the combined dependent variables, F (8, 96) = 0.40; p = 0.92; Wilks' Λ = 0.94; η2p = 0.03.

Fatigue index comparisons between competitive levels (2nd league: −6.76% ± 5.68%; 3rd league: −4.25% ± 6.48%; 4th league: −7.78% ± 4.35%; p = 0.14; η2p = 0.08) and playing positions (defenders: −6.46% ± 5.79%; midfielders: −5.99% ± 4.02%; forwards: −6.85% ± 5.54%; p = 0.89; η2p = 0.05).

Peak torque differences comparisons revealed no significant differences between competitive levels (2nd league: −7.8% ± 0.96%; 3rd league: −5.8% ± 0.86%; 4th league: −8.3% ± 0.91%; p = 0.46; η2p = 0.03) and playing positions (defenders: −6.7% ±

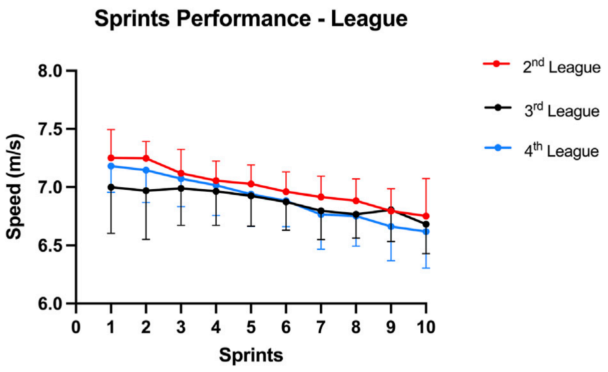

FIGURE 1
Average sprint speed (m/s) during the repeated sprinting task, in players of 2nd league (red), 3rd league (black) and 4th league (blue). Error bars represent the standard deviation.

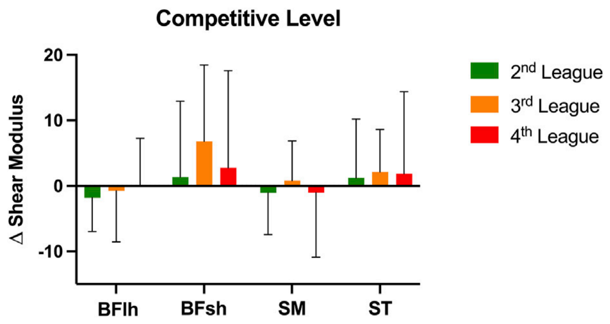

FIGURE 3
Delta (Δ) shear modulus variation (post—pre) of all hamstring muscles: Biceps Femoris long head (BFlh), Biceps Femoris short head (BFsh), Semimembranosus (SM), and Semitendinosus (ST), in each competitive level: Second League (green), Third League (orange), Fourth League (red). Bars represent mean values and error bars represent standard deviation.

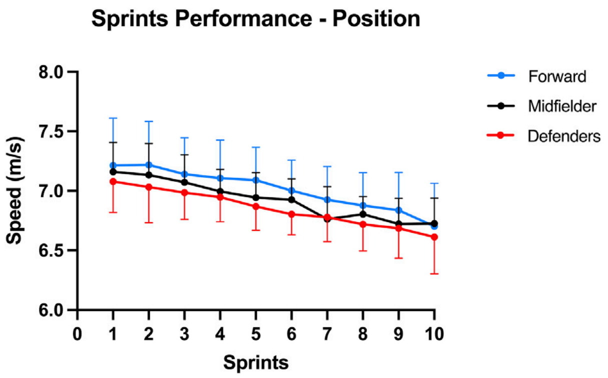

FIGURE 2
Average sprint speed (m/s) during the repeated sprint task, comparison between playing positions: in forwards (blue), in midfielders (black) and defenders (red). Error bars represent the standard deviation.

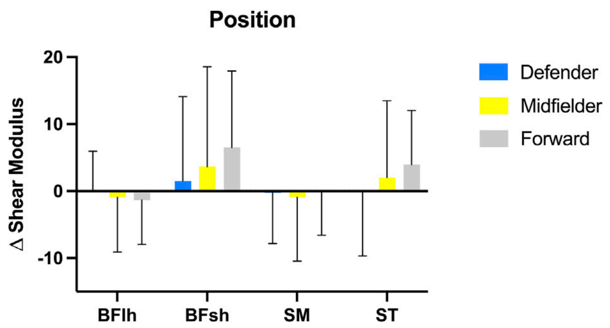

FIGURE 4
Delta (Δ) shear modulus variation (post—pre) of all hamstring muscles: Biceps Femoris long head (BFlh), Biceps Femoris short head (BFsh), Semimembranosus (SM), and Semitendinosus (ST) in each competitive field position: Defender (blue), Midfielder (yellow), Forward (gray). Bars represent mean values and error bars represent standard deviation.

0.85%; midfielders: −8.8% ± 0.93%; forwards: −5.6% ± 0.91%; p = 0.60; η2p = 0.02).

Discussion

To the best of our knowledge, this is the first study that compares the effects of a repeated sprint protocol on the sprint performance and hamstrings mechanical properties between players with different competitive levels and positions. The main findings were no differences in the sprint performance and hamstring shear modulus between competitive levels and positions. Since in our study no differences were found between competitive levels it was possible to perform a comparison between field positions using players across all competitive levels.

A higher average sprint speed was seen in 2nd league compared to 3rd and 4th league players (Figure 1); however, contrary to our initial hypothesis no significant differences were seen between the competitive levels. These results are in contrast to previous literature also assessing portuguese players, Abrantes et al. (2004) having reported significant differences in the mean sprint time using the Bangsbo repeated-sprint ability (RSA) protocol (Bangsbo, 1994) between professional football players, with players from 1st national division being significantly faster than 2nd league players. These professional players displayed significant differences in relation to semi-professionals (1st regional) (Abrantes et al., 2004). However, the present study did not include first league players and thus a comparison between professionals was not possible. Moreover, the lowest division in our study (4th league) was from the first national league which differs from a regional championship. Contrary to our protocol, the Bangsbo RSA includes a change of direction component and it has been shown that shuttle-type RSA protocols are associated with slower repetition times and a reduced sprint decrement (Thurlow et al., 2023).

Regarding the comparison between positions (Figure 2), the forwards showed a higher sprint speed, followed by midfielders and lastly defenders; however, also contrary to our hypothesis no significant differences were found between the positions. This is in accordance with previous work using the Bangsbo protocol (Bangsbo, 1994) that did not find any statistical differences with respect to best time and average time (Kaplan, 2010). Furthermore, Brahim et al. (2016) showed that forwards performed better in mixed-direction repeated sprint tests, midfielders were better in mixed-direction repeated sprint tests that involved a longer linear sprinting distance (6 × 40 m (20 + 20 m)), and defenders had better scores in linear repeated sprint tests such as our protocol. It should be noted that the above mentioned protocols cannot be compared with the present protocol as it was designed to induce fatigue on the hamstrings muscles instead of being designed according to the sprinting skills of the player positions. A similar linear repeated sprint protocol (7 × 30-m) was employed with recreational players with the results also showing no significant differences in sprint performance between players of different positions (Lockie et al., 2019). Since linear and multidirectional sprint tasks represent independent skills expression (Salaj and Markovic, 2011), it is possible that while players might present different performances in multidirectional sprint protocols, they may present no significant differences in linear sprints performance as in the present results.

The fatigue index formula used in this study was also applied in a previous study (Morcillo et al., 2015) showing a 7.10% decrease after a similar RSA protocol in professional players. The inability to maintain sprint speed in subsequent repetitions is also proposed to be affected by maximal aerobic capacity (Girard et al., 2011) which can distinguish elite from non-elite football players. In fact, higher fatigue levels were verified in amateur players (4th league) compared to semi-professional players, although non-significant. Importantly, this maximal aerobic capacity can also be influenced by the player's position (Slimani and Nikolaidis, 2019). In relation to the peak torque analysis, no significant differences were seen between competitive levels and playing positions. Using a different formula to calculate peak torque changes upon a fatiguing sprint task, Lord et al. (2018) found a −6% change for the dominant leg, a value closer to those reported in this study (Lord et al., 2018). No significant differences in peak torque changes were observed between the different field positions, contrary to previous work (Cometti et al., 2001; Śliwowski et al., 2017); given the lack of investigation regarding this topic, future studies should replicate a similar protocol comparing a different sample of football players (e.g., elite football players vs. sub-elite or amateur) to potentially enable a better explanation of these results.

Regarding the mechanical hamstring tissue properties (analyzed as Δ shear modulus) and contrary to our initial hypothesis no significant differences were found across leagues and positions. According to the mechanical tension experienced by the BFlh along the sprint cycle (Thelen et al., 2005) and the effects of an eccentric task (Goreau et al., 2022), an increase in BFlh shear modulus would have been expected. Indeed, previous studies using the same repeated sprint protocol showed a significant increase in the BFlh (Pimenta et al., 2023b; 2023c). Despite the disparity in the results, it is worth mentioning that the samples of these previous studies consisted of healthy individuals (Pimenta et al., 2023c) and of football players with hamstring strain injuries (Pimenta et al., 2023b). Healthy individuals (non-football players) may present different muscle volume configurations compared to football players, this being related to the muscle adaptations according to the sport stimulus (Krustrup et al., 2010). Supporting this assumption, Handsfield et al. (2017) reported that sprinters had considerably larger ST, BFlh and SM volumes compared to the non-sprinter sample (Handsfield et al., 2017). Nevertheless, as football players from higher competitive levels are likely submitted to higher sprinting action demands resulting in superior hamstring muscle adaptations than players in lower competitive levels, it is curious that this was not apparent in the present study.

Apart from the competitive level, the playing position has a significant effect on the game actions of a football player. Research has been consistent demonstrating that certain positions require more explosive-type efforts while others are submitted to more resistant-type efforts (Di Salvo et al., 2013). In a recent review, authors noted that male football players with a higher proportion of type II muscle fibers had faster 30 m sprint times and achieved a greater total sprinting distance, and that more type II muscle fibers and a higher muscle volume in rugby players were strong determinants of maximal muscle power in sprinting (Hopwood et al., 2023). Hence, it would be logical that players in a field position requiring explosive actions presented larger and higher proportions of type II muscle fibers and consequently a higher shear modulus change in a muscle with a type II muscle fiber phenotype.

The present study demonstrated a higher speed (Figure 1) and positive change in the ST Δ shear modulus of forwards (Figure 4), although no significant differences were found. Having a type II phenotype (Fournier et al., 2022) and being a fusiform muscle (Azizi and Deslauriers, 2014), the ST geometry and composition is well suited for explosive tasks but not as resistant as other hamstring muscles (Kellis, 2018; Fournier et al., 2022). As football sport demands vary between player positions, it would be expected that faster players could present a higher relative ST mechanical contribution and more resistant players a higher relative BFlh mechanical contribution, as BFlh has a more balanced type muscle fiber composition compared to ST (Kellis, 2018; Fournier et al., 2022). Importantly, the competitive level between professional football leagues can have an impact on the data interpretation, such as analyzing data from the Premier League (Di Salvo et al., 2013) which is more competitive than the 2nd league of the present study. For instance, there is evidence that players from top-level European leagues cover 10% of total distance at high intensity (Carling, 2011; Andrzejewski et al., 2015) compared to the 6.4% from the Croatian league (Modric et al., 2019). As such, one could expect a lower proportion of high-intensity activity (including sprints) in players from the 2nd, 3rd and 4th division. Overall, the present study indicates that a repeated sprint protocol 10 × 30 m with 30 s of rest induce fatigue in both professional and semi-professional players and between positions on the neuromuscular parameters. However, it was not possible to distinguish the response in hamstring mechanical properties and neuromuscular parameters across the assessed competitive levels. One possible reason could be in part attributed to the progress of available knowledge in strength and conditioning applications in football and its interpretation by club sports scientists. This warrants further investigation.

This study has some limitations. Firstly, shear moduli measurements were limited to one site per muscle to minimize the time required for data collection and thus allow accurate examination of the acute fatigue effects. Therefore, the present findings are based on the assumption that the effects were site-independent. Secondly, the present study examined the hamstring mechanical properties in isometric contractions after repeated sprints, whereas the magnitude of the effects would be greater during the sprints themselves as eccentric contractions are more demanding. However, to this date, the low sampling rate of this methodology prevents such measurements. Competitive level and playing position data might be significantly influenced by the football leagues analyzed due to different intensity and technical levels.

Conclusion

The results of the present study indicated that it was not possible to distinguish football players from different competitive levels and positions when analyzing the sprint performance, hamstring shear modulus and peak torque after a repeated sprint task. However, it should be noted that in the present study, the tasks were analytical, therefore the results can be task-specific since game contexts varied in terms of competitive levels and positions. These results may also suggest that the disparities in physical characteristics between competitive levels and positions have significantly diminished. This could be attributed to specific training characteristics and a heightened influence of physical attributes in football. We encourage further studies to analyze this hypothesis.

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 Comité de Ética da Faculdade de Motricidade Humana. 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

RP: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. HA: Conceptualization, Investigation, Validation, Visualization, Writing–review and editing. PB: Data curation, Formal Analysis, Writing–review and editing. AV: Project administration, Resources, Supervision, Validation, Visualization, Writing–review and editing.

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Conflict of interest

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

Publisher's note

References

Abrantes, C., Maçãs, V., and Sampaio, J. (2004). Variation in football players' sprint test performance across different ages and levels of competition. *J. Sports Sci. Med.* 3, 44–49.

Andrzejewski, M., Chmura, J., Pluta, B., and Konarski, J. M. (2015). Sprinting activities and distance covered by top level Europa league soccer players. *Int. J. Sports Sci. Coach.* 10, 39–50. doi:10.1260/1747-9541.10.1.39

Azizi, E., and Deslauriers, A. R. (2014). Regional heterogeneity in muscle fiber strain: the role of fiber architecture. *Front. Physiol.* 5, 303. doi:10.3389/fphys.2014.00303

Bangsbo, J. (1994). *Fitness training in football: a scientific approach*. Copenhagen, Denmark: August Krogh Institute - Copenhagen University.

Bercoff, J., Tanter, M., and Fink, M. (2004). Supersonic shear imaging: a new technique for soft tissue elasticity mapping. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* 51, 396–409. doi:10.1109/tuffc.2004.1295425

Bouillard, K., Nordez, A., Hodges, P. W., Cornu, C., and Hug, F. (2012). Evidence of changes in load sharing during isometric elbow flexion with ramped torque. *J. Biomech.* 45, 1424–1429. doi:10.1016/j.jbiomech.2012.02.020

Brahim, M. B., Mohamed, A., and Shalfawi, S. A. (2016). The Evaluation of soccer players performance on different repeated sprint tests: training and testing implications. *Kinesiol. Slov.* 22 (2), 49–63.

Bueno, C. A., de Araujo Ribeiro-Alvares, J. B., Oliveira, G. D. S., Grazioli, R., Veeck, F., Pinto, R. S., et al. (2021). Post-match recovery of eccentric knee flexor strength in male professional football players. *Phys. Ther. Sport* 47, 140–146. doi:10.1016/j.ptsp.2020.11.032

Carling, C. (2011). Influence of opposition team formation on physical and skill-related performance in a professional soccer team. *EJSS* 11, 155–164. doi:10.1080/17461391.2010.499972

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Abingdon, United Kingdom: Routledge.

Cometti, G., Maffiuletti, N. A., Pousson, M., Chatard, J.-C., and Maffulli, N. (2001). Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players. *Int. J. Sports Med.* 22, 45–51. doi:10.1055/s-2001-11331

Dahmane, R., Djordjevic, S., Simunic, B., and Valencic, V. (2005). Spatial fiber type distribution in normal human muscle Histochemical and tensiomyographical evaluation. *J. Biomech.* 38, 2451–2459. doi:10.1016/j.jbiomech.2004.10.020

Di Salvo, V., Pigozzi, F., González-Haro, C., Laughlin, M. S., and De Witt, J. K. (2013). Match performance comparison in top English soccer leagues. *Int. J. Sports Med.* 34, 526–532. doi:10.1055/s-0032-1327660

Edouard, P., Mendiguchia, J., Lahti, J., Arnal, P. J., Gimenez, P., Jiménez-Reyes, P., et al. (2018). Sprint acceleration mechanics in fatigue conditions: compensatory role of gluteal muscles in horizontal force production and potential protection of hamstring muscles. *Front. Physiol.* 9, 1706. doi:10.3389/fphys.2018.01706

Fournier, G., Bernard, C., Cievet-Bonfils, M., Kenney, R., Pingon, M., Sappey-Marinier, E., et al. (2022). Sex differences in semitendinosus muscle fiber-type composition. *Scand. J. Med. Sci. Sports* 32, 720–727. doi:10.1111/sms.14127

Girard, O., Mendez-Villanueva, A., and Bishop, D. (2011). Repeated-sprint ability - part I: factors contributing to fatigue. *Sports Med.* 41, 673–694. doi:10.2165/11590550-000000000-00000

Goreau, V., Pigne, R., Bernier, N., Nordez, A., Hug, F., and Lacourpaille, L. (2022). Hamstring muscle activation strategies during eccentric contractions are related to the distribution of muscle damage. *Scand. J. Med. Sci. Sports* 32, 1335–1345. doi:10.1111/sms.14191

Handsfield, G. G., Knaus, K. R., Fiorentino, N. M., Meyer, C. H., Hart, J. M., and Blemker, S. S. (2017). Adding muscle where you need it: non-uniform hypertrophy patterns in elite sprinters. *Scand. J. Med. Sci. Sports* 27, 1050–1060. doi:10.1111/sms.12723

Hopwood, H. J., Bellinger, P. M., Compton, H. R., Bourne, M. N., and Minahan, C. (2023). The relevance of muscle fiber type to physical characteristics and performance in team-sport athletes. *Int. J. Sports Physiol. Perform.* 18, 223–230. doi:10.1123/ijspp.2022-0235

Kaplan, T. (2010). Examination of repeated sprinting ability and fatigue index of soccer players according to their positions. *J. Strength Cond. Res.* 24, 1495–1501. doi:10.1519/JSC.0b013e3181d8e8ed

Kellis, E. (2018). Intra- and inter-muscular variations in hamstring architecture and mechanics and their implications for injury: a narrative review. *Sports Med.* 48, 2271–2283. doi:10.1007/s40279-018-0975-4

Krustrup, P., Christensen, J. F., Randers, M. B., Pedersen, H., Sundstrup, E., Jakobsen, M. D., et al. (2010). Muscle adaptations and performance enhancements of soccer training for untrained men. *Eur. J. Appl. Physiol.* 108, 1247–1258. doi:10.1007/s00421-009-1319-8

Lago-Peñas, C., Casais, L., Dellal, A., Rey, E., and Domínguez, E. (2011). Anthropometric and physiological characteristics of young soccer players according to their playing positions: relevance for competition success. *J. Strength Cond. Res.* 25, 3358–3367. doi:10.1519/JSC.0b013e318216305d

Lockie, R. G., Moreno, M. R., Orjalo, A. J., Stage, A. A., Liu, T. M., Birmingham-Babauta, S. A., et al. (2019). Repeated-sprint ability in division I collegiate male soccer players: positional differences and relationships with performance tests. *J. Strength Cond. Res.* 33, 1362–1370. doi:10.1519/JSC.0000000000001948

Lord, C., Ma'ayah, F., and Blazevich, A. J. (2018). Change in knee flexor torque after fatiguing exercise identifies previous hamstring injury in football players. *Scand. J. Med. Sci. Sports* 28, 1235–1243. doi:10.1111/sms.13007

Mendes, B., Firmino, T., Oliveira, R., Neto, T., Cruz-Montecinos, C., Cerda, M., et al. (2020). Effects of knee flexor submaximal isometric contraction until exhaustion on semitendinosus and biceps femoris long head shear modulus in healthy individuals. *Sci. Rep.* 10, 16433. doi:10.1038/s41598-020-73433-1

Modric, T., Versic, S., Sekulic, D., and Liposek, S. (2019). Analysis of the association between running performance and game performance indicators in professional soccer players. *Int. J. Environ. Res. Public Health* 16, 4032. doi:10.3390/ijerph16204032

Morcillo, J. A., Jiménez-Reyes, P., Cuadrado-Peñafiel, V., Lozano, E., Ortega-Becerra, M., and Párraga, J. (2015). Relationships between repeated sprint ability, mechanical parameters, and blood metabolites in professional soccer players. *J. Strength Cond. Res.* 29, 1673–1682. doi:10.1519/JSC.0000000000000782

Pimenta, R., Almeida, P., Correia, J. P., Bruno, P. M., Vaz, J. R., and Freitas, S. R. (2023a). Effects of fatigue on hamstrings and gluteus maximus shear modulus in hip extension and knee flexion submaximal contraction task. *Sports Biomech.*, 1–14. doi:10.1080/14763141.2023.2195827

Pimenta, R., Coelho, F., Correia, J. P., and Vaz, J. R. (2023d). Influence of transducer pressure and examiner experience on muscle active shear modulus measured by shear wave elastography. *Radiogr. (Lond).* 30 (1), 185–192. doi:10.1016/j.radi.2023.11.005

Pimenta, R., Lopes, T., Bruno, P., and Veloso, A. (2023b). Effects of repeated sprints on hamstring active shear modulus pattern and neuromuscular parameters in football players with and without hamstring strain injury history—a retrospective study. *Appl. Sci.* 13, 3099. doi:10.3390/app13053099

Pimenta, R., Lopes, T., Correia, J. P., and Veloso, A. P. (2023c). Effects of repeated sprinting on hamstring shear modulus pattern and knee flexor neuromuscular parameters. *Sci. Rep.* 13, 12624–12629. doi:10.1038/s41598-023-38861-9

Salaj, S., and Markovic, G. (2011). Specificity of jumping, sprinting, and quick change-of-direction motor abilities. *J. Strength Cond. Res.* 25, 1249–1255. doi:10.1519/JSC.0b013e3181da77df

Schwesig, R., Hermassi, S., Fieseler, G., Irlenbusch, L., Noack, F., Delank, K.-S., et al. (2017). Anthropometric and physical performance characteristics of professional handball players: influence of playing position. *J. Sports Med. Phys. Fit.* 57, 1471–1478. doi:10.23736/S0022-4707.16.06413-6

Slimani, M., and Nikolaidis, P. T. (2019). Anthropometric and physiological characteristics of male soccer players according to their competitive level, playing position and age group: a systematic review. *J. Sports Med. Phys. Fit.* 59, 141–163. doi:10.23736/S0022-4707.17.07950-6

Śliwowski, R., Grygorowicz, M., Hojszyk, R., and Jadczak, Ł. (2017). The isokinetic strength profile of elite soccer players according to playing position. *PLoS One* 12, e0182177. doi:10.1371/journal.pone.0182177

Sporis, G., Jukic, I., Ostojic, S. M., and Milanovic, D. (2009). Fitness profiling in soccer: physical and physiologic characteristics of elite players. *J. Strength Cond. Res.* 23, 1947–1953. doi:10.1519/JSC.0b013e3181b3e141

Thelen, D. G., Chumanov, E. S., Hoerth, D. M., Best, T. M., Swanson, S. C., Li, L., et al. (2005). Hamstring muscle kinematics during treadmill sprinting. *Med. Sci. Sports Exerc.* 37, 108–114. doi:10.1249/01.mss.0000150078.79120.c8

Thurlow, F., Weakley, J., Townshend, A. D., Timmins, R. G., Morrison, M., and McLaren, S. J. (2023). The acute demands of repeated-sprint training on physiological, neuromuscular, perceptual and performance outcomes in team sport athletes: a systematic review and meta-analysis. *Sports Med.* 53, 1609–1640. doi:10.1007/s40279-023-01853-w

Tierney, P., Blake, C., and Delahunt, E. (2021). Physical characteristics of different professional rugby union competition levels. *J. Sci. Med. Sport* 24, 1267–1271. doi:10.1016/j.jsams.2021.05.009

Zebis, M. K., Andersen, L. L., Bencke, J., Kjaer, M., and Aagaard, P. (2009). Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. *Am. J. Sports Med.* 37, 1967–1973. doi:10.1177/0363546509335000

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Identifying the ideal weekly training load for in-game performance in an elite Brazilian soccer team

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Introduction: The purpose of this study was to investigate the ideal training load to be applied during periods of fixture congestion to ensure an adequate dose-response effect for performance maintenance.

Methods: Match performance data and corresponding pre-match training load sessions (both N = 498 match performance cases and training-block session cases) were collected (with the catapult system, VECTOR7) from 36 male professional soccer players (23.5 ± 5.2 years; 178 ± 4 cm; 75.5 ± 6.0 kg) belonging to the Brazilian First Division team during the 2022 season. The following data were collected in match and training sessions: jump, acceleration, deceleration, and change of direction (COD); running distance producing metabolic power at different intensities (>20, >20–35, >35–45, >45–55, and >55 W kg^{-1}), total distance (m), relative distance (m/min), running distance at different speeds (>20, >25, and >30 km/h), number of sprints (running >25 km/h), and maximum speed (km/h). Mixed linear model (MLM), decision tree regression (DTR), and cluster K means model (SPSS v.26) approach were performed to identify the most critical variables (and their respective load) in the training sessions that could explain the athlete's match performance.

Results: MLM and DTR regression show that training load significantly affects game performance in a specific way. According to the present data, an interference phenomenon can occur when a high load of two different skills (running in a straight line vs COD, deceleration, and jumping) is applied in the same training block of the week. The cluster approach, followed by a chi-squared test, identified significant associations between training load and athlete match performance in a dose-dependent manner.

Discussion: The high load values described here have a beneficial effect on match performance, despite the interference between stimuli discussed above. We present a positive training load from a congested season from the Brazilian First Division team. The study suggests that an interference effect occurs when high physical training loads are applied to different specific physical skills throughout the season.

KEYWORDS

soccer, fixture congestion, match demands, training, load

1 Introduction

In recent years, there has been a growing interest in the detailed analysis of training and match demands in professional soccer (Sarmento et al., 2018; Clemente et al., 2019). This is partly due to the development of GPS and tracking systems that provide detailed performance analysis (i.e., training load) (Kaloop et al., 2017; Reinhardt et al., 2019).

Data collected during training and match sessions are essential to characterize match demands, define optimal training loads in preparation for competitions (Gómez-Carmona et al., 2018; Gonçalves et al., 2022), detect fatigue patterns (Filetti et al., 2019), prevent injuries, reduce the risk of overtraining (Rodrigues et al., 2023), and provide a broader understanding of each player's profile (Carling et al., 2008; Reche-Soto et al., 2019).

Modern elite soccer involves a large number of competitions and matches (typically up to 50 games) during the season between national and international competitions (Thorpe and Sunderland, 2012). Thus, it is not uncommon for a team to play two matches in a single week (Julian et al., 2021) with little recovery time in between, which represents a congested schedule. Indeed, the ability to recover between matches and intense training has previously been identified as a determinant of success (Rey et al., 2018; Dolci et al., 2020). Therefore, an approach that identifies the optimal training load and potential overload between games could be crucial for coaches.

Indeed, during periods of fixture congestion, the maintenance or improvement of performance is determined not only by adequate conditioning, but also by the ability of body systems to recover and regenerate after multiple stress stimuli (Marqués-Jiménez et al., 2017; Kalkhoven et al., 2021). Previous evidence has reported that reducing recovery time between games can lead to residual fatigue (Lago-Peñas et al., 2011), increase player stress, increase the risk of injury, and impair performance (Dellal et al., 2015; Mohr et al., 2016). Thus, in championships that face long and congested schedules with little recovery time (e.g., Brazil's Serie A) (Vieira et al., 2018), the coach's strategies in squad rotation and the application of appropriate training loads in a training context are particularly important.

Training load can be identified with a dose-response relationship between training stimuli and changes in physical fitness indicators (Branquinho et al., 2021a; Branquinho et al., 2021b), which have been widely used to identify peaks in training load. Monitoring the training load can be essential to optimize performance, reduce the risk of injury, and give the coach a general idea of how weekly stimuli affect performance in a game (Borin et al., 2007; Guerrero-Calderón et al., 2021; Guerrero-Calderón et al., 2022).

The training load is usually planned to ensure that the player is available for the next match (Garcia et al., 2022). However, in leagues (e.g., Brazil's Serie A) with a tight schedule and long travel times between games, training time is reduced. For these reasons, it is essential that the stimuli applied (i.e., training load) do not exceed recommended levels, yet little is known about the ideal training load for teams facing these challenges over the course of a season. In fact, the management and control of training load (i.e., internal load and external load) throughout the weekly periodization, if done correctly, can be critical in ensuring that players arrive at the next game in the best possible condition (Teixeira et al., 2021; Teixeira et al., 2022). New information on this topic would be of great use to coaches and sports scientists in optimizing player performance during the season.

Thus, the main objective of this study was to investigate the ideal training load to be applied during periods of fixture congestion to ensure the appropriate dose-response effect for performance maintenance. Our central hypothesis is that the weekly training load in a congested schedule is strongly associated with match performance. Also, there is an association between match performance and multiple contextual factors (such as home-away match condition, player position, amounts of training sessions in the weekly macrocycles, and the days between games). Finally, the type of stimulus applied in the macrocycles (such as jumping stimulus, change of direction, the number of explosive actions, and running in a straight line) might exert a positive or negative influence depending on the match performance variables assessed.

2 Material and methods

2.1 Participants and sample

Match performance data (N = 1,596 cases) and pitch match training load sessions (N = 5,515 cases) were collected from 36 male professional soccer players (age 23.5 ± 5.2 yr; 178 ±4 cm; 75.5 ± 6.0 kg) belonging to the Brazilian First Division team during the 2022 season. Only data corresponding to 77 official matches from 2022 season were analyzed. The 2022 season (with first official match) started on January 27th and ended on November 11th, without breaks during this entire period (that is, with one or two matches every week). Only match performances lasting ≥80 min were included in the analysis in accordance with previous recommendations (Guerrero-Calderón et al., 2021; Guerrero-Calderón et al., 2022). In this sense, the sample was limited to

498 match performance cases and their corresponding previous training load cases. Thus, 1,077 match performances cases and their corresponding previous training load (N = 2,446 cases) with match duration ≤79 min were excluded, see Figure 1. Players were divided into four positions: striker (112 pitch training sessions and match performance cases), fullback (117 cases), winger (88 cases), and midfielder (181 cases), see detailed description in Table 1. Goalkeepers were excluded from this analysis due to the different nature of their movement pattern.

2.2 Data collection

The catapult system (VECTOR7) with global and local positioning system devices (GPS, GLONASS and SBAS 18 Hz; LPS, Catapult ClearSky 10 Hz) combined with inertial sensors such as accelerometer (3D ± 16G; sampled at 1kHz, provided at 100 Hz), gyroscope (3D 2000°/second @ 100 Hz), and magnetometer (3D ±4,900 µT @100 Hz) were used to collect data for all games. All three inertial sensors collected data on acceleration, force, rotation, and body orientation.

2.3 Match performance and session training variables

The Inertial Movement Analysis (IMA) method was used to access explosive efforts such as jumps (>40 cm), acceleration (−45 to 0, 0–45°), deceleration (135–180, -180 to −135°), change of direction (COD) to the left (−135 to −45°) or to the right (45–135°). In addition, the total explosive effort (the sum of the jump, acceleration, deceleration, and COD) was recorded as the IMA explosive effort. IMA was used to derive RHIE (Repeat High-Intensity Efforts: the player performed three explosive efforts in ≤60 s) and RHIE block recovery time (the amount of time to recover and perform another RHIE). The running distance producing metabolic power (W kg^{-1}) was also collected at different intensities (>20, >20–35, >35–45, >45–55, and >55 W kg^{-1}). The player load was collected as the sum of the accelerations of the tri-axial accelerometer. GPS methods were used to collect total distance (m), relative distance (m/min), running distance >20 km/h (m), >25 km/h (m), and >30 km/h. In addition, the number of sprints (running >25 km/h) and the maximum speed (km/h) achieved during the match or training session were recorded.

2.4 Training data collection

Training and conditioning sessions between games were collected. Pre-season training was excluded from the analysis. 5,512 training sessions were collected. Only the training load corresponding to players who played in competitive matches for more than >80 min was included. The average number of training sessions per week before the game (reported here as weekly training sessions) was calculated. Players who did not complete a conditioning session but played a match were excluded from the analysis (see detailed description in Figure 1). Strength training and recovery sessions were not included in the analysis.

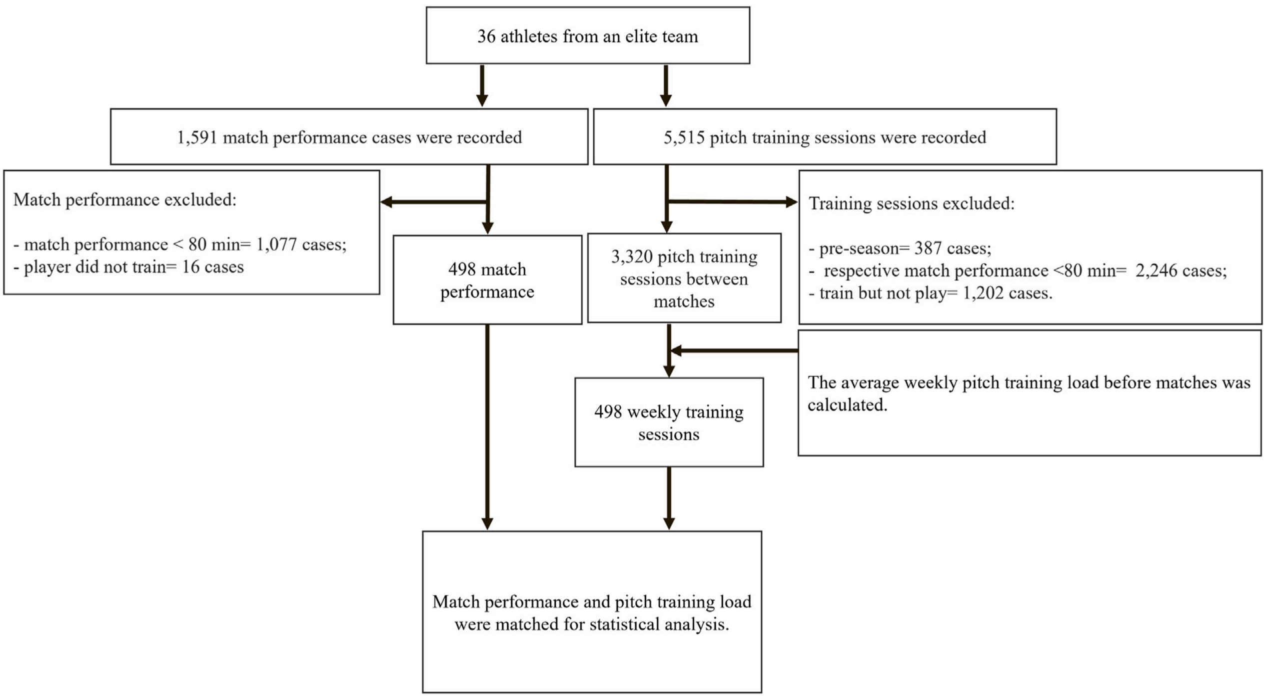

FIGURE 1
Flowchart with inclusion and exclusion criteria for match performance and pitch training data.

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TABLE 1 Match performance and pitch training load description according to player position.

Player position	Match performance				*p*-value	Training load				*p*-value
	Striker	Fullback	Winger	Midfield		Striker	Fullback	Winger	Midfield	
Total distance (m)	9890.7 (9484.5/ 10296.8)	10157.6 (9799.3/ 10515.8) &	9686.2 (9268.5/ 10103.9)	10432.2 (10135.3/ 10729.1) #	**0.025**	3199.5 (2896.1/ 3502.8)	2817.7 (2556.7/ 3078.7) &	3237.7 (2929.3/ 3546.1)	3302.3 (3083.0/ 3521.5) #	**0.032**
Relative distance (m/min)	98.4 (95.3/ 101.5) #	92.6 (89.9/ 95.3) *, &	94.0 (90.8/ 97.2) &	100.3 (98.1/ 102.6) #, @	**0.004**	64.2 (60.2/ 68.1)	63.5 (60.0/67.0)	64.9 (60.8/68.9)	65.1 (62.3/68.0)	0.876
Distance >20 km/h (m)	568.0 (488.3/ 647.7) #	422.1 (356.3/ 487.8) *, &	513.7 (434.2/ 593.3)	566.8 (509.4/ 624.4) #	**0.033**	174.1 (136.9/ 211.2)	104.6 (74.9/ 134.2)	151.1 (114.8/ 187.3)	143.4 (116.7/ 170.1)	**0.031**
Distance >25 km/h (m)	177.2 (135.5/ 219.0) #	102.3 (69.2/ 135.4) *	124.3 (83.9/ 164.8)	144.0 (114.0/ 174.1)	**0.033**	48.1 (34.1/ 62.1) #	21.7 (10.9/ 32.5) *	35.7 (22.5/49.0)	28.8 (18.7/38.8)	**0.017**
Distance >30 km/h (m)	20.8 (11.2/30.5)	11.5 (4.1/18.9)	7.9 (0.0/ 17.00)	12.6 (5.7/19.5)	0.275	5.7 (2.9/ 8.6) #	0.7 (0/2.8) *	3.2 (0.7/5.8)	1.3 (0/3.3)	**0.016**
Sprints (N)	12.4 (9.8/ 15.1)#	7.7 (5.6/9.8)*	8.9 (6.3/11.4)	9.9 (8.0/11.8)	**0.045**	3.7 (2.7/ 4.8) #	1.7 (0.9/2.5) *	2.9 (1.9/3.9)	2.2 (1.4/2.9)	**0.010**
Max. speed (km/h)	30.2 (29.5/30.8)	30.1 (29.5/30.6)	29.9 (29.3/30.6)	29.9 (29.4/30.4)	8.54	27 (25.9/ 28.0)	25.3 (24.4/ 26.2) @	27.3 (26.2/ 28.4) #	26.5 (25.7/27.3)	**0.018**
Accelerations (N)	18.5 (15.0/22.1)	17.2 (14.2/20.1)	14.0 (10.1/17.6)	13.5 (11.0/16.1)	**0.037**	5 (3.9/6)	4.6 (3.7/5.4)	5.7 (4.7/6.8)	5 (4.3/5.8)	0.332
Decelerations (N)	15.7 (12.6/19.2)	20.2 (17.4/23.1)	16.7 (13.3/20.1)	17.4 (14.9/19.9)	0.119	7.4 (5.9/8.8)	6.7 (5.5/8.0)	7.6 (6.2/9.1)	6.7 (5.7/7.8)	0.662
Jumps > 40 cm (N)	3.0 (1.8/ 4.3) #	5.4 (4.4/6.5) *, @, &	2.6 (1.4/3.9)	2.1 (1.2/3.0)	**<0.001**	0.8 (0.4/1.2)	0.5 (0.2/0.8)	0.6 (0.2/1)	0.5 (0.3/0.8)	0.503
COD to left (N)	20.2 (16.2/24.2)	21.1 (17.9/24.4)	15.9 (11.9/19.8)	18.1 (15.2/21.0)	0.087	7.4 (5.9/9)	7 (5.6/8.3)	6.2 (4.6/7.8)	7.7 (6.6/8.9)	0.424
COD to right (N)	20.6 (17.8/23.3)	21.2 (18.9/23.6)	18.6 (15.8/21.4)	20.3 (18.3/22.3)	0.500	8.6 (6.4/10.8)	7.5 (5.8/9.3)	8.9 (6.8/11)	9.1 (7.5/10.6)	0.387
Explosive effort	67.9 (59.8/ 76.0) #	84.3 (77.7/ 91.0) #, &	65.5 (57.6/ 73.6) #	70.71 (64.9/ 76.5) #	**<0.001**	29 (23.7/ 34.4)	26 (21.6/30.4)	29.3 (24.0/34.7)	29.2 (25.3/33.1)	0.543
RHIE blocks effort (N)	24.2 (21.7/26.6)	23.2 (21.1/25.3)	20.6 (18.2/23.1)	22.5 (20.8/24.3)	0.191	9 (7/11)	6 (4.4/7.6)	8.3 (6.4/10.2)	7.9 (6.5/9.4)	**0.029**
Average RHIE effort (N)	4.5 (4.4/4.7)	4.5 (4.3/4.6)	4.4 (4.3/4.5)	4.4 (4.3/4.5)	0.375	4 (3.4/4.7)	4.4 (3.8/5)	4.1 (3.4/4.8)	4.1 (3.6/4.6)	0.844
RHIE block recovery time (RHIE/min)	3.4 (3.0/ 3.9) @	4.2 (3.8/4.5)	4.4 (3.9/ 4.8) *	3.9 (3.6/4.2)	**0.023**	3.5 (2.9/4)	3.6 (3.1/4.1)	3.7 (3.2/4.3)	3.4 (3.1/3.8	8.35
Distance > 20w (m)	2008.4 (1818.4/ 2198.3)	1975.2 (1815.1/ 2135.2) &	2031.2 (1839.4/ 2223.0)	2309.8 (2172.4/ 2447.2) #	**0.004**	684.2 (587.9/ 780.4)	544 (464.0/ 624.0) &	675.2 (578.7/ 771.7)	729.2 (659.6/ 798.7) #	**0.004**
Distance > 55w (m)	250.6 (217.9/ 283.2) #	192.6 (165.7/ 219.5) *	194.1 (161.5/ 226.7)	195.7 (172.1/ 219.2)	**0.034**	101.9 (80.7/ 123.2) #	54.5 (38.0/ 70.9) *, @	85.8 (65.7/ 105.9) #	76.1 (60.9/91.3)	**0.001**
Player load	1063.5 (982.3/ 1144.8)	999.1 (933.3/ 1064.8)	1018.9 (938.8/ 1099.0)	1035.4 (976.9/ 1094.0)	0.628	350.3 (313.4/ 387.2)	310.2 (278.6/ 341.9) @	373.5 (336.0/ 411.1) #	347.5 (320.8/ 374.2)	**0.052**

Data are mean and IC, 95%. The mixed linear model was used to compare match performance and training load across player positions. For this, player ID, was used as a random effect, and player position as a fixed effect. *, $p < 0{,}05$ when compared to striker; #, $p < 0{,}05$ when compared to fullback; @, $p < 0{,}05$ when compared to winger; &, $p < 0{,}05$ when compared to midfield. Bold values indicate $p < 0.05$.

2.5 Contextual factors

Number of training sessions between matches (players are prevented from playing to safeguard themselves for more important matches and only accumulate training sessions to recover); the amount of weekly training (the number of training sessions before a match) and days between matches.

2.6 Statistical analysis

Data are presented as mean and standard deviation (SD) (or, when indicated, confidence interval (CI) 95% or minimum a maximum). To determine the influence of training load on match performance throughout the season, the mixed linear model regression fit was used for 19 dependent variables (see Table 2). Two contextual factors were used as fixed effects: player position and match location. Three contextual factors were used as covariables: training sessions between matches, weekly training sessions, and days between matches, and 17 variables were collected during the training session (see Table 2). Collinearity for the inclusion of independent variables was set at a tolerance of >0.1. Because data from the same player were used multiple times, players were used as random effects (intercept model). A decision tree regression (DTR) model was performed to identify the most important variables (and their respective load) in the training sessions that could explain the athlete's match performance. The DTR model was generated [using the Chi-square Automatic Interaction Detector (CHAID) method]. The nodes (leaves) of the DTR were cleared to compare at least 100 samples in each node. To examine the association between player performance and training session load, the match performance and training session load data were standardized to z-scores and then clustered using a k-means approach. To validate the clusters (i.e., to verify if clusters are different between then), we use the ANOVA-way (using clusters as factors and the z-score of training load variables or match performance as dependent variables). The Chi-squared was used to test the association between the clusters created by k-means and with contextual variables (player position and home-away match condition). All analyses were performed using the statistical package IBM SPSS Statistics v.26.0.

3 Results

Player match frequency was 4 ± 2 days (ranging from 3 to 20 days), training between matches was 2.7 ± 2.7 (ranging from 1 to 31 sessions), weekly sessions were 2.2 ± 1 (ranging from 1 to 5 sessions), and home/away match performances were 260 and 238, respectively.

Mixed linear model regression (Table 2) shows that training load and contextual variables significantly influence game performance. For example, match running relative distance (m/min) was positively influenced by training variables such as amount of training between matches and distance covered >20 W kg^{-1} during training sessions. On the other hand, it is negatively influenced by training variables such as distance covered >55 W kg^{-1}, large block recovery time, acceleration, and days between games, and away match. Table 2 describes those contextual variables such as match avenue, training sessions between matches, days between games, and player position has significant influence on several match performance.

The decision tree regression (DTR) model was used to identify the most important training load variables associated with match performance. In addition, the DTR model shows the extent to which match performance variables are negatively or positively affected by their most important training load variable. Because several match performance variables are affected by the location of the game and the player's position, the DTR model was controlled for these variables when necessary.

Figure 2 (controlled for game location) shows that the total distance (shown at node zero) is associated with the amount of distance spent in activities >20 W kg^{-1} (Nodes 1 and 2). The total distance is negatively impacted by decelerations (Nodes 3 and 4). Thus, Node 1 shows that the distance covered of ≤744.6 m (at intensity >20 W kg^{-1}) is associated with the predicted distance of 10,157.5 m. While running distance of >744.62 m at >20 W kg^{-1} (Node 2), the predicted distance will be statistically greater (10,795.7 m) compared to Node 1. Node 2 (with a statistically smaller total distance compared to Node 1) is divided into two more nodes (Nodes 3 and 4), indicating that in this sample subset there is a difference in performance when considering the number of decelerations performed in the training session. Thus, Node 3 indicates that performing ≤6.5 decelerations in training sessions is associated with 10,406.3 m, while Node 4 indicates that performing >6.5 decelerations in the training session is associated with 9975.5 m (statistically lower performance compared to Node 3). Here, the decision tree suggested that high running load training sessions (i.e., >744.62 m over 20 W kg^{-1}) were beneficial for overall match running performance, while deceleration (i.e., >6.5) had a negative effect.

Figure 3 analyzes which variables influence the relative distance (controlled for game location). Hence, Node 1 shows that players who run ≤744.62 m above 20 W kg^{-1} in training sessions have a predicted relative running distance of 95.431 m/min in matches, which is statistically different from Node 2 (players who run >744.62 m above 20 W kg^{-1} between matches during the training seasons).

In Figure 4A, the total distance achieved >20 km/h in the matches is associated with 45-5Wkg^{-1} running distance activities. While running distance achieved >25 km/h and 30 km/h during matches are related to distance covered >55 W kg^{-1}, and sprints during training sessions (Figures 4B, C).

Also, the maximum speed and the number of sprints (Figures 5A, B) can be explained by the distance >55 W kg^{-1}, but with interference from player load and relative distance, respectively. Likewise, the number of jumps >40 cm (Figure 6A) and decelerations (Figure 6B) were associated with it respectively variable in training sessions, but interference variables were present. Accelerations were significantly associated with sprints (Figure 6C).

Figures 7A, B show the greatest number of COD in the matches performed by the athletes with the highest incidence of jumps >40 cm during the training sessions. However, interference variables associated with performance improvement or decrement

TABLE 2 Mixed linear model regression of the variables related to the physical performance of 77 matches (2022 season) of an elite team in Brazil.

Contextual factors and variables from training sessions	Total distance (m)	Relative distance (m/min)	Distance >20 km/h (m)	Distance >25 km/h (m)	Distance >30 km/h (m)	Sprints (N)	Max. Speed (km/h)	Accelerations (N)	Decelerations (N)
Intercept	**12248,3 (10.436.0/ 13.841.5)**	**107.7 (95.8/118.3)**	**634.3 (411.4/857.2)**	**164.1 (68.2/259.9)**	19.1 (−.8 39.0)	**13.5 (7.4/19.5)**	**30.6 (28.5/32.9)**	**21.7 (11.8/31.7)**	**20.1 (10.4/29.8)**
Match avenue	**−330.8 (-596.4/-87.4)**	**−2.9 (-4.6/-1.3)**	**−59.0 (-91.8/-26.2)**	**−17.9 (-32.1/-3.7)**	−2.5 (−5.3 .4)	−1.0 (−1.9/-0.1)	−0.25 (−0.6/0.1)	0.4 (−1.0/1.8)	−0.4 (−1.8/1.0)
Player position	69.8 (−95.8/227.9)	1.0 (−0.2/2.2)	16.5 (−8.2/41.2)	−.4 (−10.7/9.9)	−1.6 (−4.3 1.1)	−0.2 (−0.8/0.4)	0.03 (−0.2/0.2)	**−1.9 (-3.2/-0.7)**	−0.6 (−1.9/0.7)
Days between games	−57.9 (−136.4/22.5)	**−0.6 (-1.1/-0.1**	**−11.0 (-21.3/-0.6)**	**−4.8 (-9.3−0.4)**	−0.7 (−1.7 .2)	**−0.4 (-0.6/-0.1)**	−0.03 (−0.1/0.1)	0.06 (−0.4/0.5)	−0.2 (−0.6/0.3)
Weekly training session	−99.6 (−264.8/67.5)	−0.6 (−1.7/0.5)	−9.2 (−30.8 12.3)	−3.0 (−12.4/6.3)	−0.7 (−2.6 1.2)	−0.5 (−1.1/0.1)	−0.11 (−0.3/0.1)	0.06 (−0.9/1.0)	−0.2 (−1.1/0.8)
Training sessions between matches	**120.04 (60.6/ 179.1)**	**0.5 (0.1/0.9)**	**14.5 (6.8/22.1)**	**5.5 (2.2/8.9)**	**1.1(.5 1.8)**	**0.4** (0.2/0.6)	0.07 (−0.01/0.15)	0.01 (−0.3/0.3)	0.1 (−0.2/0.5)
Total distance (m)	−0.1 (−0.6/0.3)	0.0 (0.00/0.00)	−0.04 (−0.1/0.0)	0.0 (0.0/0.0)	0.00 (0.0/0.0)	0.00 (0.0/0.0)	0.00 (−0.01/0.02)	−0.00 (0.0/0.0)	0.00 (0.00/0.00)
Relative distance (m/min)	**−14.8 (-27.7/-1.2)**	−0.1 (−0.15/0.00)	−1.0 (0−2.6/0.9)	−.1 (−0.8/0.7)	0.1 (−0.1/0.2	−0.01 (−0.1/0.0)	0.00 (−0.01/0.00)	0.02 (−0.1/0.1)	0.03 (−0.04/0.10)
Distance >20w (m)	**3.2 (1.2/5.2)**	**0.02 (0.00/0.03)**	**0.35 (0.1/0.6)**	.1 (0.0/0.2)	0.00 (0.0/0.0	0.00 (0.0/0.0)	**−0.00 (0.00/0.02)**	0.00 (0.0/0.0)	0.01 (0.00/0.02)
Distance >55w (m)	**−11.7 (-20.4/-3.2)**	**−0.07 (-.012/-0.01)**	0.58 (−0.6 1/0.7)	.4 (−0.1/0.9)	**0.2 (0.1/0.3**	0.03 (0.0/0.1)	**0.01 (0.00/0.02)**	−0.02 (−01/0.0)	−0.02 (−0.06/0.03)
Distance >20 km/h (m)	**−4.7 (-9.3/-0.5)**	−0.01 (−0.04/0.02)	−0.5 (−1.1/0.0)	−.2 (−0.4/0.1)	−0.01 (−0.1/0.0	−0.01 (0.0/0.0)	0.00 (0.00/0.01)	0.01 (0.0/0.0)	0.00 (−0.03/0.02)
Distance >25 km/h (m)	**24.9 (6.1/43.3)**	0.1 (−0.02 .22)	**4.2 (1.7/6.5)**	.9 (−0.1/1.9)	0.1 (−0.1/0.3	0.06 (0.0/0.1)	0.01 (−0.02/0.03)	0.07 (0.0/0.2)	0.03 (−0.07/0.13)
Distance >30 km/h (m)	6.1 (−31.2/43.2)	0.2 (−0.07/0.42)	0.4 (−4.5/5.2)	.1 (−2.0/2.1)	0.03 (−0.4/0 .5	0.02 (−0.1/0.2)	0.00 (−0.1/0.0)	−0.2 (−0.4/0.0)	−0.1 (−0.3/0.2)
Sprints (N)	−41.3 (−284.5/ 203.7)	−0.3 (−1.9/1.3)	**−35.8 (-67.4/-4.3)**	−5.4 (−19.0/8.3)	−2.1 (−4.8/0.6	−0.4 (−1.3/0.4)	−0.21 (−0.5/0.1)	−0.6 (-1.9/0.8)	−0.6 (−1.9/0.8)
Maximum speed (km/h)	−56.9 (−118.5/4.7)	−0.3 (−0.7/0.2)	−0.7 (−8.7/7.3)	.5 (−2.9/4.0)	−0.1 (−0.7/0.7)	−0.1 (−.2/0.2)	0.01 (−0.1/0.1)	−0.02 (−.4 .3)	−0.1 (−0.5/0.2)
Accelerations (N)	−52.1 (−112.5/9.8)	**−0.5(-0.9/0-.1)**	−5.0 (−12.7/3.1)	−.5 (−4.0/2.9)	−0.01 (−.7 .7)	−0.1 (−.3/0.2)	−0.07 (−0.2/0.0)	0.1 (−0.2/0.4)	−0.3 (−0.6/0.1)
Decelerations (N)	35.9 (−17.8/90.1)	0.04 (−0.3/0.4)	−1.9 (−9.0/5.1)	−.6 (−3.7/2.4)	−0.1 (−0.8/0.5)		0.00 (−0.1/0.1)	−0.1 (−0.4/0.2)	0.3 (0.0/0.6)

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TABLE 2 (*Continued*) Mixed linear model regression of the variables related to the physical performance of 77 matches (2022 season) of an elite team in Brazil.

Contextual factors and variables from training sessions	Total distance (m)	Relative distance (m/min)	Distance >20 km/h (m)	Distance >25 km/h (m)	Distance >30 km/h (m)	Sprints (N)	Max. Speed (km/h)	Accelerations (N)	Decelerations (N)
						0.00 (−0.2/0.2)			
Jumps >40 cm (N)	12.4 (−127.9/ 149.0)	0.19 (−0.7/1.1)	0.6 (−17.5/18.6)	−4.2 (−2.0/3.5)	−0.9 (−2.5/0.7)	−0.3 (−0.8/0.2)	−0.02 (−0.2/0.2)	**1.0** (0.2/1.8)	0.2 (−0.6/1.0)
COD to left (N)	−15.4 (−70.8/40.4)	0.2 (−0.2/0.6)	1.5 (−5.8/8.9)	−.1 (−.3/3.0)	0.2 (−0.4/0.9)	−0.05 (−0.2/0.2)	0.02 (−0.1/0.1)	−0.02 (−0.3/0.3)	−0.2 (−0.5/0.2)
COD to right (N)	14.2 (−37.9/67.0)	−0.03 (−0.2/0.6)	−4.1 (−11.0/2.8)	**−3.2 (-6.1/-0.2)**	**−0.7 (-1.3/-0.1)**	**−0.2 (-0.4/0.0)**	**−0.09 (-0.2/0.0)**	0.1 (−0.2/0.4)	−0.03 (−0.3/0.3)
RHIE block efforts (N)	17.5 (−78.4/111.9)	0.1 (−0.6/0.7)	1.6 (−10.7/14.0)	3.4 (-2.0/8.7)	0.1 (−1.0/1.2)	0.2 (−.1/0.6)	0.06 (−0.1/0.2)	0.2 (−0.3/0.8)	0.3 (−0.2/0.9)
Average RHIE effort (N)	−9.8 (−57.4/37.6)	−0.2 (−0.5/0.2)	3.4 (−2.8/9.5)	2.4 (−0.2/5.1)	0.4 (−.2 .9)	**0.2 (0.0/0.3)**	0.06 (0.0/0.1)	−0.1 (−0.3/0.2)	0.01 (−0.2/0.3)
RHIE block recovery time (RHIE/min)	18.1 (−46.9/83.1)	−0.1 (−0.5/0.3)	**−9.1−17.4/0-.7)**	**−4.2 (-7.9/-0.6)**	−0.2 (−1.0/0.5)	**−0.3 (-0.5/-0.1)**	−0.05 (−0.1//0.0)	−0.2 (−0.5/0.2)	0.02 (−0.3/0.4)

Jumps >40 cm (N)	COD to left (N)	COD to right (N)	Explosive effort	RHIE blocks effort (N)	Average RHIE effort (N)	RHIE block recovery time (RHIE/min)	Distance >20w (m)	Distance >55w (m)	Player load
4.4 (0.8/8.0)	**21.6 (10.7/32.4)**	**22.3** (12.2/32.3)	**83.6 (60.5/106.7)**	30.1 **(21.86/38.31)**	**4.5 (3.95 5.06)**	**2.8 (1.50 4.42)**	**2,666.0 (2,089.1/ 3,242.9)**	**312.4 (223.0/401.8)**	**1,166.2 (956.5/ 1,375.9)**
0.1 (−0.4/0.6)	0.5 (−1.1/2.0)	−1.2 (−2.7/0.3)	−1.5 (−4.8/1.7)	−0.9 (−2.08/0.35)	−0.05 (−0.13/0.03)	0.1 (−0.10/0.32)	**−204.4 (-289.6/- 119.1)**	**−17.7 (-31.1/-4.4)**	−11.9 (−41.5/17.6)
−0.9 (−1.4/-0.4)	**−1.7 (-3.1/-0.4)**	−0.5 (−1.5/0.4)	**−4.2 (-7.3/-1.1)**	−0.8 (−1.7/0.04)	−0.05 (−0.10/0.00)	0.15 (−0.03/0.32)	**84.2 (24.1/144.2)**	**−9.3 (-18.4/-0.2)**	−3.6 (−33.1/25.8)
0.1 (0.0/0.3)	−0.1 (−0.6/0.4)	0.1 (−0.6/0.4)	0.2 (−.9/1.2)	−0.3 (−0.7/0.1)	−0.02 (−0.05/0.01)	0.03 (−0.03/0.10)	−20.2 (−47.0/6.6)	**−4.2 (-8.4/-0.1)**	−2.1 (−11.8/7.6)
−0.04 (−0.4/0.3)	−0.4 (−1.4/0.7)	−0.5 (−1.5/0.5)	−1.8 (−4.0/0.4)	**−0.8 (-1.5/.01)**	0.02 (−0.04/0.07)	0.10 (−0.04/0.24)	−40.0 (−95.8/15.9)	−8.5 (−17.2/0.2)	−15.0 (−34.7/4.8)
−0.1 (−0.2/0.0)	0.2 (−0.2/0.5)	0.1 (−0.3/0.4)	0.5 (−0.3/1.2)	**0.3 (.07 .63)**	0.01 (−0.01 .03)	−0.01 (−0.06/0.04)	**37.7 (17.8/57.6)**	**6.1(3.0/9.2)**	**11.8 (4.8/18.7)**
0.00 (0.00/0.00)	0.00 (−0.0/0.02)	**−0.00 (-0.01/0.00)**	−0.01 (−0.01/0.00)	0.00 (0.00/0.00)	0.00 (0.00/0.00)	0.00 (0.00/0.00)	−0.1 (−0.3/0.1)	0.00 (0.0/0.0)	0.0 (−0.1/0.0)
0.00 (−0.02/0.03)	−0.1 (−0.03/0.1)	0.02 (−0.1/0.1)	−0.07 (−0.2/0.1)	0.00 (−0.06/0.06)	0.00 (0.00/0.01)	0.00 (−0.02/0.01)	−3.4 (−7.9/1.0)	0.01 (−.7/0.7)	−1.3 (−2.8/0.2)
0.00 (0.00/0.01)	0.01 (−0.00/ 0 .02)	**0.01 (0.00/0.02)**	**0.04 (0.01/0.1)**	**0.01 (0.00/0.02)**	0.00 (0.00/0.00)	0.00 (0.00/0.00)	**1.5 (0.8/2.2)**	0.1 (0.0/0.2)	**0.3 (0.1/0.5)**
−0.01 (−0.03/0.01)	0.02 (−0.03/0.01)	−0.04 (−0.1/0.0)	**−0.1 (-0.2/-0.00)**	0.00 (−0.04/0.04)	0.00 (0.00/0.01)	0.00 (−0.01/0.00)	−2.6 (−5.6/0.3)	**0.6 (0.1/1.1)**	**−1.2 (-2.3/-0.2)**

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TABLE 2 (*Continued*) Mixed linear model regression of the variables related to the physical performance of 77 matches (2022 season) of an elite team in Brazil.

Jumps >40 cm (N)	COD to left (N)	COD to right (N)	Explosive effort	RHIE blocks effort (N)	Average RHIE effort (N)	RHIE block recovery time (RHIE/min)	Distance >20w (m)	Distance >55w (m)	Player load
0.00 (−0.01/0.01)	−0.01 (−0.03/0.01)	−0.01 (−0.04/0.02)	−0.02 (−0.1/0.03)	0.0 (−0.03/0.02)	0.00 (0.00/0.00)	0.00 (−0.01/0.00)	**−2.2** (−3.7/-0.7)	−0.1 (−0.3/0.1)	−0.2 (−0.7/0.3)
−0.02 (−0.1/0.0)	**0.2 (0.1/0.3)**	**0.1 (0.0/0.2)**	0.2 (−0.04/0.4)	**0.1 (0.06/0.24)**	0.00 (0.00/0.01)	−0.01 (0.00/0.00)	**10.8 (4.5/17.0)**	0.9 (0.0/1.9)	**2.8 (0.7/5.0)**
−0.01 (−0.1/0.1)	−0.1 (−0.4/0.1)	−0.1 (−0.3/0.2)	−0.3 (−0.8/0.1)	−0.1 (−0.28/0.07)	0.00 (−0.02/0.01)	0.03 (0.00/0.06)	0.9 (−11.5/13.5)	0.04 (−1.9/2.0)	2.6 (-1.8/7.0)
0.2 (−0.3/0.7)	**−3.0 (-4.5–1.5)**	−1.0 (−2.5/0.4)	−1.4 (−4.6/1.7)	**−1.6 (-2.77/-0.43)**	−0.07 (−.15/0.01)	0.17 (−0.03/0.38)	−54.2 (−136.1/27.7)	−9.8 (−22.6/3.0)	−18.6 (−47.1/9.8)
0.01 (−0.1/0.1)	0.2 (−0.2/0.5)	0.1 (−0.3/0.5)	0.1 (−0.7/0.9)	−0.1 (−0.40/0.19)	0.00 (−0.01/0.03)	0.02 (−0.04/0.06)	−18.2 (−38.9/2.6)	−1.9 (−5.1/1.3)	−3.4 (−10.6/3.9)
−0.02 (−0.1/0.1)	0.13 (−0.2/0.5)	−0.2 (−0.5/0.2)	−0.1 (−0.9/0.6)	−0.2 (−.51 .07)	−0.01 (−0.03/0.01)	0.04 (−0.02/0.09)	−19.4 (−40.0/1.2)	−1.4 (−4.6/1.8)	−4.2 (−11.4/3.0)
0.04 (−0.1/0.2)	0.1 (−0.2/0.5)	0.3 (0.04/0.6)	**0.7 (0.00/1.4)**	0.2 (−0.01/0.51)	−0.01 (−0.03/0.01)	0.00 (−0.04/0.05)	7.4 (−10.8/25.6)	0.4 (−2.4/3.2)	3.5 (−2.9/10.0)
0.3 (0.0/0.6)	**1.6 (0.7/2.4)**	**1.2 (0.4/2.0)**	1.5 (−0.3/3.4)	0.6 (−0.04/1.30)	0.03 (−0.01/0.08)	−0.11 (−0.23/0.01)	−15.0 (−61.7/31.8)	1.0 (−6.3/8.2)	16.4 (−0.1/33.0)
−0.00 (−0.1/0.1)	0.1 (−0.3/0.4)	0.02 (−0.3/0.4)	0.05 (−0.7/0.8)	0.1 (−0.18/0.36)	−0.02 (−0.03/0.00)	−0.04 (−0.09/0.01)	1.5 (−17.4/20.4)	0.01 (−2.9/2.9)	0.9 (−5.9/7.7)
−0.02 (−0.1/0.1)	−0.1 (−0.5/0.2)	**0.3 (0.01/0.6)**	−0.3 (−1.0/0.4)	−0.2 (−0.49/0.02)	0.00 (−0.02/0.02)	**0.04 (0.00/0.09)**	−6.8 (−24.6 11.1)	**−3.6 (-6.4/-0.8)**	3.3 (−3.2/9.7)
0.08 (−0.1/0.3)	−0.3 (−0.9/0.3)	0.1 (−0.5/0.7)	0.4 (−0.9/1.7)	0.1 (-0.31/0.61)	0.01 (−0.02/0.04)	−0.01 (−0.09/0.07)	7.6 (−24.5/39.7)	.8 (−4.2/5.8)	1.7 (−9.6/13.1)
0.01 (−0.1/0.1)	0.1 (−0.2/0.3)	−0.2 (−0.5/0.1)	−0.1 (−0.7/0.5)	0.1 (−0.13/0.33)	0.01 (−0.01/0.03)	−0.03 (−0.06/0.02)	−0.6 (−16.5/15.4)	**2.8 (0.3/5.3)**	−1.8 (−7.3/3.8)
0.1 (−0.1/0.2)	−0.4 (−0.8/0.0)	−0.03 (−0.4/0.4)	0.00 (−0.8/0.8)	**−0.5 (-0.79/-0.17)**	−0.2 (−0.04/0.00)	**0.09 (0.04/0.15)**	−3.6 (−25.4/18.2)	**−4.7 (-8.1/-1.3)**	−4.3 (−11.8/3.2)

COD, changes of direction; RHIE, repeated high-intensity exercise. Bold values indicate $p < 0.05$.

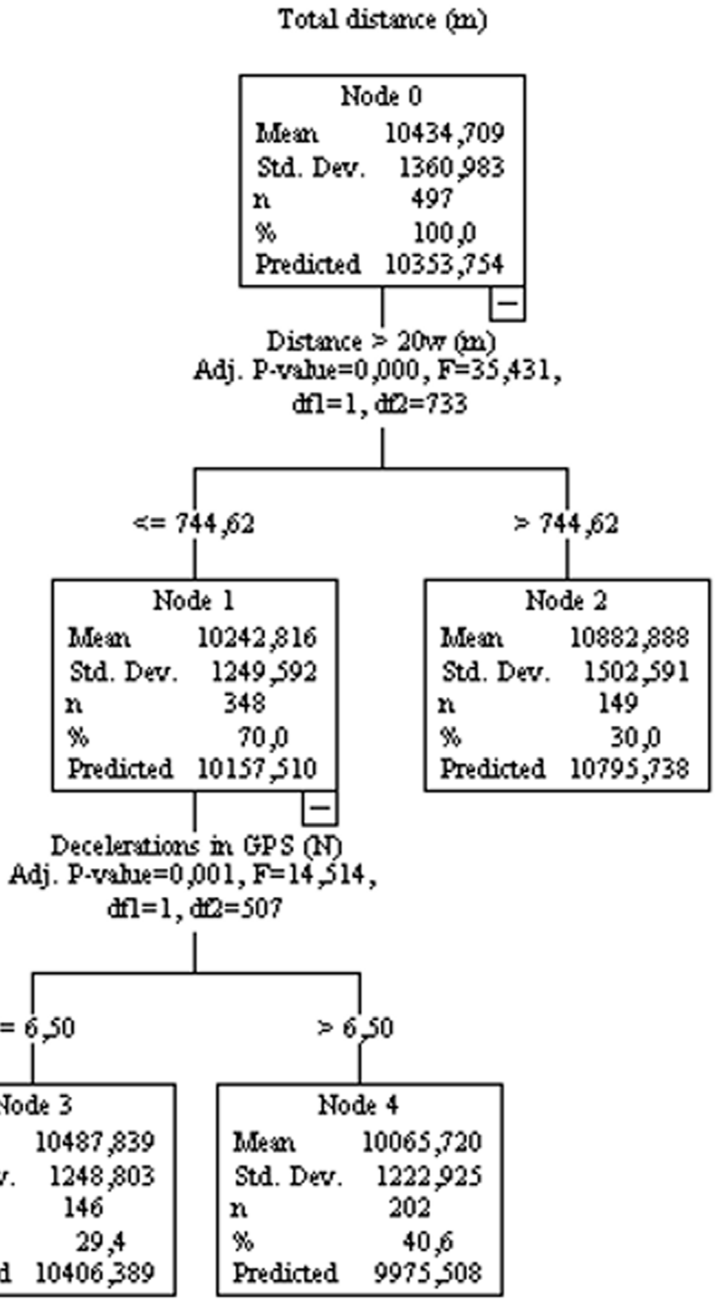

FIGURE 2
Decision tree regression for mean values of total distance controlled for Home/away condition from 77 matches from an elite team. Independent variables are data from sessions training between matches during a season.

are present. In Figure 7A, distance >20 km/h impact negatively the COD, while sprints and RHIE block recovery time improving it.

The distance running >20 or 55 W kg^{-1} was associated with the respective activity during training sessions (Figure 8).

The number of explosive efforts in matches (Figure 9A) was associated with deceleration (Nodes 1 and 2). Running distance >20 Km/h impacts the explosive effort (Nodes 3 and 4) negatively, while large RHIE block recovery time positively impacts the explosive effort (Nodes 5 and 6). RHIE block was associated with RHIE block recovery time (Figure 9B), with sprints (nodes 3 and 4) and decelerations (nodes 5 and 6) impacting positively. The average RHIE was associated with sprints and jumps (Figure 9C). RHIE block recovery time was associated with their respective training variable (Figure 9D), with the distance covered at 35–45 W kg^{-1} improving RHIE block recovery time, while sprints worsening it.

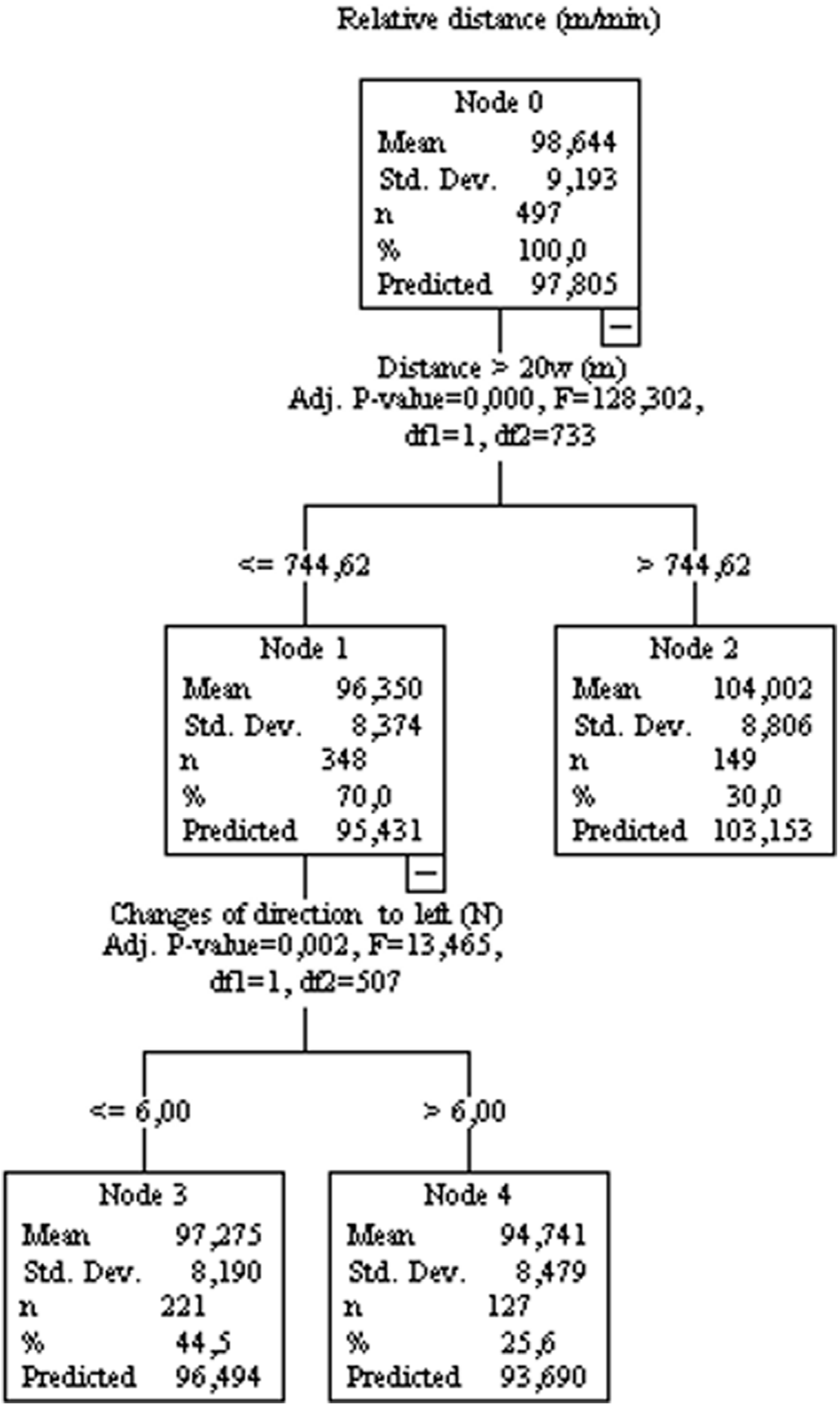

FIGURE 3
Decision tree regression for mean values of relative distance from 77 matches of an elite team. Data from training sessions between matches during a season are used as independent variables.

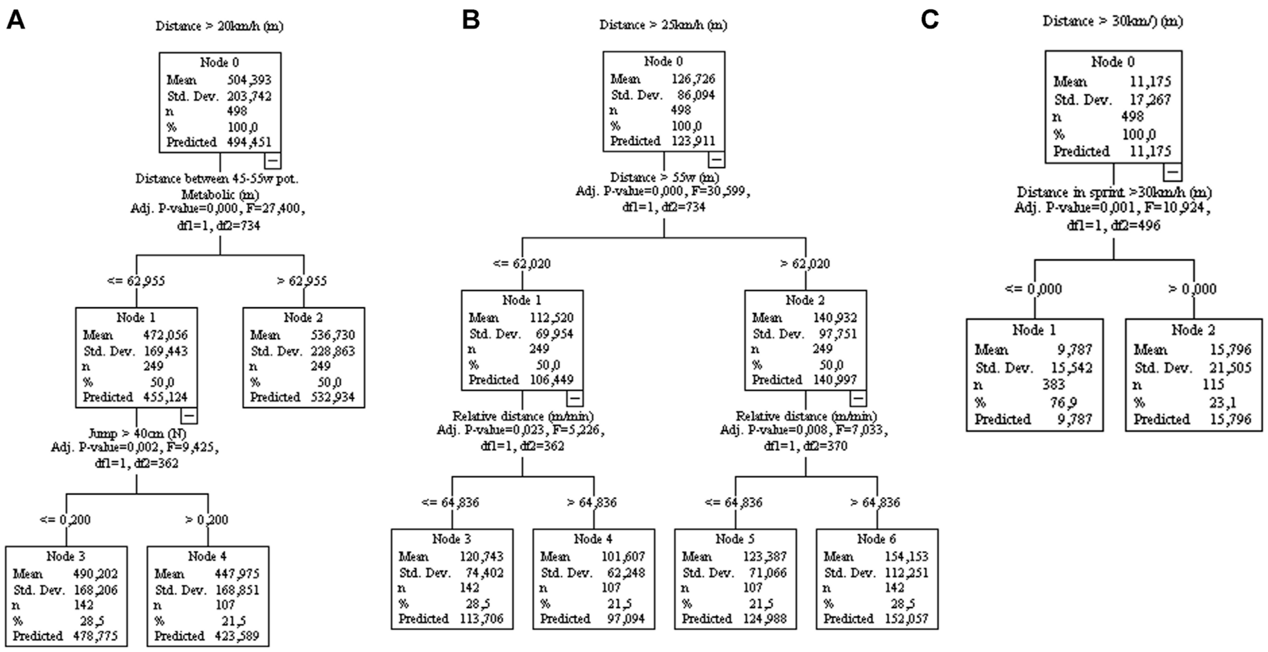

FIGURE 4
Decision tree regression for distance mean values of distance running at 20 km/h [**(A)**, controlled for home/away condition], 25 km/h [**(B)**, controlled for home/away condition], and 30 km/h **(C)** from 77 matches of an elite team. Data from training sessions between matches during a season are used as independent variables.

To verify the association between training load and match performance, in Figure 10, three clusters were created from training load (high, medium, and low load clusters) and match performance (high, medium, and low performance clusters). All the variables of the three clusters from both match performances and training load are significantly different within (ANOVA: $p < 0.001$). Figure 10 plot data from match performance data as a function of training load. The Chi-square test identified a significant association ($p < 0.001$, phi = 0.246) between training load and match performance. The training load clusters were not associated with player position or home-away match condition (data not shown, all >0.325). However, the match performances clusters were associated with player position and home-away match condition ($p = 0.001$, phi = 0.364, see Figure 11).

4 Discussion

It is important to note that these data are from a busy season of a world elite team (77 matches, i.e., one match every 4 days per player). The team has a 36-man squad that rotates throughout the season to keep up with the match schedule. This is an extremely high volume for elite soccer, although it is common in Brazil. The main challenge for the training team is to give the athletes the physical conditioning stimulus (in a few training opportunities, i.e., two training sessions between matches) without leading them to acute overtraining (high load in one session) or chronic overtraining (high load of training combined with high load of matches), which can lead to injuries due to overload (Kalkhoven et al., 2021). An optimal training load for Brazilian elite soccer players has not been reported in the literature. Therefore, Brazilian soccer coaches/trainers certainly learn from trial and error. This work presents a case study analyzing training load values and their association with field performance. In this sense, it is indicated here the load values that will benefit athletes who are subjected to a busy calendar (such as the Brazilian). The main finding of this study was to identify that performance variables in games of a team with an extensive and congested season are related to the training load variables in a specific way. Possible stimuli interference was also identified, suggesting that a periodization (or load modulation) of the stimuli is necessary to improve the performance of athletes.

The mixed linear model and regression trees suggest that the variables from running sessions (which have a greater mechanical impact on players), such as COD, accelerations, decelerations, and jumps (McBurnie et al., 2022), negatively affect game speed variables (such as running at speeds >20, >25, or >30 km/h) and total running distance. On the other hand, variables related to greater mechanical impact positively influence the performance of variables related to their domain (COD, accelerations, decelerations, and jumps), indicating the specificity of the stimulus. The variables related to running in a straight line are positively influenced by the variables related to distances covered at high intensity (running >25 km/h or >20 W kg^{-1}), which reinforces the specificity of the stimulus. For example, total distance, relative speed, or distance traveled at 20 km/h during games are all positively influenced by distances traveled >20W. In addition, covering distances >25, >30 km/h, running at maximum speed, or the number of sprints are all positively influenced by covering distances at >55 W kg^{-1} in training sessions. Previous research (Little and Williams, 2005) has shown that acceleration, agility and maximal speed are specific traits and are relatively unrelated to one another in

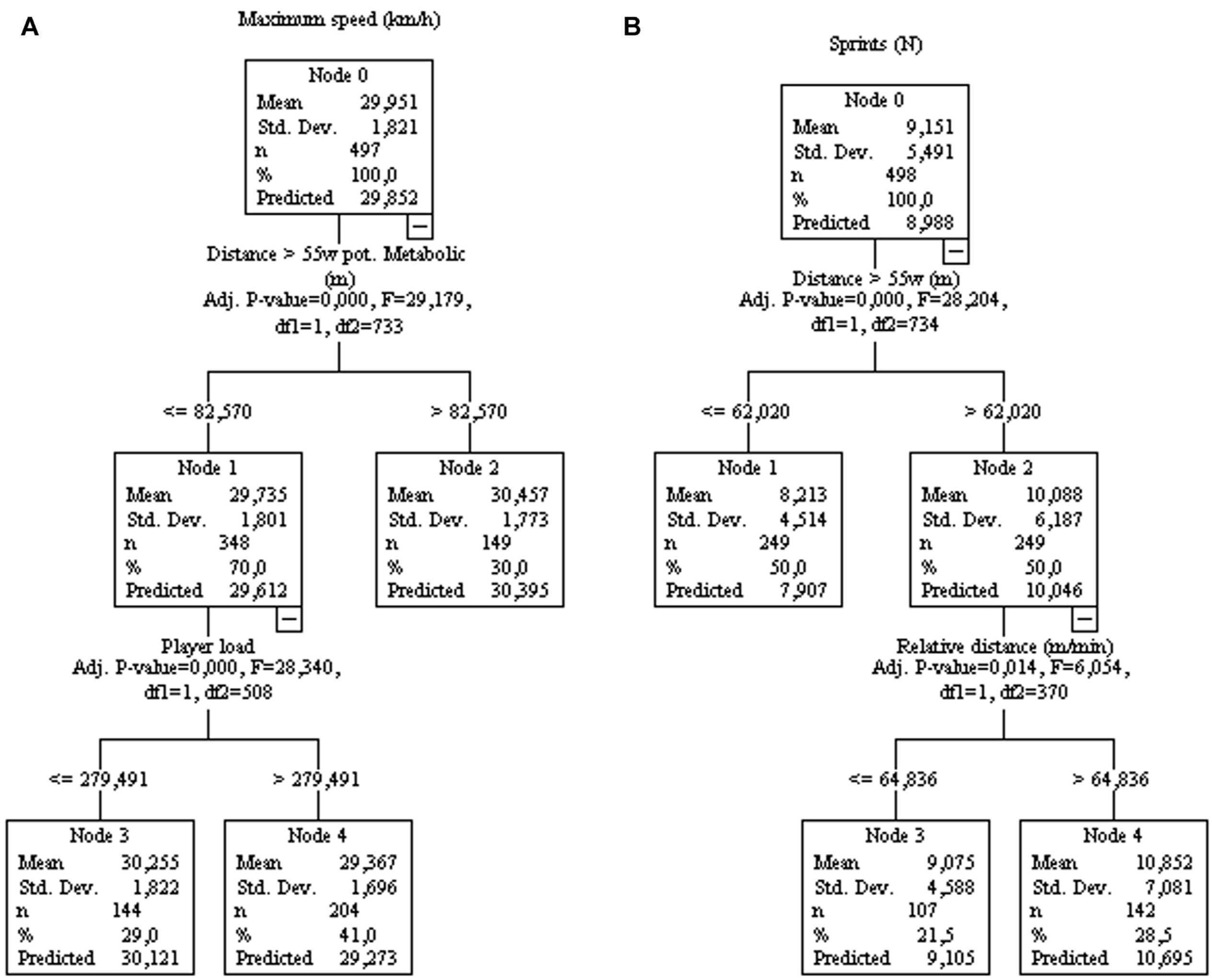

FIGURE 5
Decision tree regression for maximum speed [**(A)**, controlled for home/away condition] and amounts of sprints [**(B)**, controlled for home/away condition] from 77 matches of an elite team. Data from training sessions between matches during a season are used as independent variables.

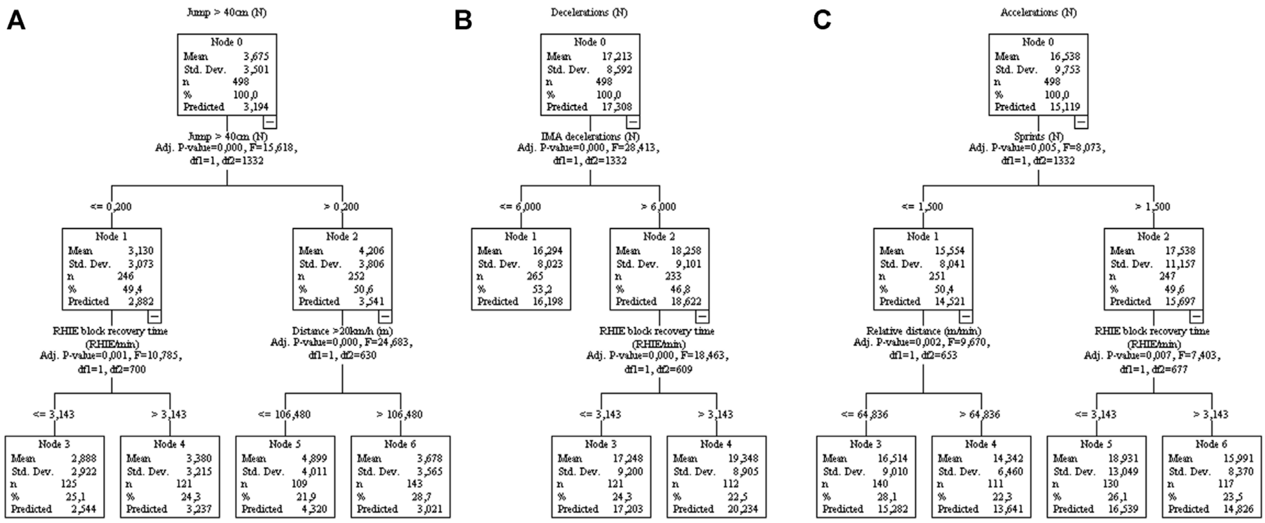

FIGURE 6
Decision tree regression for amounts of Jumps [**(A)**, controlled for home/away condition], acceleration [**(B)**, controlled for player position], and deceleration [**(C)**, controlled for player position] from 77 matches of an elite team. Data from training sessions between matches during a season are used as independent variables.

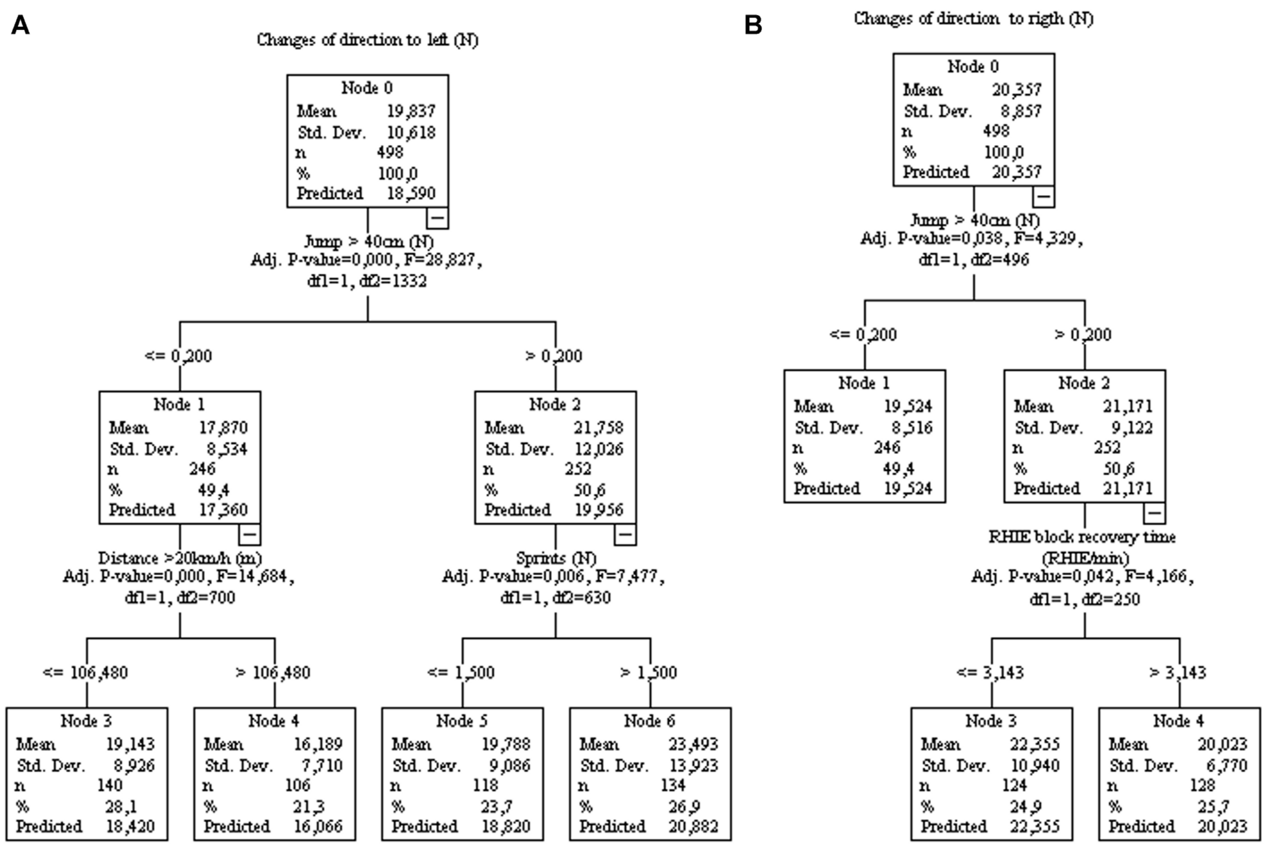

FIGURE 7
Decision tree regression for amounts of change of direction to left **(A)**, controlled for player position and to the right **(B)** from 77 matches of an elite team. Data from training sessions between matches during a season are used as independent variables.

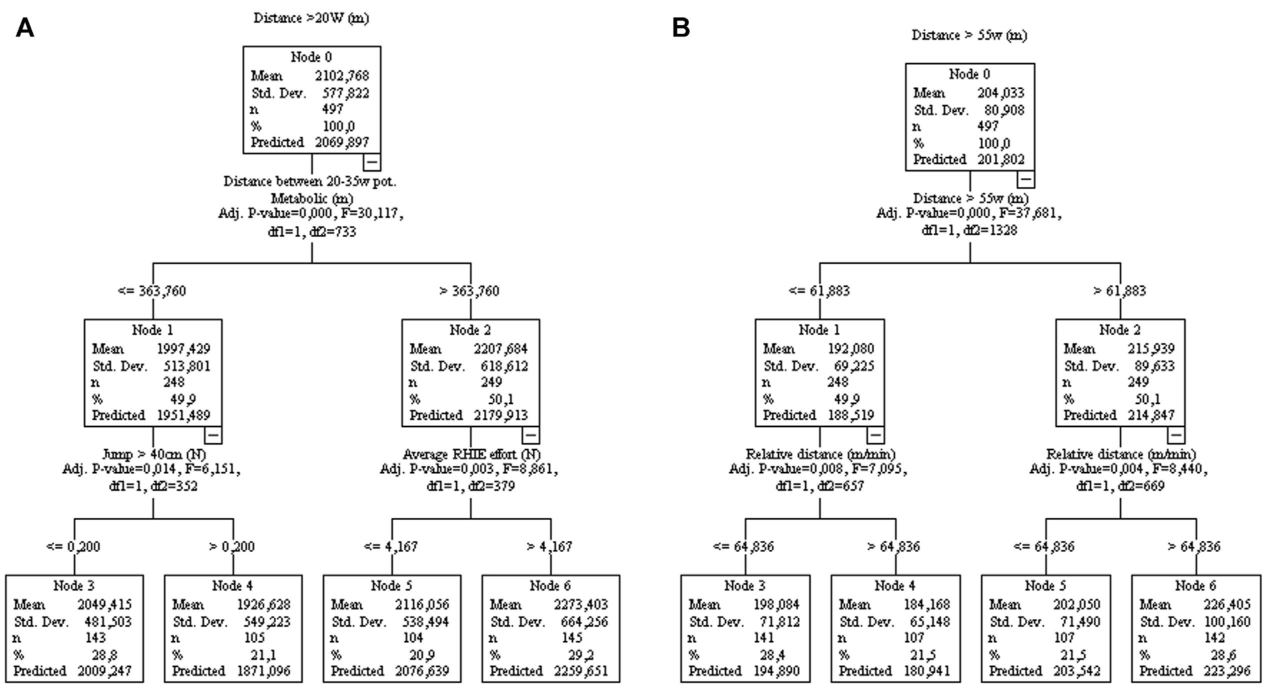

FIGURE 8
Decision tree regression for the running distance >20W [**(A)**; controlled for home/away condition] and >55W [**(B)**, controlled for player position] from 77 matches of an elite team. Data from training sessions between matches during a season are used as independent variables.

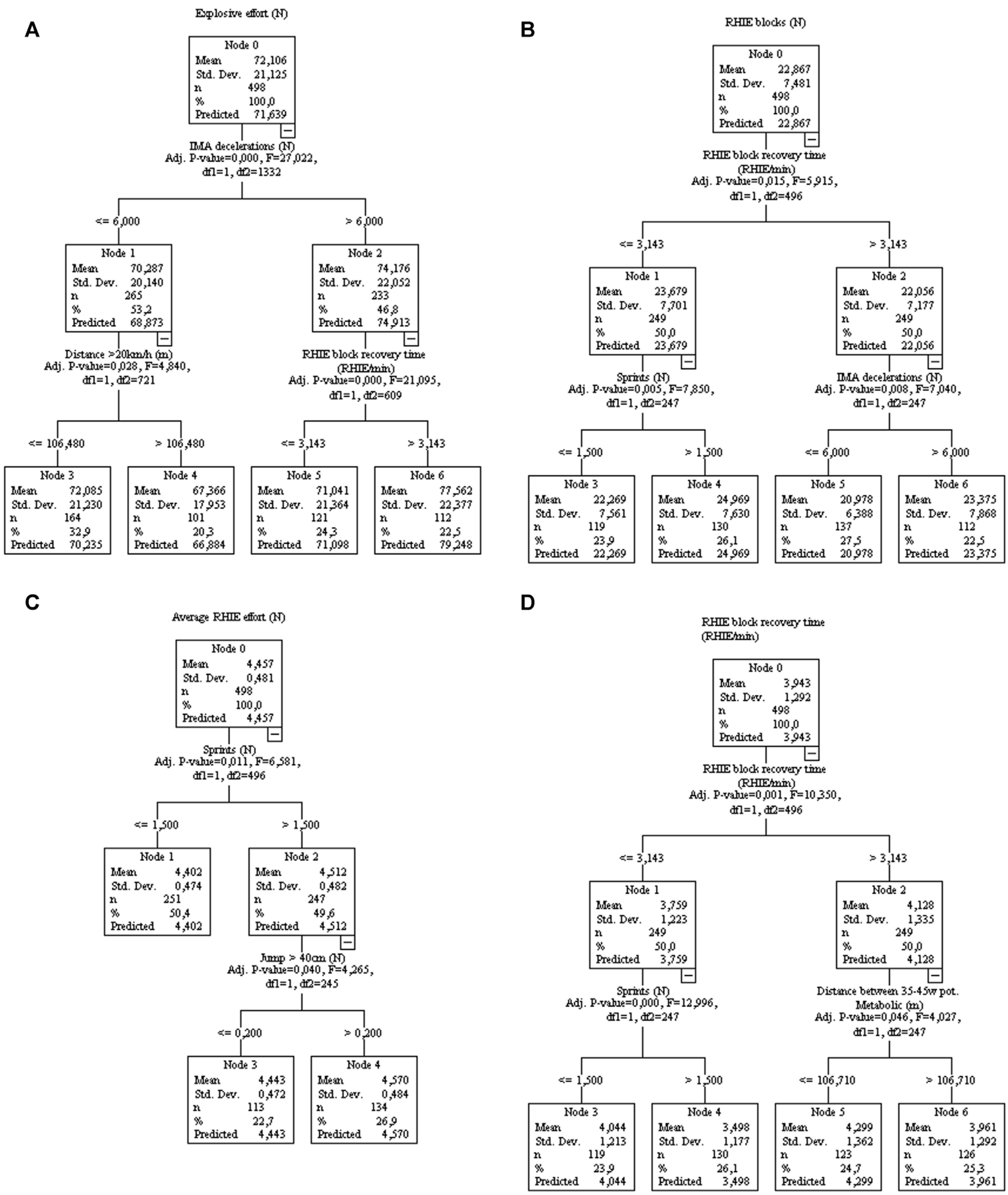

FIGURE 9
Decision tree regression for amount of explosive of effort [**(A)**, controlled for player position], repeated high-intensity effort (RHIE) block **(B)**, average RHIE **(C)**, and RHIE recovery time **(D)** from 77 matches of an elite team. Data from training sessions between matches during a season are used as independent variables.

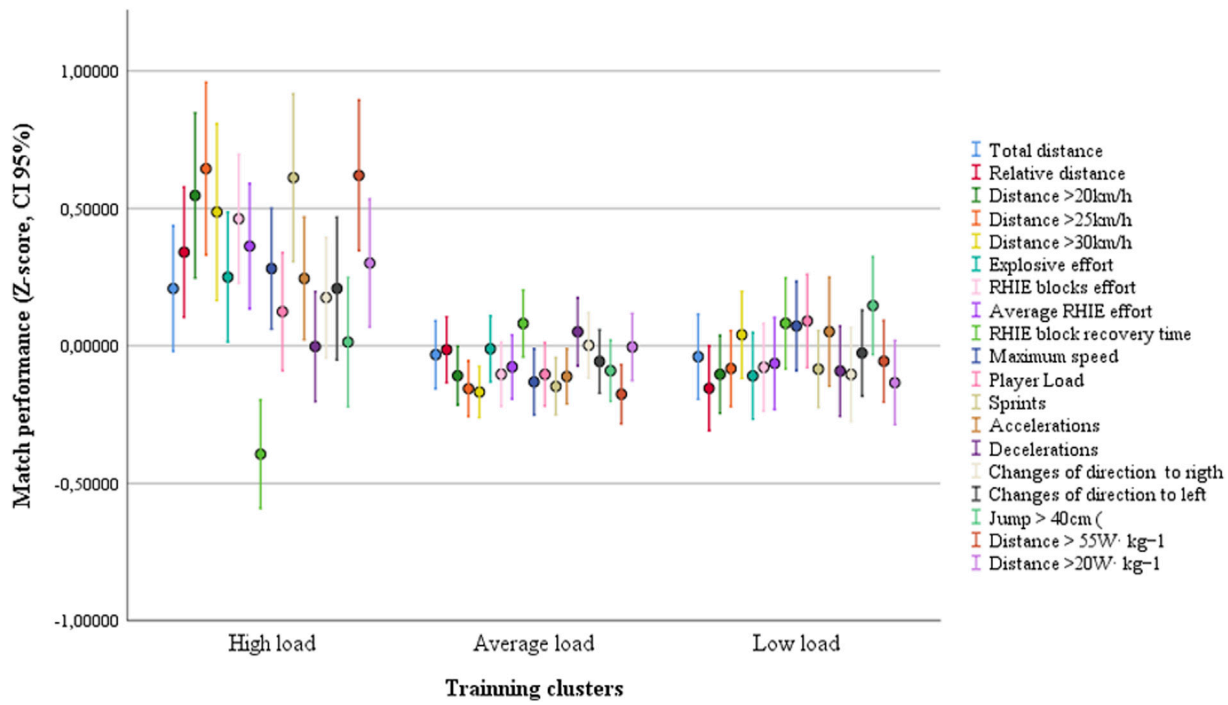

FIGURE 10
Match performance plotted as a function of three different training loads over a season from an elite Brazilian team.

soccer players. In this sense, the authors suggested that training procedures for each component need to be considered during the training process. For example, a previous experimental study (Young et al., 2001) showed that an increase in COD load reduces the gains in sprint performance. COD training improves the COD-test, but does not improve straight line speed performance. Therefore, the present data indicated that an interference phenomenon could occur in the real scenario, i.e., when a high load of two distinct capabilities (running in straight line vs COD, deceleration, and jump) is applied throughout the season. same training block. It is important to note that individuals with poor performance in straight-line running (always on the left side of the decision trees) are influenced by the variables COD, decelerations, jumps, or player load. For example, the total distance covered in games is positively influenced by the distance covered at >20 W kg^{-1}; however, individuals who cover a distance ≤744.62 m at 20 W kg^{-1} (left side of the tree, Figure 2A) are the ones who suffer a negative influence from the high load of deceleration activities (>6.5 actions). The same pattern can be observed for running variables such as relative distance, running at different speeds (>20, >25, >30 km/h or maximal speed) or intensities >20 or 55 W kg^{-1}.

In Figure 11, three match performances were plotted as a function of three training loads. Significant associations were identified between training load and performance in matches. The high load values described here have a beneficial effect on match performance, despite inter-stimuli interference discussed above. In addition, our cluster analysis revealed that there are three distinct performances in both match and training performance. As expected, the match performance cluster was significantly associated with the player position and the home-away factor (Figure 11). However, the training load was not associated with player position or the match venue. Thus, we can rule out the possibility that the association between training load and match performance found in the present study is significantly influenced by player position or the home-away factor.

In a practical application, the decision tree regression model suggests beneficial loads and possible corrections to improve athlete performance. In this sense, the training blocks to improve agility, accelerations/decelerations, and jumps must be carefully planned to improve their respective qualities on the match, and at the same time, strategies must be tested to mitigate drops in straight-line running performance. For example, match relative speed was associated with running a distance greater than 744.62 m at an intensity of >20W. However, athletes who do not reach this distance can improve their relative speed if they have a lower the activities related to mechanical impacts (e.g., COD or jumps). As these data are based on observational data, future studies experimenting with this load modulation and periodizing the stimuli may confirm our findings. Also, future studies investigating whether the interferences identified here are due to a lack of specific stimulus (due to the short training time to provide the stimuli in a busy schedule) or due to cross interference.

5 Conclusion

This study presents a positive training load from a busy season of an elite Brazilian professional team. In addition, it can be stated that

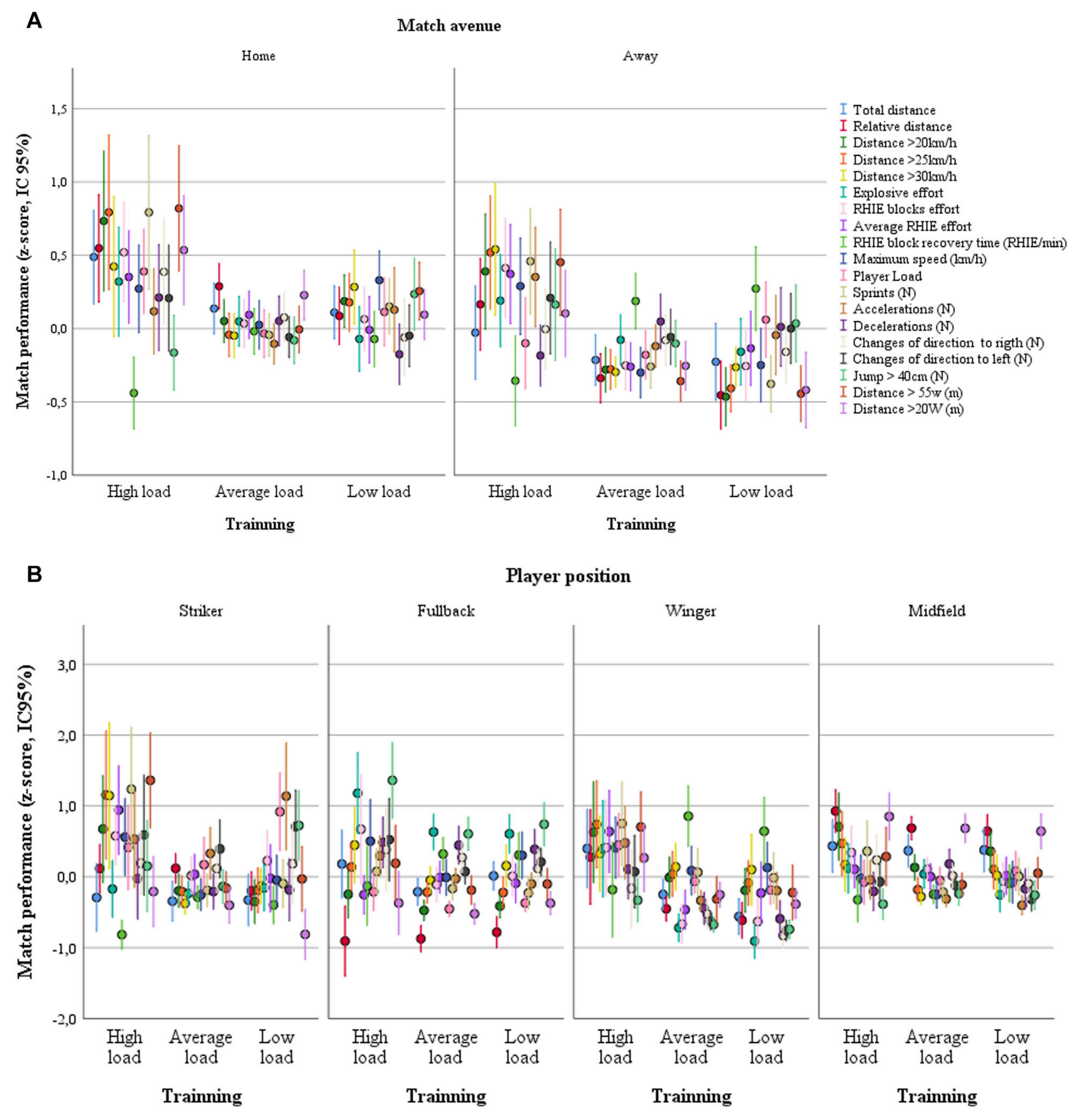

FIGURE 11
Match performance plotted as a function of training load separated by home-away match condition **(A)** and player position **(B)**.

the interference effect occurs when high physical training is applied to different physical skills (e.g., COD and running in a straight line) throughout the season. Additionally, the regression tree model can be a useful tool to identify optimal loads and possible corrections to improve the athlete's match 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 humans were approved by the UNIVERSIDADE SÃO JUDAS TADEU - AMC SERVIÇOS EDUCACIONAIS. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

LB: Conceptualization, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. EF: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Supervision, Visualization, Writing–original draft, Writing–review and editing. JT: Investigation, Writing–original draft, Writing–review and editing. AT: Investigation, Resources, Writing–review and editing. LL: Investigation, Resources, Writing–review and editing. PC: Investigation, Resources, Writing–review and editing. DM: Funding acquisition, Investigation, Writing–original draft, Writing–review and editing. PF: Investigation, Writing–original draft, Writing–review and editing. EC: Investigation, Writing–review and editing. RT: Conceptualization, Data curation, Funding acquisition, Project administration, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. RF: Conceptualization, Data curation, Funding acquisition, Project administration, Supervision, Validation, Writing–original draft, Writing–review and editing, Resources.

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Conflict of interest

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

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

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References

Borin, J., Prestes, J., and Moura, N. A. (2007). Caracterização, Controle e Avaliação: limitações e Possibilidades no Âmbito do Treinamento Desportivo. *Rev. Treinamento Desport.* 8 (1), 6–11.

Branquinho, L., Ferraz, R., and Marques, M. C. (2021a). 5-a-Side game as a tool for the coach in soccer training. *Strength and Cond. J.* 43 (5), 96–108. doi:10.1519/ssc.0000000000000629

Branquinho, L., Ferraz, R., Travassos, B., Marinho, D. A., and Marques, M. C. (2021b). Effects of different recovery times on internal and external load during small-sided games in soccer. *Sports Health* 1941738121995469, 324–331. doi:10.1177/1941738121995469

Carling, C., Reilly, T., and Williams, A. M. (2008). "Performance assessment for field sports," in *Performance assessment for field sports* (England, UK: Routledge). doi:10.4324/9780203890691

Clemente, F. M., Rabbani, A., Conte, D., Castillo, D., Afonso, J., Clark, C. C. T., et al. (2019). Training/match external load ratios in professional soccer players: a full-season study. *Int. J. Environ. Res. Public Health* 16 (17), 3057. doi:10.3390/ijerph16173057

Dellal, A., Lago-Peñas, C., Rey, E., Chamari, K., and Orhant, E. (2015). The effects of a congested fixture period on physical performance, technical activity and injury rate during matches in a professional soccer team. *Br. J. Sports Med.* 49 (6), 390–394. doi:10.1136/bjsports-2012-091290

Dolci, F., Hart, N. H., Kilding, A. E., Chivers, P., Piggott, B., and Spiteri, T. (2020). Physical and energetic demand of soccer: a brief review. *Strength Cond. J.* 42 (3), 70–77. doi:10.1519/SSC.0000000000000533

Filetti, C., Ruscello, B., Ascenzi, G., Di Mascio, M., and D'ottavio, S. (2019). Physical performance metrics in elite soccer: do power and acceleration metrics provide insight into positional demands and match-related fatigue in the 4-3-3 system? *J. Sports Med. Phys. Fit.* 59 (10), 1640–1650. doi:10.23736/S0022-4707.19.09772-X

Garcia, G. R., Gonçalves, L. G. C., Clemente, F. M., Nakamura, F. Y., Nobari, H., Bedo, B. L. S., et al. (2022). Effects of congested fixture and matches' participation on internal and external workload indices in professional soccer players. *Sci. Rep.* 12 (1), 1864. doi:10.1038/s41598-022-05792-w

Gómez-Carmona, C. D., Gamonales, J. M., Pino-Ortega, J., and Ibáñez, S. J. (2018). Comparative analysis of load profile between small-sided games and official matches in youth soccer players. *Sports* 6 (4), 173. doi:10.3390/sports6040173

Gonçalves, L., Camões, M., Lima, R., Bezerra, P., Nikolaidis, P. T., Rosemann, T., et al. (2022). Characterization of external load in different types of exercise in professional soccer. *Hum. Mov.* 23 (1), 89–95. doi:10.5114/hm.2021.104190

Guerrero-Calderón, B., Klemp, M., Morcillo, J. A., and Memmert, D. (2021). How does the workload applied during the training week and the contextual factors affect the physical responses of professional soccer players in the match? *Int. J. Sports Sci. Coach.* 16 (4), 994–1003. doi:10.1177/1747954121995610

Guerrero-Calderón, B., Morcillo, J. A., Chena, M., and Castillo-Rodríguez, A. (2022). Comparison of training and match load between metabolic and running speed metrics of professional Spanish soccer players by playing position. *Biol. Sport* 39 (4), 933–941. doi:10.5114/biolsport.2022.110884

Julian, R., Page, R. M., and Harper, L. D. (2021). The effect of fixture congestion on performance during professional male soccer match-play: a systematic critical review with meta-analysis. *Sports Med.* 51 (2), 255–273. doi:10.1007/s40279-020-01359-9

Kalkhoven, J. T., Watsford, M. L., Coutts, A. J., Edwards, W. B., and Impellizzeri, F. M. (2021). Training load and injury: causal pathways and future directions. *Sports Med.* 51, 1137–1150. doi:10.1007/s40279-020-01413-6

Kaloop, M. R., Elbeltagi, E., Hu, J. W., and Elrefai, A. (2017). Recent advances of structures monitoring and evaluation using GPS-time series monitoring systems: a review. *ISPRS Int. J. Geo-Information* 6 (12), 382. doi:10.3390/ijgi6120382

Lago-Peñas, C., Rey, E., Lago-Ballesteros, J., Casáis, L., and Domínguez, E. (2011). The influence of a congested calendar on physical performance in elite soccer. *J. Strength and Cond. Res.* 25 (8), 2111–2117. doi:10.1519/JSC.0b013e3181eccdd2

Little, T., and Williams, A. G. (2005). Specificity of acceleration, maximum speed, and agility in professional soccer players. *J. Strength Cond. Res.* 19 (1), 76–78. doi:10.1519/14253.1

Marqués-Jiménez, D., Calleja-González, J., Arratibel, I., Delextrat, A., and Terrados, N. (2017). Fatigue and recovery in soccer: evidence and challenges. *Open Sports Sci. J.* 10 (1), 52–70. doi:10.2174/1875399x01710010052

McBurnie, A. J., Harper, D. J., Jones, P. A., and Dos' Santos, T. (2022). Deceleration training in team sports: another potential 'vaccine'for sports-related injury? *Sports Med.* 52, 1–12. doi:10.1007/s40279-021-01583-x

Mohr, M., Draganidis, D., Chatzinikolaou, A., Barbero-Álvarez, J. C., Castagna, C., Douroudos, I., et al. (2016). Muscle damage, inflammatory, immune and performance responses to three football games in 1 week in competitive male players. *Eur. J. Appl. Physiology* 116 (1), 179–193. doi:10.1007/s00421-015-3245-2

Reche-Soto, P., Cardona-Nieto, D., Diaz-Suarez, A., Bastida-Castillo, A., Gomez-Carmona, C., Garcia-Rubio, J., et al. (2019). Player load and metabolic power dynamics as load quantifiers in soccer. *J. Hum. Kinet.* 69, 259–269. doi:10.2478/hukin-2018-0072

Reinhardt, L., Schwesig, R., Lauenroth, A., Schulze, S., and Kurz, E. (2019). Enhanced sprint performance analysis in soccer: new insights from a GPS-based tracking system. *PloS one* 14 (5), e0217782. doi:10.1371/journal.pone.0217782

Rey, E., Padrón-Cabo, A., Barcala-Furelos, R., Casamichana, D., and Romo-Pérez, V. (2018). Practical active and passive recovery strategies for soccer players. *Strength Cond. J.* 40 (3), 45–57. doi:10.1519/SSC.0000000000000247

Rodrigues, F., Monteiro, D., Ferraz, R., Branquinho, L., and Forte, P. (2023). The association between training frequency, symptoms of overtraining and injuries in young men soccer players. *Int. J. Environ. Res. Public Health* 20 (8), 5466. doi:10.3390/ijerph20085466

Sarmento, H., Clemente, F. M., Araújo, D., Davids, K., McRobert, A., and Figueiredo, A. (2018). What performance analysts need to know about research trends in association football (2012–2016): a systematic review. *Sports Med.* 48 (4), 799–836. doi:10.1007/s40279-017-0836-6

Teixeira, J. E., Forte, P., Ferraz, R., Branquinho, L., Silva, A. J., Monteiro, A. M., et al. (2022). Integrating physical and tactical factors in football using positional data: a systematic review. *PeerJ* 10, e14381. doi:10.7717/peerj.14381

Teixeira, J. E., Leal, M., Ferraz, R., Ribeiro, J., Cachada, J. M., Barbosa, T. M., et al. (2021). Effects of match location, quality of opposition and match outcome on match running performance in a Portuguese professional football team. *Entropy* 23 (8), 973–1016. doi:10.3390/e23080973

Thorpe, R., and Sunderland, C. (2012). Muscle damage, endocrine, and immune marker response to a soccer match. *J. Strength Cond. Res.* 26 (10), 2783–2790. doi:10.1519/JSC.0b013e318241e174

Vieira, L. H. P., Aquino, R., Lago-Peñas, C., Martins, G. H. M., Puggina, E. F., and Barbieri, F. A. (2018). Running performance in Brazilian professional football players during a congested match schedule. *J. Strength Cond. Res.* 32 (2), 313–325. doi:10.1519/JSC.0000000000002342

Young, W. B., McDowell, M. H., and Scarlett, B. J. (2001). Specificity of sprint and agility training methods. *J. Strength Cond. Res.* 15 (3), 315–319. doi:10.1519/1533-4287(2001)015<0315:SOSAAT>2.0.CO;2

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A survey into the current fitness testing practices of elite male soccer practitioners: from assessment to communicating results

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This study provides insight into the current fitness testing practices in elite male soccer. One hundred and two practitioners from professional soccer leagues across 24 countries completed an online survey comprising 29 questions, with five sections: a) background information, b) testing selection, c) testing implementation, d) data analysis, and e) data reporting. Frequency analysis was used to evaluate the responses to fixed response questions and thematic analysis was used for open-ended questions to generate clear and distinct themes. Strength (85%) and aerobic capacity (82%) represent the most frequently assessed physical qualities. Scientific literature (80%) is the most influential factor in testing selection and practitioners conduct fitness testing less frequently than their perceived ideal frequency per season (3.6 $\pm$ 2 vs. 4.5 $\pm$ 2). Time and competitive schedule were the greatest barriers to fitness testing administration. Practitioners mostly used a 'hybrid' approach (45%) to fitness testing, blending 'traditional' (i.e., a day dedicated to testing) and 'integrated' (i.e., testing within regular training sessions) methods. Microsoft Excel is the most used software for data analysis (95%) and visualization (79%). An equal use of the combination of best and mean scores of multiple trials (44%) and the best score (42%) was reported. Comparing a player's test performance with previous scores (89%) was the most common method for interpreting test results. However, only 38% considered measurement error. Digital displays and verbal feedback are the most common data reporting methods, with different data reporting processes for coaches and players. Practitioners can use data and findings from this study to inform their current testing practices and researchers to further identify areas for investigation, with the overarching aim of developing the field of fitness testing in elite male soccer.

KEYWORDS

football, professional, data analysis, data reporting, physical performance, assessment

Introduction

Soccer is a sport where success depends on technical, tactical, physical, and psychological factors (Turner and Stewart, 2014). Accordingly, soccer match-play requires players to execute different high-intensity activities, such as kicking, tackling, turning, jumping, and sprinting (Stølen et al., 2005). The physical demands are ever-increasing (Bush et al., 2015; Zhou et al., 2020), with elite soccer players covering distances of ~14 km per game, with ~10% being at speeds >19.8 km/h (Dolci et al., 2020). The number of matches played by professional players has also increased, with a soccer season in the English Premier League and other major European soccer leagues comprising ~60 matches, including domestic, cup, and international competitions (Nassis et al., 2020). A high level of athleticism seems to be essential to cope with the demands of the modern game. For example, research has shown differences in physical attributes (e.g., speed, power, strength, change of direction ability, and aerobic capacity) between starting vs. non-starting players (Hoppe et al., 2020), senior vs. youth (Cardoso De Araújo et al., 2018), and elite vs. non-elite players (Kobal et al., 2016). Therefore, fitness testing is necessary to provide practitioners (e.g., strength and conditioning [S&C] coaches, sports scientists) with objective information on the physical capacity of individuals and teams, which can be used to benchmark players, design and evaluate individualized training programs, reduce injury risk, inform return-to-play processes, and contribute to talent identification (Turner et al., 2011; Taylor et al., 2022; Weakley et al., 2023).

Employing a comprehensive fitness testing battery supports the development of well-rounded and physically robust soccer players (Svensson and Drust, 2005; Beato et al., 2023). Therefore, testing selection should be based on general and position-specific requirements of soccer (e.g., biomechanical and physiological aspects) (Turner et al., 2011), and 'testing for the sake of testing' should be avoided if it does not provide value to the training process. Practitioners face the challenge of choosing between various assessments and outcome variables, since a standardized universal testing battery in soccer has yet to be established. Typically, soccer fitness testing batteries include aerobic capacity, linear speed, strength, power, reactive strength, change of direction (COD), and repeated sprint ability (RSA) tests (Turner et al., 2011; Taylor et al., 2022). To navigate the uncertainty of the testing selection process, practitioners must select tests that measure the intended capacity (validity) and ensure results are representative of the athlete's ability (reliability) (McGuigan, 2016; Weakley et al., 2023). Furthermore, tests should be sensitive enough to detect small but meaningful changes in performance to demonstrate players' physical progress (Paul and Nassis, 2015). Accordingly, external factors such as equipment availability, number of athletes, age and training status of athletes, competitive schedule, time efficiency, simplicity, practicality, and timing can influence the testing selection and administration process (McGuigan et al., 2013).

The selected fitness testing battery will likely result in vast amounts of data requiring in-depth analysis for teams and individual players (Turner et al., 2021; Turner, 2022). Therefore, practitioners require advanced data analysis skills to distinguish the 'signal' from the 'noise' (Hopkins, 2000). This will enable them to interpret and present results effectively to other members of the athlete support team (e.g., coaches) and inform the wider training process (Buchheit, 2017). Therefore, practitioners should aim to create intuitive and informative reports, as coaches may not possess a statistical background (Thornton et al., 2019). As players are in the middle of the data collection and reporting process, results must be clearly communicated to them and actioned accordingly, thus leading to increased buy-in. Nevertheless, there is no 'one size fits all' when reporting test results, and the audience's preference will determine the output.

Although research has extensively examined different methods to measure fitness in elite soccer players, limited evidence exists on how the 'science' of fitness testing is translated into practice, particularly concerning testing data analysis and reporting. Previous survey-based research provided insight into fitness testing in soccer; however, this formed part of a larger survey instrument and did not directly ask about data analysis and reporting (Beere and Jeffreys, 2021; Weldon et al., 2021), or the sample consisted of mixed backgrounds (elite and non-elite, male and female) (McQuilliam et al., 2023). Therefore, this survey study aims to acquire real-world insights into the fitness testing processes being conducted in elite male soccer. Our results will provide valuable information on the selection, implementation, data analysis, and data reporting of fitness tests, providing a basis of information for practitioners and researchers. Furthermore, potential areas for further investigation and research will also be highlighted.

Materials and methods

Participants

Participants were recruited using a digital invitation via the research team's network and use of online platforms (i.e., X [formerly Twitter] and LinkedIn). Chain sampling was used to maximize the sample size, whereby practitioners were requested to share the survey with their elite soccer network. The inclusion criteria to ensure that collected responses represented the current testing practices in elite soccer required participants to be involved in a professional soccer club working with male players >17 years old. Participants gave their consent by clicking the relevant box on the introductory page of the survey. All participants were ≥18 years old. ***REMOVED FOR PEER REVIEW*** research and ethics committee at ***REMOVED FOR PEER REVIEW*** provided ethical approval for the study.

Study design

The online survey platform SurveyMonkey (San Mateo, California, United States) was used to create and host the survey. Initially, the survey underwent pilot testing with three S&C coaches working in elite male soccer; two with a PhD and one with a master's degree, all with more than 7 years' of experience in elite soccer, and three researchers with an applied soccer background and more than 9 years in academia, to assess content validity. This led to minor modifications and rewording of questions to ensure they were clear and appropriate for the intended population. The introductory page of the survey outlined the purpose of the study, general information, confidentiality of information, and included the informed consent statement. The survey lasted ~15 min, contained five sections: 1) background information, 2) testing selection, 3) testing implementation, 4) data analysis, and 5) data reporting), and included a combination of fixed response and open-ended questions (see Supplementary Appendix S1). Some questions allowed more than one answer, resulting in some questions having more answers than others.

Data acquisition and statistical analyses

All responses from SurveyMonkey were exported into a customized Excel spreadsheet (Microsoft Corporation, Redmond, Washington, United States) for further analysis. The data collection period was from the first of July 2023 to the 15th of December 2023. Data were analysed and presented using a range of descriptive statistics, including the calculation of the mean, standard deviation, absolute frequencies (counts), and relative frequencies (percentages). A frequency analysis was undertaken with fixed response questions. Open-ended questions were evaluated using a thematic analysis approach (Braun and Clarke, 2019), similar to previous survey studies in elite soccer (Weldon et al., 2021; Loturco et al., 2022). This thematic analysis approach consisted of the subsequent six-step framework: 1) familiarization with the data, 2) generating initial codes, 3) searching for themes, 4) reviewing themes, 5) defining and naming themes, and 6) producing the report. The key themes arising from the raw responses were generated for each open-ended question by the lead author and agreed upon by all co-authors with extensive experience physically testing athletes.

Results

Demographics

One hundred and two elite male soccer practitioners, consisting of 32 S&C coaches, 27 physical performance coaches, 24 sports scientists, nine directors/heads of performance, seven physiotherapists, and three technical coaches, with professional experience of 8.2 ± 5.7 years, took part in this study. Practitioners worked in professional soccer across 24 countries, including Italy (28.4%), The United Kingdom (24.5%), Germany (7.8%), The United States of America and Portugal (each 4.9%), Spain (3.9%), Greece (2.9%), Australia, Cyprus, Denmark, India, Scotland and Sweden (each 1.9%), and Belgium, Bosnia and Herzegovina, Croatia, France, Georgia, Ireland, Netherlands, Northern Ireland, Saudi Arabia, Singapore and Turkey (each 1%). Regarding academic background, 63% had a master's degree, 18% had a PhD degree, 15% had a bachelor's degree, and 4% were PhD candidates. Professional qualifications were widely held by respondents, including soccer coaching licenses (62.7%), National Strength and Conditioning Association (NSCA) Certified Strength and Conditioning Specialist (CSCS) (22.5%), United Kingdom Strength and Conditioning Association (UKSCA) Accredited Strength and Conditioning Coach (ASCC) (8.8%), British Association of Sport and Exercise Sciences (BASES) Accredited Sport and Exercise Scientist (7.1%), and NSCA Certified Performance and Sport Scientist (CPSS) (2.9%).

Testing selection

Figure 1 illustrates the frequency of responses regarding the physical capacities that practitioners assessed within their fitness testing batteries. Table 1 represents the most common tests used to assess each physical capacity. For the factors influencing the selection of testing methods, 83 participants (81%) responded. The most common responses were published scientific literature (80%), constraints (e.g., time, budget, equipment) (60%), expert opinion or professional experience (59%), needs analysis of the sport (58%), specific needs or goals of the team or players (40%), usefulness of a test (established from in-house test-retest reliability) (35%), prescribed from national governing bodies (10%), and 'other' reasons (7%) (e.g., the ability of a test to inform programming, the ability to inform the return-to-play process, and the historical use of tests in the club).

Testing implementation

In total, 75 participants (74%) answered the questions regarding testing implementation. Practitioners reported conducting 3.6 ± 2 formalized fitness testing sessions with their players per season. However, practitioners believed the optimal formalized fitness testing frequency should be 4.5 ± 2 times per season. Figure 2 illustrates when practitioners conduct formalized fitness testing during the season. Figure 3 shows the perceived degree of burden (barriers) in elite male soccer concerning the implementation of fitness testing. In terms of how fitness testing is carried out, 45% reported following a 'hybrid' approach, which blended 'traditional' (i.e., a day dedicated to testing) and 'integrated' (i.e., testing within regular training sessions) methods. Whereas 28% specifically used an 'integrated approach' and 27% used a 'traditional approach'.

Data analysis

Overall, 73 participants (72%) answered the questions regarding data analysis. Of those, 71% reported using statistical software to analyse fitness testing data, with Microsoft Excel being the most prevalent (95%), followed by R (24%), Google Sheets (22%), SPSS (22%), 'other' software (16%) (i.e., Microsoft Power BI, Tableau, and athlete management systems), JASP (9%), and Python (5%). For the analysis of fitness test results, 44% of practitioners use the best and average scores of repeated trials to evaluate performance, while 42% use the best score and 14% use the average score. Regarding the selection of raw or standardized values from fitness testing to analyse and interpret results, 36% of practitioners use raw values, 31% use both, 26% use the method determined by the audience (i.e., coaches or players), and 7% use standardized scores. Table 2 shows the methods practitioners use to interpret fitness test results and determine changes in a player's performance.

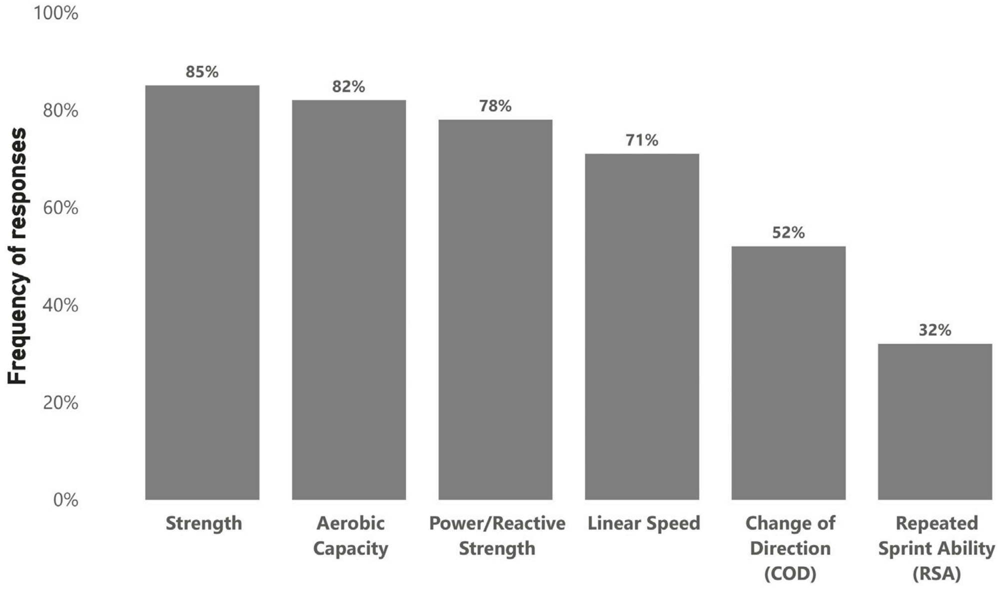

FIGURE 1
Physical capacities that practitioners assess (n = 102).

Data reporting

In total, 72 participants (71%) answered the questions regarding data reporting. Most practitioners (96%) reported testing results to their players. Figure 4 illustrates the preferred means for reporting testing results to players and coaches. Microsoft Excel (79%) was the most commonly used software for data visualization, followed by Microsoft Power BI (32%), Google Sheets (21%), 'other' software (18%) (i.e., athlete management systems, Microsoft PowerPoint, Prism GraphPad, and Statistica), R (7%), Tableau (7%), Python (4%), and JASP (4%). Interestingly, 55% of practitioners reported using different data visualization methods for coaches and players. Open-ended responses revealed that practitioners generally tailored reports and volume of information to the audience's needs. For example, players typically received intuitive, individualized reports related to their performance and areas of improvement (i.e., targets for the subsequent testing assessment). Meanwhile, coaches received more comprehensive reports, such as an increased number of variables and more in-depth analyses and comparisons (i.e., team- and position-specific comparisons, use of total score of athleticism).

Discussion

This study provides insight into the current practices of fitness testing in elite male soccer. To the authors' knowledge, this is the first study that acquires in-depth information regarding fitness testing selection and implementation in elite soccer across different professional leagues, as well as providing unique insights into the previously unexplored areas of testing results analysis and reporting. The findings of this study can be beneficial for practitioners and researchers working in elite male soccer, illustrating the fitness testing process, analysis and presentation of results, and highlighting areas where standardization may be needed. The discussion will be organized into four sections: a) testing selection, b) testing implementation, c) data analysis, and d) data reporting.

Testing selection

Strength and aerobic capacity were reported as the most frequently assessed physical capacities in this study, which aligns with a previous survey conducted in elite soccer (Weldon et al., 2021), followed closely by power/reactive strength, and linear speed.

Strength is a fundamental capacity for completing in-game explosive actions, such as sprinting, jumping, and engaging in physical duels (Wing et al., 2020). Moreover, high strength levels can help reduce injury risk (Arnason et al., 2004; Lehance et al., 2008), thereby contributing to increased training and match availability. The isometric mid-thigh pull (IMTP) and adductor squeeze tests are the most commonly performed strength assessments. Both tests present high levels of between-day reliability in elite soccer players, with peak force during the IMTP exhibiting an ICC of 0.88, CV of 5.8%, and SEM of 131 N (Musham and Fitzpatrick, 2020). Furthermore, relative peak torque during the adductor squeeze test showed ICC values ranging from 0.77 to 0.95 and an SEM ranging from 0.08 to 0.18 Nm/kg, depending on the lever length assessed (Light and Thorborg, 2016). The IMTP is an isometric multi-joint test that assesses lower-body strength in a more time-efficient and less fatiguing manner than dynamic testing (e.g., one repetition maximum [RM] back squat) while also providing data and insight into various components of an athlete's force production ability within a single trial (i.e., peak force, force at specific time points,

TABLE 1 Most common tests reported by practitioners to assess each physical quality.

Physical capacity (number of respondents)	Test	Percentage of respondents
Strength (n = 79)	Isometric Mid-Thigh Pull (IMTP)	28/79 (35%)
	Isometric Adductor Strength (Groin Squeeze Test)	27/79 (34%)
	Isokinetic Strength of the Quadriceps and/or Hamstrings	23/79 (29%)
	3RM Squat	18/79 (23%)
	3RM Bench Press	13/79 (16%)
	Other: Nordic Hamstring Strength Test, Isometric Hamstring Strength Test, Max Pull-Ups, 3RM Pull-Up, Isometric Calf Raise, 1RM Trap Bar Deadlift	13/79 (16%)
	1RM Squat	12/79 (15%)
	Predicted 1RM using Barbell Velocity	10/79 (13%)
	1RM Bench Press	8/79 (10%)
	Isometric Squat	7/79 (9%)
	Flywheel Testing	4/79 (5%)
Aerobic Capacity (n = 78)	30–15 Intermittent Fitness Test	23/78 (29%)
	Yo-Yo Intermittent Recovery Test 2	19/78 (24%)
	Yo-Yo Intermittent Recovery Test 1	17/78 (22%)
	Specified Distance for Time	17/78 (22%)
	Incremental Treadmill Test to Exhaustion	12/78 (15%)
	Submaximal Test	10/78 (13%)
	Specified Time for Distance	9/78 (12%)
	Multi-stage Fitness Test (Beep Test)	7/78 (9%)
	VAMEVAL Test	4/78 (5%)
	Other: Mognoni's Test, Bosco Test	3/78 (4%)
	University of Montreal Track test	1/78 (1%)
Power/Reactive Strength (n = 74)	Countermovement Jump (CMJ)	68/74 (92%)
	Squat Jump (SJ)	33/74 (45%)
	Single-leg Countermovement Jump (SL CMJ)	32/74 (43%)
	Drop Jump (DJ)	28/74 (38%)
	10/5 Repeated Jumps Test	18/74 (24%)
	Triple Hop Test	15/74 (20%)
	Single-leg Hop Test	14/74 (19%)
	Single-leg Drop Jump	12/74 (16%)
	Other: Standing Broad Jump, Triple Broad Jump, Trap Bar Squat Jump	8/74 (11%)
	Vertical Jump with Free Arms	7/74 (9%)
Linear Speed (n = 67)	10 m	43/67 (64%)
	30 m	39/67 (58%)
	20 m	32/67 (48%)
	5 m	28/67 (42%)
	40 m	11/67 (16%)

(Continued on following page)

TABLE 1 (*Continued*) Most common tests reported by practitioners to assess each physical quality.

Physical capacity (number of respondents)	Test	Percentage of respondents
	20 m Flying	8/67 (12%)
	30 m Flying	7/67 (10%)
	Other: 50m, 60m, Max Velocity with GPS	5/67 (7%)
	10 m Flying	4/67 (6%)
	40 m Flying	4/67 (6%)
	5 m Flying	0/67 (0%)
COD (n = 49)	505 Test	27/49 (55%)
	t-Test	9/49 (18%)
	Illinois Agility Test	8/49 (16%)
	Other: COD Test, Pro Agility Test, Modified 505 Test, In-house COD Test (10 + 10 m with 90° Cut)	8/49 (16%)
	Arrowhead Agility Test	6/49 (12%)
	Zig-Zag Test	0/49 (0%)
RSA (n = 30)	7 × 30 m Sprint with 20s Rest	10/30 (33%)
	6 × 40 m Sprint with 20s Rest	7/30 (23%)
	8 × 30 m Sprint with 25s Active Recovery	6/30 (20%)
	6 × 40 m (20 + 20 m with 180° Turns) Shuttle Sprint with 20s Rest	6/30 (20%)
	Other: 6 × 35 m Sprint with 10s Rest, 6 × 25 m Sprint with 25s Rest, 5 × 30 m with 20s Active Recovery	5/30 (17%)

[a]RM: repetition maximum.
[a]GPS: global positioning system.

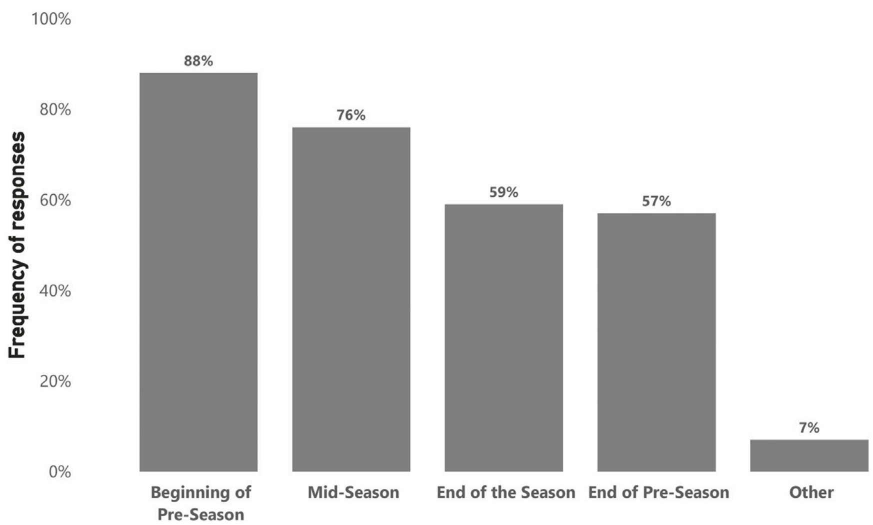

FIGURE 2
Timing of testing (n = 75).

rate of force development, and impulse) (Brady et al., 2018; Comfort et al., 2019). On the other hand, the adductor squeeze test has been widely implemented due to the role adductor muscles play in soccer-specific tasks, such as kicking, landing, and cutting (Charnock et al., 2009; Rouissi et al., 2016). Also, groin injuries are one of the most affected areas for injury in professional soccer, contributing to 12%–

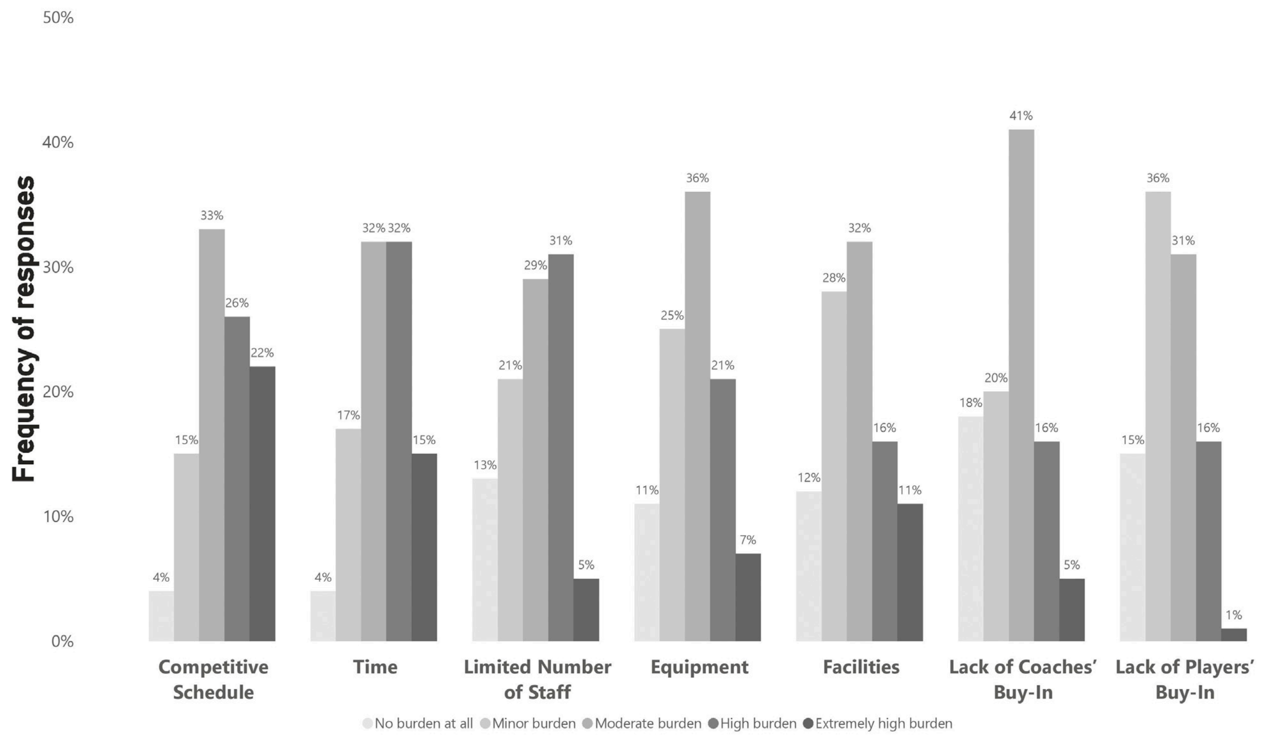

FIGURE 3
Perceived degree of burden (n = 75).

TABLE 2 Methods of interpreting fitness test results (n = 73).

Factors	Percentage of respondents
Based on athlete's previous performance	65/73 (89%)
Based on comparison with normative data or benchmarks (published/squad)	50/73 (68%)
Position-specific comparisons	38/73 (52%)
Taking into account some form of error of the measurement (typical error, minimal detectable change, standard deviation, smallest worthwhile change, confidence intervals)	28/73 (38%)
Based on expert opinions or professional consensus	12/73 (16%)
Other (please specify)	0/73 (0%)

16% of all injuries per season, with an injury incidence of 1.1/1000 h of training and match play (Werner et al., 2009). Previous research has shown that greater isometric adductor strength levels can help reduce injury risk (Moreno-Pérez et al., 2019). In both cases, the growing accessibility of specialized equipment such as force plates and specialized adductor strength testing systems (i.e., ForceFrame, GroinBar, Kangatech KT360) may contribute to their use.

The high prevalence of aerobic capacity testing is unsurprising, considering the high aerobic demands of soccer, where players are required to cover distances up to 14 km per match (Dolci et al., 2020) and the role that aerobic capacity plays in the quick recovery from explosive actions (Stølen et al., 2005). For aerobic capacity assessments, field tests were the most frequently used, such as the 30–15 intermittent fitness test (30–15 IFT) (ICC: 0.80–0.99, CV: 1.5%–6.0%) (Grgic et al., 2021), Yo-yo intermittent recovery test level 1 (YYIR1) (ICC: 0.78–0.98, CV: 4.1%–19.0%) and 2 (YYIR2) (ICC: 0.86–0.96, CV: 4.2%–12.7%) (Grgic et al., 2019), and specified distance time trials. This is unsurprising as field tests are a simple and quick option for practitioners to assess the aerobic capacity of groups of individuals with minimal equipment and preparation (Bok and Foster, 2021).

The occurrence of sprints and jumps preceding some of the most decisive moments of a game, such as scoring a goal (Faude et al., 2012), may explain the high percentage of practitioners that assess power/reactive strength and linear speed capacities. Furthermore, their administration is simple and quick, which allows their integration within gym and field sessions. For power assessments, the countermovement jump (CMJ) (92%) was the most used by practitioners in this study. The CMJ is a time-efficient test that requires minimal athlete familiarization, exhibiting high within-

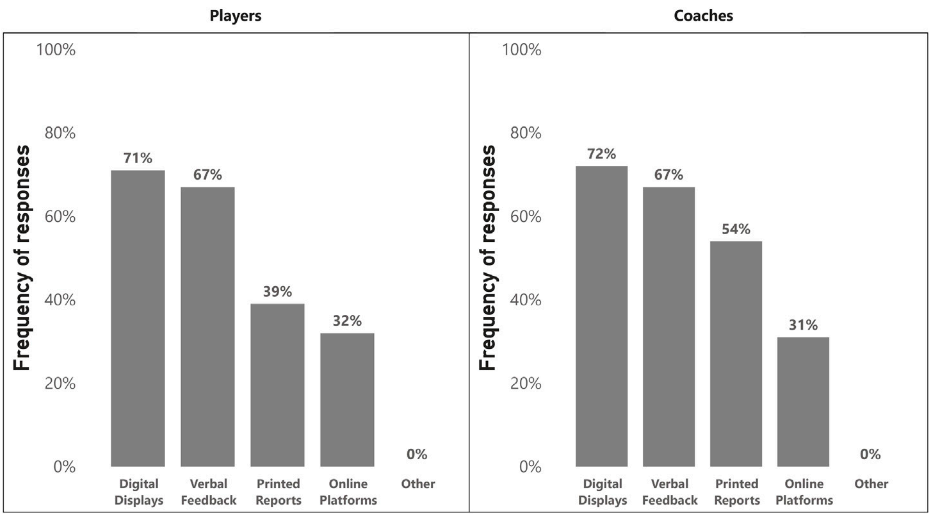

FIGURE 4
Means of reporting test results (n = 73).

(i.e., ICC: 0.97, CV: 2.7%, SEM: 1.4 cm) and between-day (i.e., ICC: 0.83, CV: 4.3%, SEM: 1.7 cm) reliability in elite soccer players (Enright et al., 2018; Maestroni et al., 2023). Results show that practitioners use a multi-faceted approach to power testing, including other tests such as the squat jump (SJ) (ICC: 0.89, CV: 3.7%, SEM: 1.4 cm) (Enright et al., 2018), single-leg CMJ (SLCMJ) (ICC: 0.70–0.96, CV: 3.7%–13.7%) (Bishop and Read, 2019) and drop jump (DJ) (ICC: 0.95, CV: 2.5%) (Requena et al., 2014), to possibly gain a broader picture of stretch-shortening cycle (SSC) characteristics and inter-limb asymmetry. Concerning linear speed assessment, practitioners generally tested distances <40 m, with 10 m (ICC: 0.78–0.87, CV: 0.8%–3.6%, SEM: 0.02 s) (Bishop and Brashill, 2019; Stern et al., 2020; Bishop et al., 2022), 30 m (ICC: 0.86–0.94, CV: 1.1%–2.3%) (Bishop et al., 2022; 2023), 20 m (ICC: 0.82–0.99, CV: 0.9%–1.3%. SEM: 0.02 s) (Ben Brahim et al., 2021; Bishop et al., 2023), and 5 m (ICC: 0.87–0.99, CV: 1.7%–2.5%, SEM: 0.01–0.02 s) (Bishop and Brashill, 2019; Ben Brahim et al., 2021) sprints being the most commonly selected, in respective order. This selection may be based on match activity profiles, as individual sprints usually last between 2 and 4 s and are typically <20 m in distance (Vigne et al., 2010).

Published scientific literature was reported as the most influential factor for test selection, which could indicate the intention of practitioners to utilize scientifically scrutinized testing methods (i.e., ensuring reliability and validity). The constraints faced in practice (e.g., time, budget, and equipment), expert opinions, and previous professional experience also highly influenced testing selection. These findings support the notion that research may inform practice and practice may inform research. Finally, only one-third of practitioners conducted in-house test-retest reliability to determine their selected tests and metrics, possibly due to time constraints within elite soccer. In-house test-retest reliability helps identify the measurement error, which informs future test selection, selected outcome variables, analysis methods, and interpretation of results (Hopkins, 2000; Turner, 2022). However, an inability to administer in-house reliability analysis can present limitations since within-day and between-day test reliability is not always the same owing to biological variations (Hopkins, 2000; Altmann et al., 2019). Furthermore, the measurement error depends on the familiarity of the athletes with the tests (Comyns et al., 2019), underscoring the importance of assessing the reliability within the specific cohort.

Testing implementation

Practitioners believed their implemented testing frequency was less than optimal, which suggests practitioners cannot administer fitness testing as frequently or as extensively as desired. The two prominent burdens were time availability and congested competitive schedules, similar to a previous survey in elite soccer (Weldon et al., 2021). Almost half of practitioners adopted a ‘hybrid’ fitness testing approach to overcome this issue. This allows practitioners to combine the benefits of a traditional testing approach (i.e., testing in standalone sessions at specific timepoints) with the continuous monitoring during data collection in regular training sessions, facilitating on-going data-informed decisions.

Regarding timing, fitness testing occurs predominantly at the beginning of the pre-season, which is supported by a previous survey conducted in professional soccer (Weldon et al., 2021). This may be due to time availability as few competitions are held during this period, therefore offering the opportunity to conduct thorough, uninterrupted assessments. Furthermore, fitness testing early in pre-season establishes baseline fitness levels, which lays the foundation for performance goal setting, fatigue monitoring, and return-to-play processes (Maestroni et al., 2023; Weakley et al., 2023). A large proportion of fitness testing was also conducted during mid-season, possibly due to competition breaks, with data being used to assess mid-term progress and inform training adjustments and prescriptions. Fewer practitioners tested at the end of the pre-season period, possibly due to the start of the competitive period, where the main focus is on winning games, and consequently, fitness testing becomes less of a priority. Equally, few practitioners tested during the end of the season as players usually depart for their off-season period immediately after the last game. However, this could inform individualized off-season programming.

Data analysis

The substantial number of practitioners using statistical analysis or statistical software to analyse fitness testing data supports the notion that practitioners should be proficient with the range of methods by which testing data can be analysed (Turner et al., 2015). Most practitioners used Microsoft Excel, highlighting its role as a fundamental tool for practitioners working in elite soccer. Nevertheless, Microsoft Excel has performance limitations when handling large datasets and has limited advanced statistical analysis capabilities. Consequently, R and SPSS are increasingly utilised beyond academic settings.

Concerning the analysis of fitness testing results, the responses of practitioners indicate the discrepancy and the lack of consensus that exist in the field. Overall, 44% of practitioners use both the best and the mean score of multiple trials, which may suggest that practitioners aim to capture a comprehensive picture of an athlete's performance. In contrast, 42% reported using only the best score to analyse testing results, which aligns with what is generally performed in research (Claudino et al., 2017). This approach may have limitations since a single trial may not accurately reflect an individual's overall performance, as previous studies have shown that analysing the results using the best score leads to reduced reliability and sensitivity (Kennedy and Drake, 2021; Howarth et al., 2022). Nevertheless, it would also be prudent to record the best score as the mean score could mask an athlete's maximal physical capacity by including trials where performance was suboptimal. This highlighted disparity in the methods practitioners use may be an area for future investigation to inform a standardized approach to data analysis in elite soccer.

Differences were also observed for the use of raw or standardized scores in the data analysis and interpretation process. Results demonstrated a similar preference for practitioners to analyse the results based on raw values (36%) and the combination of raw and standardized scores (31%). Raw scores offer the advantage of immediate feedback and direct comparison with an individual's performance over time. On the other hand, standardized scores express the test results as a standard deviation from the mean, which is valuable to show where the player ranks relative to the group or comparing test performance with different outcome variables (McGuigan et al., 2013; Turner et al., 2019).

Last but not least, some valuable insights can be drawn from the responses on how practitioners interpret fitness testing results. Most practitioners (89%) compared current test results to previous results, which is reasonable as assessing individual changes is the most relevant for the practitioners working in the practical setting to inform the continuation or modification of a training intervention (Ward et al., 2018). Nevertheless, a lower percentage (38%) accounted for measurement error, which allows for the identification of normal variation between testing sessions. This may have major implications for the interpretation of fitness test results, because if a change in performance is not greater than the measurement error, then the change cannot be deemed with confidence as meaningful (Hopkins, 2000). Therefore, this may lead to training interventions being perceived as successful or unsuccessful, and subsequent decisions being ill-informed. Therefore, adopting a more holistic approach to interpreting performance changes may be beneficial. A large percentage (68%) of practitioners compared results with normative data or established benchmarks, which can play a key role in setting performance goals and talent identification (McGuigan et al., 2013). Finally, a position-specific comparison (52%) is performed by practitioners, as different positions have varying physical demands, thus different expected physical profiles (Walker and Hawkins, 2018; Turner et al., 2019).

Data reporting

Most practitioners (96%) report testing results to the players, demonstrating the importance placed on performance feedback in the athletic development process. Furthermore, informing players of their strengths, weaknesses, and longitudinal progress could increase their engagement and overall buy-in. Digital displays (e.g., static and interactive dashboards) and verbal feedback represent the most prevalent methods of reporting fitness testing results to coaches and players, illustrating a delicate balance between technological use and interpersonal communication. In addition, information from multiple tests can be incorporated into a single document, which is convenient and time-efficient. Nevertheless, verbal feedback remains a critical component of the testing data reporting process since it represents a direct communication method that can convey the nuanced insights and clarifications that a digital display may fail to and provide a basis for discussions about an individual's progress.

As with data analysis, Microsoft Excel is the most commonly employed software for the visualization of testing results, followed by Microsoft Power BI (32%), which offers more advanced visualization capabilities. Over half (55%) of practitioners differentiated their data visualization strategies for coaches and players. This may indicate the tendency to create tailored data visualization based on the needs of the end audience since the roles of coaches and players are distinct. When delving deeper into those differences, it appears that coaches typically receive more elaborate and in-depth analyses. This increased analysis provides a broader range of information to better assist coaches in their holistic decision-making processes around player development and selection. Conversely, players receive more concise reports primarily focused on their performance, which is key to increasing their awareness of focus areas.

Limitations and future research

This survey study, although extensive in scope, is not without its limitations. Firstly, a survey cannot encompass all the nuances of fitness testing, and certain components may have been overlooked. Secondly, no comparative analysis was performed between testing practices between first team and youth settings, the objective was to provide an overview of the fitness testing procedures in elite soccer. Future research should examine the nuanced differences between these settings. Thirdly, the lack of transparent definition of the terms

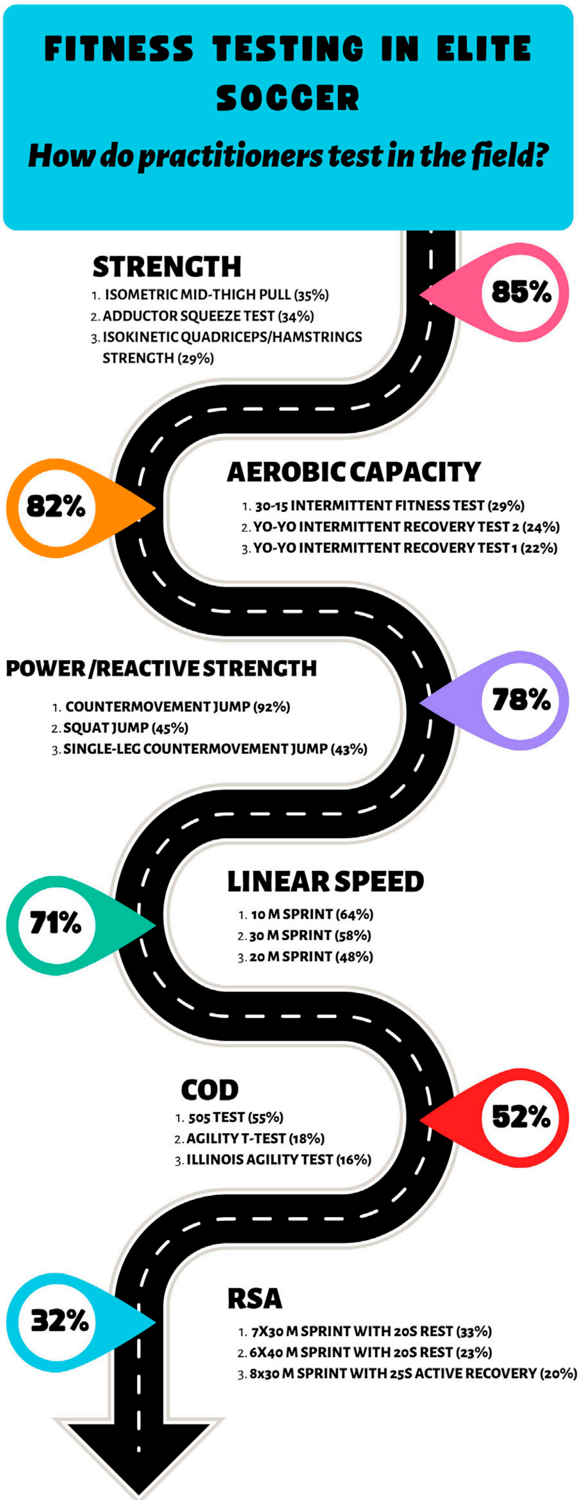

FIGURE 5
Most commonly assessed physical capacities and tests.

"professional" and "elite" may affect the interpretation of the eligibility of the participants in the study (McAuley et al., 2022). For example, in this study, 'elite' refers to practitioners working within a professional soccer club with players older than 17 (i.e., first team or youth).

Given the wide range of tests used by practitioners, there is a need for 'ecologically valid' (i.e., reflecting and respecting the constraints of the applied elite soccer settings), reliability, and sensitivity studies to determine the practical utility of these tests and their outcome variables.

This will inform a simplified testing selection by facilitating an informative and efficient fitness testing process. In addition, future research should investigate the 'ideal' approach for analysing fitness testing data to advance the current knowledge in interpreting fitness changes. Last but not least, given the importance of effectively communicating the results from fitness testing, further information on the specific preferences of key stakeholders (i.e., players, coaches, and support staff) in elite soccer should be sought.

Conclusion

This study presents an in-depth overview of the fitness testing processes in elite male soccer. The infographic in Figure 5 illustrates the most commonly assessed physical abilities and the most commonly administered tests to assess them. Scientific literature is the main influence of test selection, although a pragmatic approach is adopted, as practical constraints and professional experience play an important role. Practitioners tested less frequently than they believed optimal, with time and competitive schedules being the biggest barriers. Consequently, the beginning of the pre-season is the most common time to conduct fitness testing, with competitive periods during the season leaving less time for fitness testing. Therefore, the adoption of 'hybrid' fitness testing, whereby standalone testing sessions are concurrently supplemented with integrated testing within training sessions, may help overcome this issue. Microsoft Excel is the most popular software amongst practitioners for testing data analysis and visualization. A similar number of practitioners use either the combination of the mean and the best score or the best score in results analysis, possibly indicating a need for a standardized approach. Comparing a player's test performance with previous scores was the most commonly reported method for interpreting test results. However, a substantially lower percentage utilizes some form of error measurement. Digital displays and verbal feedback are the most commonly used data reporting methods. A tendency towards tailored visualizations for coaches and players was identified, with the main difference being that coaches may receive a greater depth of information than players.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Middlesex University London, London Sport Institute. 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

NA: Conceptualization, Formal Analysis, Software, Visualization, Writing–original draft, Writing–review and editing. CB: Methodology, Supervision, Writing–original draft, Writing–review and editing. MB: Methodology, Supervision, Writing–original draft, Writing–review and editing. IM: Methodology, Resources, Writing–original draft, Writing–review and editing. AK: Methodology, Supervision, Writing–original draft, Writing–review and editing. AW: Methodology, Supervision, Writing–original draft, Writing–review and editing. AT: Data curation, Resources, Supervision, Writing–original draft, Writing–review and editing.

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References

Altmann, S., Ringhof, S., Neumann, R., Woll, A., and Rumpf, M. C. (2019). Validity and reliability of speed tests used in soccer: a systematic review. *PLOS ONE* 14 (8), e0220982. doi:10.1371/journal.pone.0220982

Arnason, A., Sigurdsson, S. B., Gudmundsson, A., Holme, I., Engebretsen, L., and Bahr, R. (2004). Physical fitness, injuries, and team performance in soccer. *Med. Sci. Sports Exerc.* 36 (2), 278–285. doi:10.1249/01.MSS.0000113478.92945.CA

Brady, C. J., Harrison, A. J., Flanagan, E. P., Haff, G. G., and Comyns, T. M. (2018). A comparison of the isometric midthigh pull and isometric squat: Intraday reliability, usefulness, and the magnitude of difference between tests. *Inter J. of Sports Physio and Perform* 13, 844–852. doi:10.1123/ijspp.2017-0480

Beato, M., Datson, N., Anderson, L., Brownlee, T., Coates, A., and Hulton, A. (2023). Rationale and practical recommendations for testing protocols in female soccer: a narrative review. *J. Strength Cond. Res.* 37 (9), 1912–1922. doi:10.1519/JSC.0000000000004509

Beere, M., and Jeffreys, I. (2021). Physical testing and monitoring practices in elite male football. *Prof. Strength and Cond.* 29–42.

Ben Brahim, M., Bougatfa, R., Makni, E., Gonzalez, P. P., Yasin, H., Tarwneh, R., et al. (2021). Effects of combined strength and resisted sprint training on physical performance in U-19 elite soccer players. *J. Strength Cond. Res.* 35 (12), 3432–3439. doi:10.1519/JSC.0000000000003829

Bishop, C., Brashill, C., Abbott, W., Read, P., Lake, J., and Turner, A. (2019). Jumping asymmetries are associated with speed, change of direction speed, and jump performance in elite academy soccer players. *J. Strength Cond. Res.* Publish Ahead of Print. doi:10.1519/JSC.0000000000003058

Bishop, C., Read, P., Bromley, T., Brazier, J., Jarvis, P., Chavda, S., et al. (2022). The association between interlimb asymmetry and athletic performance tasks: a season-long study in elite academy soccer players. *J. Strength Cond. Res.* 36 (3), 787–795. doi:10.1519/JSC.0000000000003526

Bishop, C., Read, P., Chavda, S., Jarvis, P., Brazier, J., Bromley, T., et al. (2023). Seasonal variation of physical performance, bilateral deficit, and interlimb asymmetry in elite academy soccer players: which metrics are sensitive to change?. *J. Strength Cond. Res.* 37 (2), 358–365. doi:10.1519/JSC.0000000000004248

Bishop, C., Read, P., Chavda, S., Jarvis, P., and Turner, A. (2019). Using unilateral strength, power and reactive strength tests to detect the magnitude and direction of asymmetry: a test-retest design. *Sports* 7 (3), 58. doi:10.3390/sports7030058

Bok, D., and Foster, C. (2021). Applicability of field aerobic fitness tests in soccer: which one to choose?. *J. Funct. Morphol. Kinesiol.* 6 (3), 69. doi:10.3390/jfmk6030069

Braun, V., and Clarke, V. (2019). Reflecting on reflexive thematic analysis. *Qual. Res. Sport, Exerc. Health* 11 (4), 589–597. doi:10.1080/2159676X.2019.1628806

Buchheit, M. (2017). Want to see my report, coach?. *Aspetar Sports Med. J.* 6, 36–42.

Bush, M., Barnes, C., Archer, D. T., Hogg, B., and Bradley, P. S. (2015). Evolution of match performance parameters for various playing positions in the English Premier League. *Hum. Mov. Sci.* 39, 1–11. doi:10.1016/j.humov.2014.10.003

Cardoso De Araújo, M., Baumgart, C., Freiwald, J., and Hoppe, M. W. (2018). Nonlinear sprint performance differentiates professional from young soccer players. *J. Sports Med. Phys. Fit.* 58 (9), 1204–1210. doi:10.23736/S0022-4707.17.07116-X

Charnock, B. L., Lewis, C. L., Garrett, W. E., and Queen, R. M. (2009). Adductor longus mechanics during the maximal effort soccer kick. *Sports Biomech.* 8, 223–234. doi:10.1080/14763140903229500

Claudino, J. G., Cronin, J., Mezêncio, B., McMaster, D. T., McGuigan, M., Tricoli, V., et al. (2017). The countermovement jump to monitor neuromuscular status: a meta-analysis. *J. Sci. Med. Sport* 20 (4), 397–402. doi:10.1016/j.jsams.2016.08.011

Comyns, T. M., Flanagan, E. P., Fleming, S., Fitzgerald, E., and Harper, D. J. (2019). Interday reliability and usefulness of a reactive strength index derived from 2 maximal rebound jump tests. *Int. J. Sports Physiology Perform.* 14 (9), 1200–1204. doi:10.1123/ijspp.2018-0829

Comfort, P., Dos'Santos, T., Beckham, G. K., Stone, M. H., Guppy, S. N., Haff, G. G., et al. (2019). Standardization and methodological considerations for the isometric midthigh pull. *Streng and Cond J.* 41, 57–79. doi:10.1519/SSC.0000000000000433

Dolci, F., Hart, N. H., Kilding, A. E., Chivers, P., Piggott, B., and Spiteri, T. (2020). Physical and energetic demand of soccer: a brief review. *Strength and Cond. J.* 42 (3), 70–77. doi:10.1519/SSC.0000000000000533

Enright, K., Morton, J., Iga, J., Lothian, D., Roberts, S., and Drust, B. (2018). Reliability of "in-season" fitness assessments in youth elite soccer players: a working model for practitioners and coaches. *Sci. Med. Footb.* 2 (3), 177–183. doi:10.1080/24733938.2017.1411603

Faude, O., Koch, T., and Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *J. Sports Sci.* 30 (7), 625–631. doi:10.1080/02640414.2012.665940

Grgic, J., Lazinica, B., and Pedisic, Z. (2021). Test–retest reliability of the 30–15 Intermittent Fitness Test: a systematic review. *J. Sport Health Sci.* 10 (4), 413–418. doi:10.1016/j.jshs.2020.04.010

Grgic, J., Oppici, L., Mikulic, P., Bangsbo, J., Krustrup, P., and Pedisic, Z. (2019). Test–retest reliability of the yo-yo test: a systematic review. *Sports Med.* 49 (10), 1547–1557. doi:10.1007/s40279-019-01143-4

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Med.* 30 (1), 1–15. doi:10.2165/00007256-200030010-00001

Hoppe, M. W., Barnics, V., Freiwald, J., and Baumgart, C. (2020). Contrary to endurance, power associated capacities differ between different aged and starting-nonstarting elite junior soccer players'. *PLOS ONE* 15 (4), e0232118. doi:10.1371/journal.pone.0232118

Howarth, D. J., Cohen, D. D., McLean, B. D., and Coutts, A. J. (2022). Establishing the noise: interday ecological reliability of countermovement jump variables in professional rugby union players. *J. Strength Cond. Res.* 36 (11), 3159–3166. doi:10.1519/JSC.0000000000004037

Kennedy, R. A., and Drake, D. (2021). Improving the signal-to-noise ratio when monitoring countermovement jump performance. *J. Strength Cond. Res.* 35 (1), 85–90. doi:10.1519/JSC.0000000000002615

Kobal, R., Loturco, I., Gil, S., Cal Abad, C. C., Cuniyochi, R., Barroso, R., et al. (2016). Comparison of physical performance among Brazilian elite soccer players of different age-categories. *J. Sports Med. Phys. Fit.* 56 (4), 376–382.

Lehance, C., Binet, J., Bury, T., and Croisier, J. L. (2008). Muscular strength, functional performances and injury risk in professional and junior elite soccer players: muscular strength in soccer players. *Scand. J. Med. Sci. Sports* 19 (2), 243–251. doi:10.1111/j.1600-0838.2008.00780.x

Light, N., and Thorborg, K. (2016). The precision and torque production of common hip adductor squeeze tests used in elite football. *J. Sci. Med. Sport* 19 (11), 888–892. doi:10.1016/j.jsams.2015.12.009

Loturco, I., Freitas, T. T., Alcaraz, P. E., Kobal, R., Hartmann Nunes, R. F., Weldon, A., et al. (2022). Practices of strength and conditioning coaches in Brazilian elite soccer. *Biol. Sport* 39 (3), 779–791. doi:10.5114/biolsport.2022.108703

Maestroni, L., Turner, A., Papadopoulos, K., Cohen, D., Sideris, V., Graham-Smith, P., et al. (2023). Comparison of strength and power characteristics before ACL rupture and at the end of rehabilitation before return to sport in professional soccer players. *Sports Health A Multidiscip. Approach* 15, 814–823. doi:10.1177/19417381231171566

McAuley, A. B. T., Baker, J., and Kelly, A. L. (2022). Defining "elite" status in sport: from chaos to clarity. *Ger. J. Exerc. Sport Res.* 52 (1), 193–197. doi:10.1007/s12662-021-00737-3

McGuigan, M. (2016). "Principles of test selection and administration," in *Essentials of strength training and conditioning*. Editors G. G. Haff and N. T. Triplett 4th edn. Champaign, Illinois: (Human Kinetics), 249–258.

McGuigan, M. R., Cormack, S. J., and Gill, N. D. (2013). Strength and power profiling of athletes: selecting tests and how to use the information for program design. *Strength and Cond. J.* 35 (6), 7–14. doi:10.1519/SSC.0000000000000011

McQuilliam, S. J., Clark, D. R., Erskine, R. M., and Brownlee, T. E. (2023). Physical testing and strength and conditioning practices differ between coaches working in academy and first team soccer. *Int. J. Sports Sci. Coach.* 18 (4), 1045–1055. doi:10.1177/17479541231155108

Moreno-Pérez, V., Travassos, B., Calado, A., Gonzalo-Skok, O., Del Coso, J., Mendez-Villanueva, A., et al. (2019). Adductor squeeze test and groin injuries in elite football players: A prospective study. *Phys Therap in Sport.* 37, 54–59. doi:10.1016/j.ptsp.2019.03.001

Musham, C., and Fitzpatrick, J. F. (2020). Familiarisation and reliability of the isometric mid-thigh pull in elite youth soccer players. *Sport Perform. Sci. Rep.* 85, 1–4.

Nassis, G. P., Massey, A., Jacobsen, P., Brito, J., Randers, M. B., Castagna, C., et al. (2020). Elite football of 2030 will not be the same as that of 2020: preparing players, coaches, and support staff for the evolution. *Scand. J. Med. Sci. Sports* 30 (6), 962–964. doi:10.1111/sms.13681

Paul, D. J., and Nassis, G. P. (2015). Physical fitness testing in youth soccer: issues and considerations regarding reliability, validity, and sensitivity. *Pediatr. Exerc. Sci.* 27 (3), 301–313. doi:10.1123/mc.2014-0085

Requena, B., Garcia, I., Requena, F., Bressel, E., Saez-Saez de Villarreal, E., and Cronin, J. (2014). Association between traditional standing vertical jumps and a soccer-specific vertical jump. *Eur. J. Sport Sci.* 14, S398–S405. doi:10.1080/17461391.2012.708790

Rouissi, M., Chtara, M., Owen, A., Chaalali, A., Chaouachi, A., Gabbett, T., et al. (2016). Effect of leg dominance on change of direction ability amongst young elite soccer players. *J. of Sport Sci.* 34, 542–548. doi:10.1080/02640414.2015.1129432

Stern, D., Gonzalo-Skok, O., Loturco, I., Turner, A., and Bishop, C. (2020). A comparison of bilateral vs. Unilateral-biased strength and power training interventions on measures of physical performance in elite youth soccer players. *J. Strength Cond. Res.* 34 (8), 2105–2111. doi:10.1519/JSC.0000000000003659

Stølen, T., Chamari, K., Castagna, C., and Wisløff, U. (2005). Physiology of soccer: an update. *Sports Med. Auckl. N.Z.* 35 (6), 501–536. doi:10.2165/00007256-200535060-00004

Svensson, M., and Drust, B. (2005). Testing soccer players. *J. Sports Sci.* 23 (6), 601–618. doi:10.1080/02640410400021294

Taylor, J. M., Madden, J. L., Cunningham, L. P., and Wright, M. (2022). Fitness testing in soccer revisited: developing a contemporary testing battery. *Strength and Cond. J.* 44 (5), 10–21. doi:10.1519/SSC.0000000000000702

Thornton, H. R., Delaney, J. A., Duthie, G. M., and Dascombe, B. J. (2019). Developing athlete monitoring systems in team sports: data analysis and visualization. *Int. J. Sports Physiology Perform.* 14 (6), 698–705. doi:10.1123/ijspp.2018-0169

Turner, A., Beach, D. G., Foss, A., Samdal, I. A., Løvberg, K. L. E., Waack, J., et al. (2022). A feasibility study into the production of a mussel matrix reference material for the cyanobacterial toxins microcystins and nodularins. *Prof. Strength and Cond.* 15 (63), 27–31. doi:10.3390/toxins15010027

Turner, A., Walker, S., Stembridge, M., Coneyworth, P., Reed, G., Birdsey, L., et al. (2011). A testing battery for the assessment of fitness in soccer players. *Strength and Cond. J.* 33 (5), 29–39. doi:10.1519/SSC.0b013e31822fc80a

Turner, A. N., Jones, B., Stewart, P., Bishop, C., Parmar, N., Chavda, S., et al. (2019). Total score of athleticism: holistic athlete profiling to enhance decision-making. *Strength and Cond. J.* 41 (6), 91–101. doi:10.1519/SSC.0000000000000506

Turner, A. N., Parmar, N., Jovanovski, A., and Hearne, G. (2021). Assessing group-based changes in high-performance sport. Part 1: null hypothesis significance testing and the utility of p values. *Strength and Cond. J.* 43 (3), 112–116. doi:10.1519/SSC.0000000000000625

Turner, A. N., and Stewart, P. F. (2014). Strength and conditioning for soccer players. *Strength and Cond. J.* 36 (4), 1–13. doi:10.1519/SSC.0000000000000054

Turner, A., Brazier, J., Bishop, C., Chavda, S., Cree, J., Read, P., et al. (2015). Data analysis for strength and conditioning coaches: Using excel to analyze reliability, differences, and relationships. *Strength and Cond J.* 37, 76–83. doi:10.1519/SSC.0000000000000113

Vigne, G., Gaudino, C., Rogowski, I., Alloatti, G., and Hautier, C. (2010). Activity profile in elite Italian soccer team. *Int. J. Sports Med.* 31 (05), 304–310. doi:10.1055/s-0030-1248320

Walker, G. J., and Hawkins, R. (2018). Structuring a program in elite professional soccer. *Strength and Cond. J.* 40 (3), 72–82. doi:10.1519/SSC.0000000000000345

Ward, P., Coutts, A. J., Pruna, R., and McCall, A. (2018). Putting the "I" back in team. *Int. J. Sports Physiology Perform.* 13 (8), 1107–1111. doi:10.1123/ijspp.2018-0154

Werner, J., Hagglund, M., Walden, M., and Ekstrand, J. (2009). UEFA injury study: a prospective study of hip and groin injuries in professional football over seven consecutive seasons. *British J. of Sport Medi.* 43, 1036–1040. doi:10.1136/bjsm.2009.066944

Weakley, J., Black, G., McLaren, S., Scantlebury, S., Suchomel, T. J., McMahon, E., et al. (2023) Testing and profiling athletes: recommendations for test selection, implementation, and maximizing information, *Strength and Cond. J.* 35(6):7–14. doi:10.1519/SSC.0000000000000784

Weldon, A., Duncan, M. J., Turner, A., Sampaio, J., Noon, M., Wong, D. P., et al. (2021). Contemporary practices of strength and conditioning coaches in professional soccer. *Biol. Sport* 38 (3), 377–390. doi:10.5114/biolsport.2021.99328

Wing, C. E., Turner, A. N., and Bishop, C. J. (2020). Importance of strength and power on key performance indicators in elite youth soccer. *J. Strength Cond. Res.* 34 (7), 2006–2014. doi:10.1519/JSC.0000000000002446

Zhou, C., Gómez, M.-Á., and Lorenzo, A. (2020). The evolution of physical and technical performance parameters in the Chinese Soccer Super League. *Biol. Sport* 37 (2), 139–145. doi:10.5114/biolsport.2020.93039

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Effects of bi-hemispheric anodal transcranial direct current stimulation on soccer player performance: a triple-blinded, controlled, and randomized study

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The search for increased performance and physical performance are linked to the use of ergogenic resources. The vertical jump is one of the measures commonly used to evaluate the performance of lower limbs in athletes. Transcranial direct current stimulation (tDCS) is a non-invasive, safe, economically viable technique that can modulate cortical excitability, which can influence the increase in the performance of athletes in general. This study aimed to investigate whether the use of tDCS on the primary motor cortex (M1) improves the performance of soccer players. A cross-sectional study was conducted. Twenty-seven players were randomized into three groups: Active tDCS group ($n = 9$), Sham group ($n = 9$), and control group ($n = 9$). Stimulation was applied at 2 mA for 15 min using a cephalic mount. Visual Pain Scale (VAS) and Subjective Recovery Scale (SRS) were monitored before and after tDCS. In addition, the participants performed the Countermovement Jump (CMJ) before and after the stimulation intercalated with Heart Rate (HR) and Rating of Perceived Exertion (RPE CR-10). No differences were found in any of the performance variables analyzed ($p > 0.05$) nor in the responses of HR ($p > 0.05$), RPE ($p > 0.05$), VAS ($p > 0.05$), and SRS ($p > 0.05$) between groups. The tDCS in M1 did not change the performance of the vertical jump, and there was no improvement in the subjective scales. New studies should also be developed with different stimulus intensities in different cortical areas and sports modalities.

KEYWORDS
neuromodulation, neurophysiology, electrical stimulation, tDCS, performance, football, soccer

Introduction

During the competition season, athletes need to seek to improve their performance. In this sense, training loads (i.e., frequency, duration, and intensity) become high (1). Therefore, athletes may experience symptoms of fatigue that decrease muscle capacity for performance (1, 2). Consequently, controlling the training load throughout the season is essential to evaluate performance and avoid fatigue-related problems, such as non-functional overreaching (fatigue lasting from weeks to months), injuries, and illnesses (1).

One of the methods to monitor training load and recovery is the countermovement jump (CMJ) (1, 3, 4). The CMJ test assesses neuromuscular function through lower body power, quantified through jump height (i.e., power). During CMJ, power can be measured using various tools such as contact mats, force platforms, infrared platforms, accelerometers, linear position transducers, and/or video analysis (5, 6). Thus, the participant is asked to squat quickly for a self-selected downward action, followed by a reciprocal upward action, jumping as high as possible (5, 7). The CMJ assessment may indicate a decrease or increase in performance since the rate of strength development analyzed is related to muscle strength. Therefore, the greater the height of the CMJ, the more muscle force is used being an indication of low muscle fatigue (8).

Exercise induced muscle fatigue involves processes at various level of the motor pathway, from the brain to the muscle (9). These processes involve reductions in motor cortex excitability (10, 11), spinal excitability (12, 13), and in the contractile capacity of the recruited muscle fibers (14).

Currently, several ergogenic strategies are used to optimize sports performance. These strategies are beneficial ergogenic measures for recovery and performance, such as rest, adequate sleep, hydration, physiotherapeutic resources, nutrition, and neurostimulation techniques (15, 16). In addition, ergogenic measures that aim to increase supraspinal excitability can lead to a more efficient motor command that, ultimately, could increase the time in which a fixed output could be maintained (for example: muscle power benefit). This hypothesis is already being tested in some sports and several studies have shown improvement in a neuromodulatory technique called transcranial direct current stimulation (tDCS) (17–20). Neurostimulation techniques have been proposed to improve athletes cognitive and psychomotor performance. Among them, non-invasive brain stimulation, such as transcranial direct current stimulation (tDCS), is becoming famous for improving sports performance. The reason is the safety, low-cost, and easy-to-apply technique (19). The use of tDCS consists of applying two electrodes with a low-intensity continuous current (1–2 mA) in specific areas of the brain for a particular time (7–25 min) (21). This stimulation appears to induce changes in cortical excitability lasting from minutes to several hours after its use (22).

Among the areas that can be stimulated by tDCS, the primary motor cortex (M1) stands out as the brain region most related to sports performance due to its role in driving the exercised muscles (19). Research has shown that core fatigue can impact overall exercise performance. In this context, the decrease in motor neuron excitability and the limited ability of M1 and other supraspinal areas to maintain or increase the neural impulse may decrease the muscular capacity to produce force/ power, thus leading to fatigue. It is known a single anodal tDCS session in M1 can lead to performance enhancement in athletes in sport-specific motor tasks (17).

However, the literature indicates that results about the effects of tDCS on jumping performance are controversial. For example, Lattari et al. (23) observed an increase in the vertical jump performance of young men with experience in strength training from 20 min of tDCS in the primary motor cortex. On the other hand, Arenas et al. (24), found no significant improvement in vertical jump performance with 15 min of tDCS in the left dorsum lateral prefrontal cortex of healthy young non-athletes. These results may have occurred due to differences in the study methods, such as voltage, stimulation time, target brain area stimulated, or studied population.

Also, as indicated in the literature, studies investigating the effect of tDCS on the performance of soccer players are scarce and necessary (25, 26). These surveys, primarily carried out during the competition period, can help coaches and soccer players control the training and recovery load. In this context, the present study aimed to evaluate the effect of 15 min of anodic tDCS at M1 on vertical jump performance in young soccer players. Based on the available evidence regarding the role of tDCS on performance in athletes, the hypothesis of this study is that tDCS will increase vertical jump performance and improve perceived exertion and recovery compared to sham tDCS.

Methods

Subjects

The sample size was calculated using the G*Power software (version 3.1) (27–29) based on the prior analysis method. For analysis, the following commands were used: test family 5 *F*-tests, statistical test 5 analysis of variance: MANOVA repeated measures within-between interaction, error probability α 0.05 and statistical power of 0.96. Effect size was defined as a moderate effect size of 0.25, sphericity $\epsilon = 1$. The sample size was determined at 27 individuals. The 27 soccer players of the U20 team (age: 18 ± 0.77, body mass: 73.8 ± 6.50 kg, height: 178 cm $\pm$ 8.44 cm, body fat: $8.7 \pm 2.55\%$, BMI: 23.30 ± 1.9 kg/m^2).

Subjects were randomized one of the conditions experimental: (1) anodic tDCS over the motor cortex, (2) sham tDCS and (3) control group. The player-specific training schedule consisted of 5–6 weekly sessions, each lasting −90–120 min, and one or two competitive games per week. The inclusion criteria for participation contain the application of the Physical Activity Readiness Questionnaire (PAR-Q+) (30). Players between 18 and 20 years old without injuries and available to play. The exclusion criteria include any orthopedic injuries and/or mental health problems (e.g., schizophrenia) and/or brain disorders (e.g., epilepsy), intracranial implants, and using any psychoactive medication during the study. Before signing the written informed consent, the participants were informed about the procedures and possible risks. The research was approved by the local Research Ethics Committee (approval number: 40396120.6.1001.5106) under the Declaration of Helsinki.

Study design

Participants made four visits, one preliminary and three experimental sessions. All experimental sessions were separated by

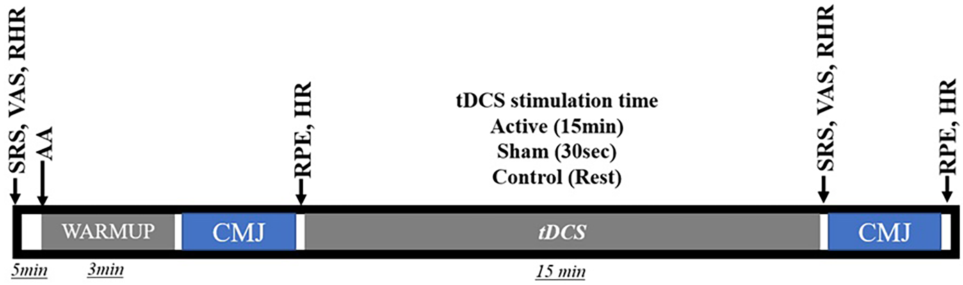

FIGURE 1
Study flow diagram; RHR, resting heart rate; SRS, subjective recovery scale; RVAS, resting visual analogue scale; CMJ, countermovement jump; RPE, rating of perceived exertion; HRP, rate heart post CMJ; VASP, visual analogue scale post CMJ.

24 h. Visits were simultaneously on the experimental days in a temperature-controlled room (−24°C). Participants were instructed to keep the same diet except for drinking coffee or energy drinks during the test week. On the first visit, they were familiarized with all procedures of all three sessions, which included, respectively, (a) the assessment of the Subjective Recovery Scale (SRS) and Visual Analogue Scale (VAS), (b) after 5 min seated the measurement of Rest Heart Rate (RHR); (c) the warmup which includes 1× with 10 s of interval of the following exercises: reverse lunge (20 reps), walking holding the knee unilaterally (20 reps for 3 m), isometric squat (for 15 s) with arms extended in front, low and medium skipping (20 reps). Warmup estimated time (3 min); (d) 3reps of CMJ followed by the Rating of Perceived Exertion (RPE) scale (CR-10) and the Rate Heart (HR) assessment; (e) After this, they did the *Intervention*, which means the adjustment of the tDCS apparatus and the stimulus for each group [for the active group (15 min of stimulus), sham (30 s of stimulus) and control (rest for 15 min, with no stimulus and without device)]; (f) The SRS, VAS and RHR; (g) 3 reps of CMJ; (h) RPE, and HR assessment. All data included all participants who completed the four sessions' experimental procedures (Figure 1). During the procedures, unique in the CMJ, all participants were stimulated to do their best. The study design is a triple-blinded, controlled, and randomized fashion.

Allocation

Randomization results were generated using a computer-generated random number sequence by an outsider researcher who was not involved in allocating or assessing study participants. Subjects were randomized one of the conditions experimental: (1) anodic tDCS over the motor cortex, (2) sham tDCS and (3) control group. A second researcher opened randomly ordered, consecutively numbered envelopes containing the results of group allocation after the initial assessment.

Blinding

In the active and sham tDCS conditions, researchers and participants were blinded by an independent researcher who did not participate in the other stages of the study. However, during the controlled condition, it was not possible to maintain blinding, as this condition did not require the use of equipment. The choice to carry out a control condition was determined with the intention of ensuring that at least one intervention avoided any possible psychological effects (placebo) generated using the equipment.

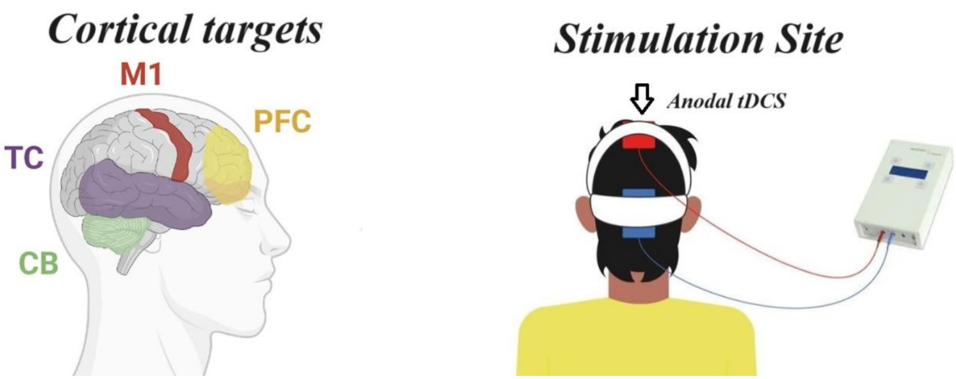

FIGURE 2
tDCS position.

Transcranial direct current stimulation procedures

Consistent with previous research, the study targeted the primary motor cortex (M1). For the anodal condition (a-tDCS), the electrodes were positioned to target the M1 bilaterally points CZ according to the international 10–20 EEG system (21, 25, 31, 32). Anodal tDCS over M1 facilitates motor performance and learning (33, 34), most likely by eliciting long-lasting, polarity-dependent changes in cortex excitability (22, 35). While the cathodal electrodes were placed on the inion (Figure 2) (36). Is possible to the tDCS montage influence other brain areas related to performance, such as parietal cortex or occipital. A more specific stimulation should be applied to investigate each area separately (36).

The intensity and duration of tDCS were based on previous studies (19, 20, 36). tDCS might strengthen synaptic connections through a mechanism that is like long-term potentiation (LTP), a cellular mechanism that underlies memory consolidation and learning (37, 38). The tDCS was administered using a battery-powered stimulator (Neuroconn, Ilmenau, Germany) through a pair of rubber electrodes (size: 6 cm × 8 cm, 48 cm^2) wrapped in a sponge soaked in saline liquid (9% NaCl). The electrodes were fixed to the head by elastic straps. Stimulation intensity was set at 2 mA for a period of 15 min. In both experimental conditions (active or sham), the amplitude of the electrical current was progressively increased and decreased over the first and last 30 s of the session, and in the sham group, the current was interrupted after this initial period. Activation of the transcranial direct current stimulation (tDCS) device occurred using a code provided by an external researcher, responsible for correcting the blinding. The automatic shutdown or not of the equipment (active or sham) was programmed using stimulation codes (active or sham) kept confidential, using the program in research mode of the mobile stimulator (DC-Stimulator, Neuroconn Mobile tDCS). This program provided a list of codes provided for the allocation of participants in relation to the active or simulated stimulation condition. Electrical resistance was maintained between 4 and 6 kΩ. In the control condition, participants rested quietly for 15 min. A total of 3 consecutive sessions were performed on different days in the afternoon with a 24-hour interval between sessions. At the end of each session, participants were asked to answer a questionnaire to assess any adverse effects, and no adverse effect was pointed out except for itching and tingling sensation under the electrodes during tDCS.

Performance assessments

In each experimental session, several measurements were taken, including HR, VAS, SRS, and RPE, to assess the physiological and subjective responses. Additionally, the jump height and power evaluation during the CMJ was conducted at two specific time points: after the warmup (Pre) and after 15 min of stimulation/sham/control (Post).

Heart rate (HR)

Each rest HR measurement was taken before the warmup, immediately after stimulation, respectively, after five and 15 min of rest. Also, the HR was taken after the first and second CMJ. This variable was used to get the participant's effort measuring the internal load (1, 39).

Visual analog scale (VAS)

In each experimental session, VAS measurements were conducted at two time points: at rest and immediately after the Intervention (to the active and sham group) or after the rest to the control group. The VAS is a prevalent instrument for pain measurement (40).

Subjective recovery scale (SRS)

The SRS was taken in 2 moments, in rest condition, immediately after Intervention (to the active and sham group) or after the rest to the control group. This variable shows whether the participants recovered from the previous game and/or session. Furthermore, this is essential in determining the participant's physical status and readiness for the next session (41). This subjective approach may be practical for assessing recovery daily under similar conditions (42).

Countermovement jump (CMJ)

Before the first CMJ, the participants did the warmup protocol, Afterward, each group followed their procedures, according to the Intervention described before, and performed the CMJ again. Each CMJ was performed with three consecutive jumps, which involved

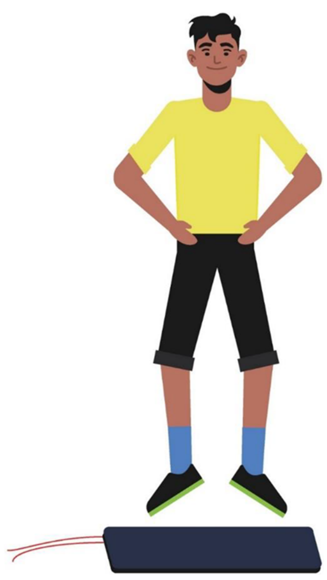

FIGURE 3
Countermovement jump.

three consecutive jumps (adaptation of the Abalakov protocol) (43). CMJ was performed with the subject standing in a with the hand on the hips to avoid arm swings. A fast downward movement was immediately followed by a fast upward vertical movement as high as possible, all in one sequence (Figure 3). The jumps were executed on a Jumptest® platform (Hidrofit Ltda, Brazil) measuring 50 cm × 60 cm, connected to the Multisprint® software (Hidrofit Ltda, Brazil) (44). The average CMJ data provided by the software, according to Claudino et al. (45), were used in the results. The variables assessed were the Jump Height (CMJ-JH), Power (CMJ-PO). Based on meta-analysis (5), the average CMJ height is more sensitive than the highest CMJ height in detecting fatigue and CMJ overcompensation. Furthermore, other CMJ variables, such as power, average power, peak velocity, peak force, average impulse and power, were evaluated better at the average height compared to the maximum height of the CMJ.

Rating of perceived exertion borg (RPE-CR-10)

After each CMJ, the participants provided their RPE from 0 (noticeable) to 10 (max), according to Foster et al. (39). Then they proceeded to their respective groups at the (active/sham or control). After a 15-minute interval, they performed the CMJ again, followed by the RPE. The RPE method can estimate exercise load, including high-intensity interval training, team sport practice, and competition (39).

Statistical analysis

The normality assumptions of the data were checked using the Shapiro-Wilk test. MANOVA test was performed for all variables using a significance level of $p < 0.05$. All the assumptions of MANOVA were checked, such as multivariate normality, absence of multivariate outliers, absence of multicollinearity, linear relationship between dependent variables at each level of independent variables, homogeneity of variance-covariance matrices, and independent observations. The partial eta-squared (ηp^2) was used as the effect size measure (classified as small: 0.01, moderate: 0.09, large: 0.25). A two-way ANOVA was used to generate statistical interaction (time × groups) and repeated one-way ANOVA was used to test between and within-group differences throughout the protocol variables, which is included the anthropometric measurement differences determination. The Tukey test was used as a *post hoc* analysis for the MANOVA procedures and Bonferroni to the ANOVA procedures.

The analyses used the Statistical Package for the Social Sciences (SPSS) version 21. GraphPad Prism software version 8.0 (GraphPad Software, Inc., San Diego, CA, USA) generated graphs.

Results

The results of the Rest Heart Rate (RHR) are described in Table 1. The MANOVA results [Wilks' Lambda $(W) = 0.446$,

TABLE 1 HR, heart rate; RHR, resting heart rate; PHR, post-intervention rate heart; pre-intervention (pre); post-intervention (post); confidence interval in 95% (CI 95%); M, mean; SD, standard deviation; IL, inferior limit; SL, superior limit.

HR	Group	Pré day 1			Post day 1			Pré day 2			Post day 2			Pré day 3			Post day 3		
		M ± SD	CI (95%)		M ± SD	CI (95%)		M ± SD	CI (95%)		M ± SD	CI (95%)		M ± SD	CI (95%)		M ± SD	CI (95%)	
			IL	SL		IL	SL		IL	SL		IL	SL		IL	SL		IL	SL
HRR	INT	62.5 ± 3	55.6	69.5	66.1 ± 4.2	56.31	75.9	61.8 ± 2.2	56.7	67	68.4 ± 4.7	57.4	79.4	64.1 ± 3.6	55.6	72.5	68.1 ± 5.7	54.8	81.4
	SHAM	64.5 ± 3.3	56.9	72.1	68.6 ± 3.4	60.6	76.5	65.3 ± 2.9	58.5	72	65.2 ± 2.8	58.5	71.8	61.3 ± 2.8	54.8	67.8	65.2 ± 1.9	60.6	69.7
	CON	63.5 ± 4.5	53	74	66.7 ± 4.6	56.1	77.4	62.7 ± 4.3	52.7	72.8	66.8 ± 4.4	56.5	77.2	64.1 ± 3.4	56	71.1	66.8 ± 3.3	59.2	74.5
PHR	INT	73.7 ± 4.8	62.5	84.9	73.1 ± 4.5	62.6	83.5	73.8 ± 5.9	60.2	87.5	73.4 ± 6.2	59	87.8	79 ± 4.6	68.3	89.6	74.5 ± 7.5	57.2	91.9
	SHAM	74.6 ± 5.6	61.5	87.7	72.1 ± 4.5	61.6	82.6	73.8 ± 5.2	61.6	86.1	69.4 ± 3.8	66.6	78.2	79.4 ± 6.9	63.5	95.3	76.2 ± 6.96	60.1	92.2
	CON	72.7 ± 8.8	52.2	93.2	77.4 ± 7	61.2	93.6	71.5 ± 8.4	52	91	76.1 ± 7.1	59.6	92.5	75.6 ± 7	59.4	91.8	76.6 ± 5.5	73.8	89.5

TABLE 2 VAS, visual analog scale; RVAS, rest visual analog scale; PVAS, post-intervention visual analog scale; CI 95%, confidence interval in 95%; M, mean; SD, standard deviation; IL, inferior limit; SL, superior limit.

VAS	GROUP	DAY 1			DAY 2			DAY 3		
		M ± SD	CI (95%)		M ± SD	CI (95%)		M ± SD	CI (95%)	
			IL	SL		IL	SL		IL	SL
RVAS	INT	1.6 ± 0.8	−0.37	3.7	1.7 ± 0.8	−0.1	3.7	2.1 ± 0.6	0.7	3.5
	SHAM	2.1 ± 0.6	0.6	3.6	4.6 ± 1	2.3	7	4 ± 0.3	3.2	4.7
	CON	3 ± 0.7	1.1	4.8	3 ± 0.7	1.2	4.8	3.2 ± 0.7	1.5	4.9
PVAS	INT	1.7 ± 0.8	−0.1	3.7	1.8 ± 0.5	0.5	3.2	2.7 ± 0.5	1.4	4.1
	SHAM	1.4 ± 0.5	0.2	2.6	3.7 ± 1.1	1.3	6.1	1.4 ± 0.4	2.3	4.5
	CON	1.8 ± 0.7	0.1	3.5	2.6 ± 0.7	0.8	4.4	2.6 ± 0.6	1.3	4.1

F (2.24) = 0.537, p = 0.934, effect size (ηp^2) = 0.331] did not detect differences between groups for RHR before the first CMJ. The absence of difference persists at the univariate ANOVA in all three days within the groups, respectively RHR day 1 (RHRD1) [F (2.24) = 0.074, p = 0.929, ηp^2 = 0.006], RHRD2 [F (2.24) = 0.295, p = 0.747, ηp^2 = 0.024], and RHRD3 [F (2.24) = 0.230, p = 0.796, ηp^2 = 0.019].

The MANOVA test did not detect differences between groups for the RHR after 15 min of *Intervention* between all groups [W = 0.446, F (2.24) = 0.537, p = 0.934, ηp^2 = 0.331]. For this variable, in this moment, univariate ANOVA results for RHR post-day 1 (RHRP1) [F (2.24) = 0.103, p = 0.903, ηp^2 = 0.008], RHRP2 [F (2.24) = 0.152, p = 0.860, ηp^2 = 0.012] and RHRP3 [F (2.24) = 0.131, p = 0.878, ηp^2 = 0.011].

Differences were not detected for the HR after the first CMJ (HR-CMJ) according to MANOVA [W = 0.446, F (2.24) = 0.537, p = 0.934, ηp^2 = 0.331]. The results of the univariate ANOVA also did not show significant differences according to the following results of HR-CMJ Day 1 (HR-CMJD1) [F (2.24) = 0.020, p = 0.980, ηp^2 = 0.002], HR-CMJD2 [F (2.24) = 0.040, p = 0.960, ηp^2 = 0.003], HR-CMJD3 [F (2.24) = 0.108, p = 0.898, ηp^2 = 0.009].

For the HR assessed after the *Intervention* (HR-CMJI), the MANOVA [W = 0.446, F (2.24) = 0.537, p = 0.934, ηp^2 = 0.331] did not detect differences between groups. For the same variable and moment, univariate ANOVA was conducted, HR-CMJI Day 1 (HR-CMJID1) [F (2.24) = 0.266, p = 0.769, ηp^2 = 0.022], HR-CMJID2 [F (2.24) = 0.323, p = 0.727, ηp^2 = 0.026], HR-CMJID3 [F (2.24) = 0.027, p = 0.973, ηp^2 = 0.002], no difference was detected.

The Visual Analogic Scale (VAS) results are described in Table 2. The MANOVA [W = 0.027, F (2.24) = 1.991, p = 0.084, ηp^2 = 0.837] did not detect any differences between the groups. As well as the univariate ANOVA at rest on Day 1 (RVASD1) [F (2.24) = 0.749, p =, ηp^2 = 0.059]; RVASD2 [F (2.24) = 2.648, p = 0.091, ηp^2 = 0.181]; and RVASD3 (RVAS-day 3) [F (2.24) = 2.615, p = 0.094, ηp^2 = 0.179]. The same situation occurred after the *Intervention* (PVAS), as seen on Day 1 (PVASD1) [F (2.24) = 0.106, p = 0.900, ηp^{22} = 0.009]; Day 2 PVASD2 [F (2.24) = 1.329, p = 0.283, ηp^2 = 0.100]; and PVASD3 [F (2.24) = 0.564, p = 0.576, ηp^2 = 0.045].

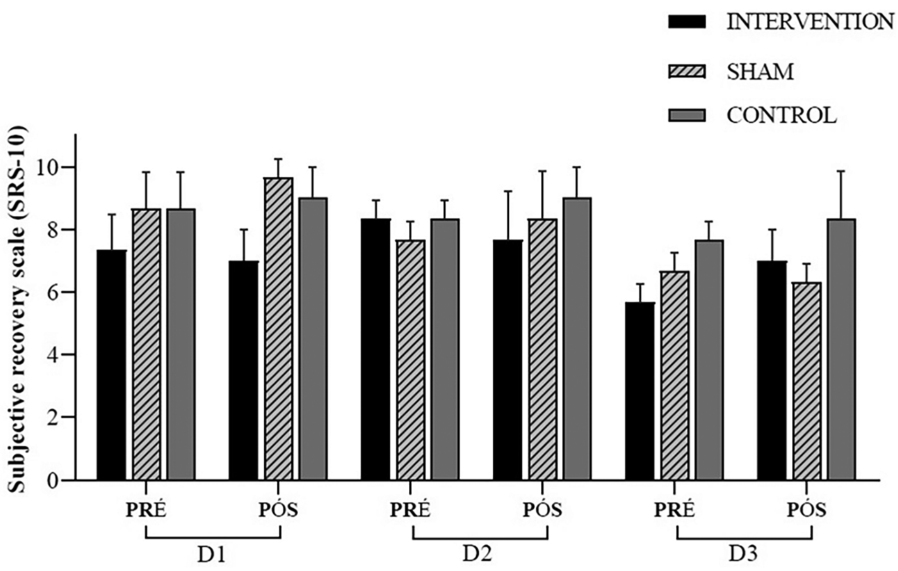

FIGURE 4
Subjective recovery scale (SRS-10); experimental session—day 1 (D1); experimental session—day 2 (D2); experimental session—day 3 (D3); pre-intervention (pre); post-intervention (post).

For the Subjective Recovery Scale (SRS), the MANOVA results showed no differences [$W = 0.027$, F (2.24) = 1.991, $p = 0.084$, $\eta p^2 = 0.837$], as well as the univariate ANOVA in the pre-day 1 (SRSPreD1) [F (2.24) = 0.035, $p = 0.965$, $\eta p^2 = 0.003$], SRSPreD2 [F (2.24) = 0.000, $p = 1.000$, $\eta p^2 = 0.000$], SRSPreD3 [F (2.24) = 2.452, $p = 0.107$, $\eta p^2 = 0.170$], and SRS post-day 1 (SRSPostD1) [F (2.24) = 0.304, $p = 0.740$, $\eta p^2 = 0.025$], SRSPostD2 [F (2.24) = 0.041, $p = 0.960$, $\eta p^2 = 0.003$], and SRSPostD3 [F (2.24) = 1.532, $p = 0.237$, $\eta p^2 = 0.113$] the similarity was maintained (Figure 4).

The one-way ANOVA did not detect variation between all groups at the anthropometric variables. Respectively to the Weight, Height, BMI, and Fat Percentual, the statistical procedure shows the following results [F (2.24) = 2.640; $p = 0.092$]; [F (2.24) = 1.187; $p = 0.322$]; [F (2.24) = 1.156; $p = 0.332$] and [F (2.24) = 3.132; $p = 0.062$].

Thus, for the performance variables, the Jump Height (CMJ-JH) was submitted by the MANOVA test. The result did not detect any significance [$W = 0.862$, F (2.24) = 0.244, $p = 0.994$, $\eta p^2 = 0.071$]. Additionally, the one-way ANOVA procedures did not reveal any differences at any time, which was confirmed by the *post hoc* analysis (Figure 5). As seen in the moments Pre Day 1 (CMJ-JHPreD1) [F (2.24) = 0.051, $p = 0.950$, $\eta p^2 = 0.004$], Post Day 1 (CMJ-JHPostD1) [F (2.24) = 0.155, $p = 0.857$, $\eta p^2 = 0.013$], CMJ-JHPreD2 [F (2.24) = 0.161, $p = 0.852$, $\eta p^2 = 0.013$], CMJ-JHPostD2 [F (2.24) = 0.294, $p = 0.748$, $\eta p^2 = 0.024$], CMJ-JHPreD3 [F (2.24) = 0.124, $p = 0.884$, $\eta p^2 = 0.010$], and CMJ-JHPostD3 [F (2.24) = 0.358, $p = 0.703$, $\eta p^2 = 0.029$]. The Table 3 contains results in interactions (time × groups) and time (groups throughout the protocol) according to study variables. The Table 4 contains individual pre and post changes in vertical jump height between groups (Intervention/ Sham/Control).

For the Vertical Jump Power (CMJ-PO), the MANOVA results did not detect any differences [$W = 0.629$, F (2.24) = 0.827, $p = 0.623$, $\eta p^2 = 0.207$] according to Figure 6. When examining the data in the univariate ANOVA, no differences were observed. These moments are as follows: CMJ-PO Pre Day 1 (CMJ-POPreD1) [F (2.24) = 0.435, $p = 0.652$, $\eta p^2 = 0.035$], CMJ-PO Post Day 1 (CMJ-POPostD1) [F (2.24) = 0.407, $p = 0.670$, $\eta p^2 = 0.033$], CMJ-POPreD2 [F (2.24) = 0.726, $p = 0.494$, $\eta p^2 = 0.057$], CMJ-POPostD2 [F (2.24) = 0.310, $p = 0.736$, $\eta p^2 = 0.025$], CMJ-POPreD3 [F (2.24) = 0.285, $p = 0.754$, $\eta p^2 = 0.023$], and CMJ-POPostD3 [F (2.24) = 1.627, $p = 0.217$, $\eta p^2 = 0.119$].

The MANOVA did not detect any differences in Rating of Perceived Exertion (RPE) throughout the protocol [Wilks' Lambda = 0.027, F (2.24) = 1.991, $p = 0.084$, $\eta p^2 = 0.837$] (Figure 7). When examining the data in a univariate manner (univariate ANOVA), no differences were observed. These moments are as follows: moment Pre Day 1 (RPEPreD1) [F (2.24) = 0.225, $p = 0.801$, $\eta p^2 = 0.018$], Post Day 1 (RPEPostD1) [F (2.24) = 0.695, $p = 0.509$, $\eta p^2 = 0.055$], RPEPreD2 [F (2.24) = 0.626, $p = 0.543$, $\eta p^2 = 0.050$], and at RPEPostD2 [F (2.24) = 1.109, $p = 0.346$, $\eta p^2 = 0.085$], RPEPreD3 [F (2.24) = 0.960, $p = 0.397$, $\eta p^2 = 0.074$], and RPEPostD3 [F (2.24) = 0.304, $p = 0.740$, $\eta p^2 = 0.025$], the similarity was maintained.

Discussion

The present study investigated the effect of transcranial direct current stimulation on CMJ in soccer players. Some

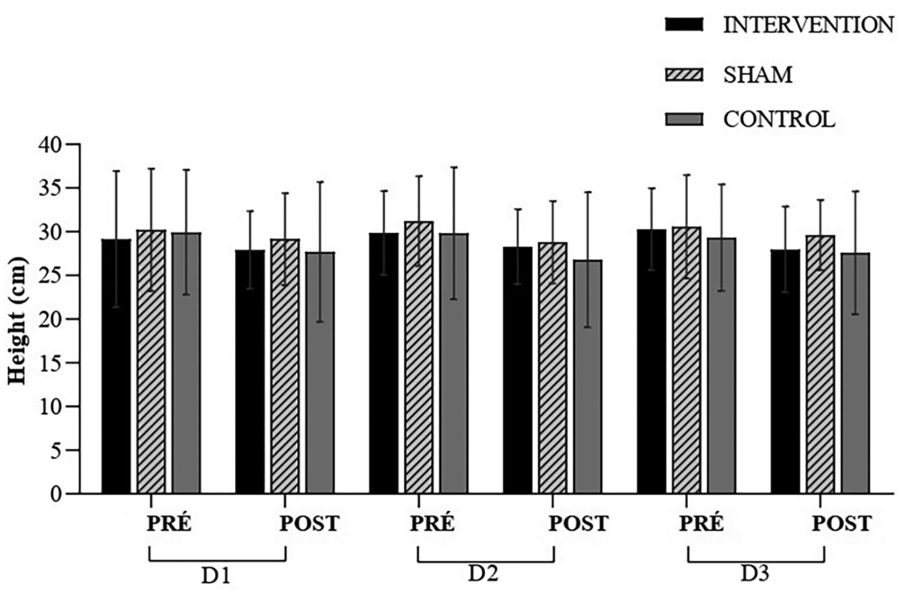

FIGURE 5
Height (cm); D1; experimental session—day 1 (D1); experimental session—day 2 (D2); experimental session—day 3 (D3); pre-intervention (pre); post-intervention (post).

TABLE 3 Results in interactions (time × groups) and time (groups throughout the protocol) according to study variables.

	Interaction			Time		
	F [df]	*p*-value	ηp^2	*F* [df]	*p*-value	ηp^2
RHR (Bpm)						
Active	3.402 (1–16)[a]	0.084[a]	0.175[a]	1.639 (5–40)	0.172	0.170
Sham	0.362 (1–16)[b]	0.556[b]	0.022[b]	1.470 (5–40)	0.247	0.155
Control	2.093 (1–16)[c]	0.167[c]	0.116[c]	0.815 (5–40)	0.546	0.092
HR (Bpm)						
Active	0.009 (1–16)[a]	0.924[a]	0.001[a]	0.295 (5–40)	0.913	0.036
Sham	0.001 (1–16)[b]	0.976[b]	0.000[b]	0.686 (5–40)	0.522	0.079
Control	0.018 (1–16)[c]	0.894[c]	0.001[c]	0.579 (5–40)	0.716	0.067
VAS (VAS-10)						
Active	0.778 (1–16)[a]	0.391[a]	0.046[a]	0.423 (5–40)	0.830	0.050
Sham	3.879 (1–16)[b]	0.066[b]	0.195[b]	4.137 (5–40)	0.033	0.341
Control	0.009 (1–16)[c]	0.924[c]	0.001[c]	0.862 (5–40)	0.451	0.97
SRS (SRS-10)						
Active	4.445 (1–16)[a]	0.051[a]	0.217[a]	3.067 (5–40)	0.066	0.277
Sham	0.000 (1–16)[b]	1.000[b]	0.000[b]	2.709 (5–40)	0.093	0.253
Control	0.778 (1–16)[c]	0.391[c]	0.395[c]	2.782 (5–40)	0.735	0.510
HCMJ (cm)						
Active	0.102 (1–16)[a]	0.753[a]	0.006[a]	1.173 (5–40)	0.339	0.128
Sham	0.678 (1–16)[b]	0.422[b]	0.041[b]	1.009 (5–40)	0.395	0.112
Control	0.310 (1–16)[c]	0.585[c]	0.019[c]	2.685 (5–40)	0.076	0.251
PCMJ (W)						
Active	0.157 (1–16)[a]	0.698[a]	0.010[a]	1.515 (5–40)	0.207	0.159
Sham	0.123 (1–16)[b]	0.730[b]	0.008[b]	0.585 (5–40)	0.712	0.068
Control	0.010 (1–16)[c]	0.920[c]	0.001[c]	1.231 (5–40)	0.312	0.133
RPE (CR-10)						
Active	0.061 (1–16)[a]	0.809[a]	0.004[a]	0.432 (5–40)	0.823	0.051
Sham	0.119 (1–16)[b]	0.734[b]	0.007[b]	1.105 (5–40)	0.373	0.121
Control	0.729 (1–16)[c]	0.406[c]	0.044[c]	1.205 (5–40)	0.325	0.131

SRS, subjective recovery scale from 0 to 10; VAS, visual analogic scale from 0 to 10; RHR, rest heart rate; HR, heart rate; RPE (CR-10), rating of perceived exertion from 0 to 10; PCMJ (W), vertical jump power in watts; HCMJ (cm), vertical jump height in centimetres; F, Fisher's F; df, degree of freedom; ηp^2, partial eta squared.
[a]Interaction between Active and Sham group.
[b]Interaction between Active and Control group.
[c]Interactions between Sham and Control group.
*Statistical difference.
p-value, $p < 0.05$.

studies show that the tDCS technique can influence physical/sports performance (17, 26). However, according to the results presented related to the tDCS montage contrary to our hypothesis, tDCS did not influence performance on the CMJ and perception of effort and recovery. These results are in line with previous studies that did not report significant improvements in performance (46, 47). However, other studies showed positive effects of tDCS on performance (48, 49).

The tDCS has been considered a technique influencing different physical/sports performance aspects. However, studies conducted with athletes involving specific tasks are scarce, and the heterogeneity of the adopted protocols does not allow for any conclusions about its ergogenic effects (19).

In terms of performance variables, several ergogenic measures aimed at optimizing physical performance, attenuating fatigue mechanisms, and facilitating post-physical exertion recovery have been widely studied (50–52). For example, caffeine (53) has shown improvements in vertical jump performance in soccer players, while in another study (54), caffeine ingestion was found to improve tactical performance in soccer athletes. As for tDCS used as an ergogenic measure to improve performance, Lattari et al. (23) demonstrated that anodal tDCS (2 mA for 20 min, with the anode positioned over the Cz point and the cathode over the right supraorbital area) led to improved jump performance in individuals considered advanced in strength training. However, unlike the individuals Lattari et al. (23) investigated, the individuals included in the present study are frequently exposed to CMJ as part of training load control. Therefore, they are likely better trained in the task, presenting a lower potential for improvement.

Regarding the subjective variables, a study by Moreira et al. (26) demonstrated improvement in the Well-Being Questionnaire of soccer players after 20 min of tDCS was applied in the Left Dorsolateral Prefrontal Cortex (DLPC) on the day following an official match. In another study by Valenzuela et al. (32) with swimmers, an improvement in the RPE was observed. In contrast to the present study's hypothesis, anodic tDCS applied to the M1 did not influence the responses of subjective scales in soccer players. It is worth noting that the stimulated area in the cited articles differs from the present study. Although it is not clear how the DLPFC and M1 are connected, a recent study reported that their excitabilities are linked (55). These findings agree with previous studies that also failed to show a reduction in RPE or an increase in performance after the application of tDCS over (20, 56).

Subjective assessments are recommended to monitor the psychometric recovery status of football players to detect early signs of fatigue and optimize high-level training performance (57). The decrease in these measurements are used to express the lesser subjective state of fatigue, effort and recovery of a player or team during training or competition. Improvements in these scores are significant predictors of performance in football athletes (58, 59). Likewise, insufficient recovery, poor quality of sleep from the previous night and increased levels of stress, fatigue (60, 61) during training can negatively impact athletic performance (62, 63). Thus, monitoring these psychometric measures (i.e., through subjective scales) in football players can assist coaches in programming and appropriately adapting training loads in order to maximize performance and reduce the risk of injuries, overtraining and overreaching functional (64–66).

Machado et al. (19) demonstrated that this topic still has limitations, mainly related to the type of montage, stimulation duration, the task performed, and athlete's level.

According to the established montage, performance was sometimes even better for the SHAM group. Therefore, the proposed montage in this study (CZ + Inion) did not seem to be effective for this Intervention, unlike classic montages such as the motor cortex and LDPC (M1 + Fp2) (67) or only the M1 (C3, and C4) (68), among other montages presented by Alix-Fages (20) and Machado (19).

However, this study was conducted in only three sessions, representing acute effects. Therefore, conducting further studies with this montage in a more prolonged intervention approach (chronic effect) would be interesting.

TABLE 4 Individual outcomes: CMJ, countermovement jump; Int, intervention; Pre, pre-intervention; Post, post-intervention; GM, group media; SD, standard deviation.

Group	Pré day 1	Post day 1	Pré day 2	Post day 2	Pré day 3	Post day 3	SD
INT	CMJ height (CM)	CMJ height (CM)	CMJ height (CM)	CMJ height (CM)	CMJ height (CM)	CMJ height (CM)	
1	35.43	31.00	34.67	33.27	27.60	31.23	2.62
2	30.10	30.67	30.10	30.67	32.60	25.13	2.28
3	38.27	30.93	38.27	30.93	37.50	33.03	3.27
4	37.93	35.17	31.87	33.00	35.93	37.43	2.20
5	26.63	24.50	29.63	28.67	29.90	26.00	1.99
6	14.63	22.50	24.67	26.17	25.93	25.23	4.01
7	21.47	21.97	23.50	21.30	22.48	21.63	0.75
8	27.00	26.67	25.57	28.07	30.40	26.27	1.57
9	30.90	27.90	30.52	22.50	30.13	25.70	3.02
GM	28.93	27.93	29.78	29.01	30.29	28.25	
SD	8.29	4.73	5.12	3.95	5.02	5.18	
SHAM							
1	31.87	27.87	30.43	26.47	27.83	28.23	1.81
2	29.30	26.33	28.00	24.73	31.23	30.63	2.30
3	28.97	23.90	35.77	27.47	25.43	28.33	3.75
4	30.63	27.73	27.90	27.87	29.27	27.80	1.08
5	39.93	36.20	38.70	36.87	39.32	36.53	1.45
6	41.07	39.47	38.40	36.83	38.70	35.73	1.73
7	27.10	27.20	27.03	26.60	31.97	28.23	1.83
8	24.30	24.56	29.90	24.56	20.60	24.57	2.71
9	18.80	29.27	24.84	27.93	30.87	26.60	3.89
GM	30.22	29.17	31.22	28.81	30.58	29.63	
SD	7.00	5.25	5.12	4.71	5.92	4.03	
CON							
1	31.20	27.50	29.53	21.73	26.63	27.43	2.93
2	30.43	24.40	26.50	22.87	26.50	22.87	2.63
3	25.70	30.97	26.70	24.57	23.57	24.90	2.39
4	39.43	37.77	39.83	40.40	40.50	41.00	1.05
5	37.83	37.63	39.97	34.83	36.23	34.33	1.92
6	26.73	22.57	30.13	26.43	27.17	26.40	2.20
7	34.67	32.66	36.64	33.89	34.63	33.91	1.20
8	35.30	31.70	33.17	31.70	34.23	31.70	1.41
9	16.27	12.37	15.07	14.50	24.30	19.23	3.88
GM	30.84	28.62	30.84	27.88	30.42	29.09	
SD	7.19	8.03	7.83	7.99	6.05	6.73	

Nevertheless, this is the first study to evaluate the CMJ performance in soccer players throughout the competition period in soccer players. It also is the first study with this tDCS montage in the sports literature. Therefore, this article opens new possibilities for studying the essential effects of various ergogenic measures related to tDCS or other techniques, such as transcranial magnetic stimulation (TMS), as well as different montage configurations and performance variables in soccer or other specificities.

Conclusion

The results the present study showed that transcranial direct current stimulation (tDCS) in the CZ area at the M1 cortex for 15 min, in three sessions, did not improve vertical jump in the CMJ performance and did not improve the results at the subjective scales in soccer players. Future research should explore the effects of tDCS on the performance of professional football athletes. Furthermore, different tDCS configurations such as intensity, sessions, areas (e.i) should be explored in order to find optimal tDCS protocols to improve performance in different physical conditions. The application of tDCS in the setting of this study is not recommended to increase vertical jump performance or reduce perceived exertion and recovery.

Limitations

There are limitations in the present study besides the prolonged stimulation mentioned above. First, this study should have included measurements to explain the neurophysiological effects of tDCS. Future studies should employ measures to assess neurophysiological effects, such as electromyography and electroencephalography, among others, at the target muscle areas. Additionally, the players were not separated by position, which may result in differences in CMJ performance, as specific

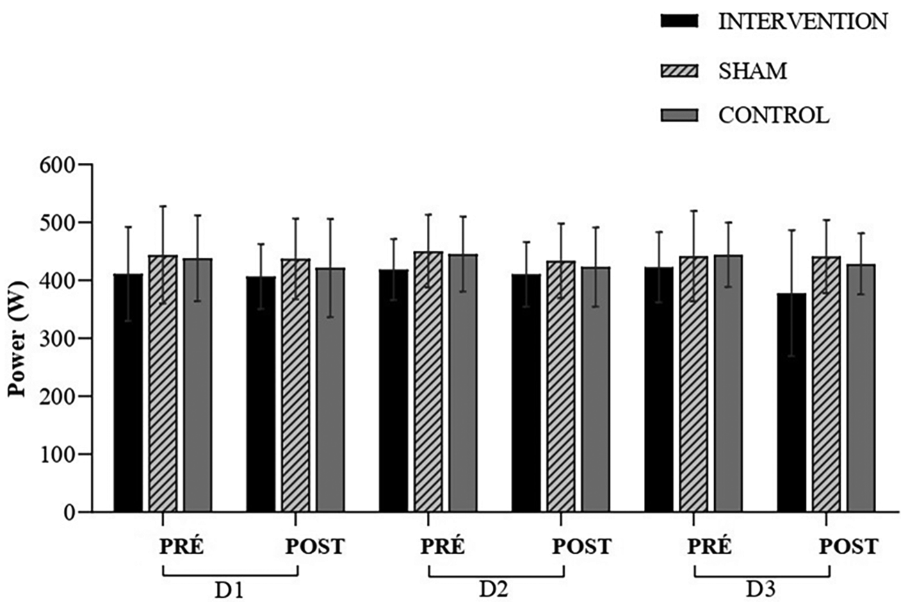

FIGURE 6
Power (W); experimental session—day 1 (D1); experimental session—day 2 (D2); experimental session—day 3 (D3); pre-intervention (pre); post-intervention (post).

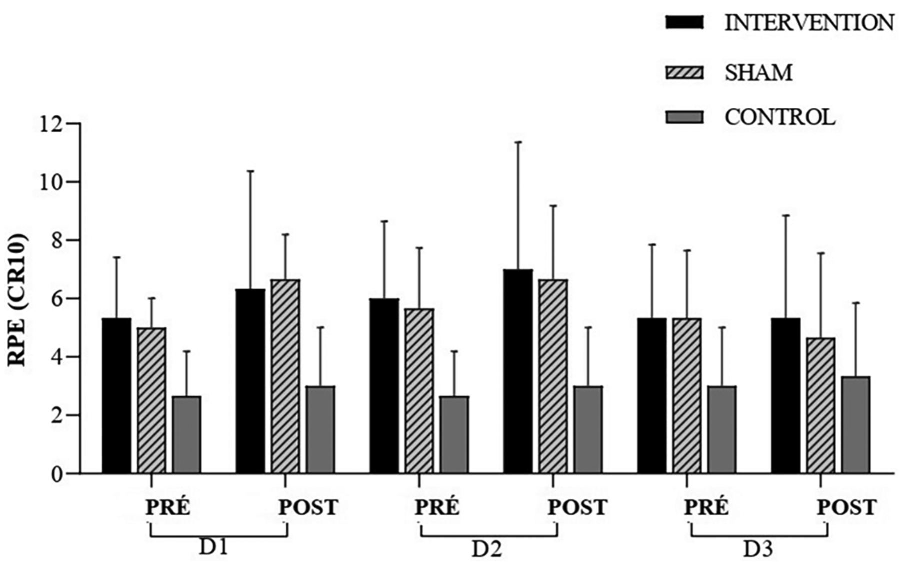

FIGURE 7
RPE, rating of perceived exertion; experimental session—day 1 (D1); experimental session—day 2 (D2); experimental session—day 3 (D3); pre-intervention (pre); post-intervention (post).

position-specific requirements may involve more jumping, such as goalkeepers or defenders.

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 SOCIEDADE DE ENSINO SUPERIOR DE MANHUACU. 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

JR: Writing – original draft. RA: Writing – review & editing, Conceptualization. BL: Writing – original draft, Methodology. CC: Writing – original draft, Investigation. CZ: Writing – review & editing, Conceptualization. FA: Writing – review & editing, Supervision, Methodology, Investigation.

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Conflict of interest

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

Publisher's note

References

1. Halson SL. Monitoring training load to understand fatigue in athletes. *Sports Med.* (2014) 44(Suppl 2):S139–47. doi: 10.1007/s40279-014-0253-z

2. Layzer RB. Muscle metabolism during fatigue and work. *Baillieres Clin Endocrinol Metab.* (1990) 4(3):441–59. doi: 10.1016/s0950-351x(05)80064-3

3. He L, Li YG, Wu C, Yao S, Su Y, Ma GD, et al. The influence of repeated drop jump training on countermovement jump performance. *Appl Bionics Biomech.* (2022) 2022:9609588. doi: 10.1155/2022/9609588

4. Hughes W, Healy R, Lyons M, Nevill A, Higginbotham C, Lane A, et al. The effect of different strength training modalities on sprint performance in female team-sport athletes: a systematic review and meta-analysis. *Sports Med.* (2023) 53(5):993–1015. doi: 10.1007/s40279-023-01820-5

5. Claudino JG, Cronin J, Mezêncio B, McMaster DT, McGuigan M, Tricoli V, et al. The countermovement jump to monitor neuromuscular status: a meta-analysis. *J Sci Med Sport.* (2017) 20(4):397–402. doi: 10.1016/j.jsams.2016.08.011

6. Stahl CA, Lindsay KG, Mann JB, Hunt M, Dawes JJ. A comparison of lower body power characteristics between collegiate athletes from different competition levels. *Int J Exerc Sci.* (2020) 13(6):470–9. PMID: 32509133.

7. Van Hooren B, Zolotarjova J. The difference between countermovement and squat jump performances: a review of underlying mechanisms with practical applications. *J Strength Cond Res.* (2017) 31(7):2011–20. doi: 10.1519/JSC.0000000000001913

8. McLellan CP, Lovell DI, Gass GC. The role of rate of force development on vertical jump performance. *J Strength Cond Res.* (2011) 25(2):379–85. doi: 10.1519/JSC.0b013e3181be305c

9. Gandevia SC. Spinal and supraspinal factors in human muscle fatigue. *Physiol Rev.* (2001) 81(4):1725–89. doi: 10.1152/physrev.2001.81.4.1725

10. Søgaard K, Gandevia SC, Todd G, Petersen NT, Taylor JL. The effect of sustained low-intensity contractions on supraspinal fatigue in human elbow flexor muscles. *J Physiol.* (2006) 573(Pt 2):511–23. doi: 10.1113/jphysiol.2005.103598

11. Weavil JC, Sidhu SK, Mangum TS, Richardson RS, Amann M. Fatigue diminishes motoneuronal excitability during cycling exercise. *J Neurophysiol.* (2016) 116(4):1743–51. doi: 10.1152/jn.00300.2016

12. Klass M, Lévénez M, Enoka RM, Duchateau J. Spinal mechanisms contribute to differences in the time to failure of submaximal fatiguing contractions performed with different loads. *J Neurophysiol.* (2008) 99(3):1096–104. doi: 10.1152/jn.01252.2007

13. McNeil CJ, Giesebrecht S, Gandevia SC, Taylor JL. Behaviour of the motoneurone pool in a fatiguing submaximal contraction. *J Physiol.* (2011a) 589:3533–44. doi: 10.1113/jphysiol.2011.207191

14. Allen DG, Lamb GD, Westerblad H. Skeletal muscle fatigue: cellular mechanisms. *Physiol Rev.* (2008) 88(1):287–332. doi: 10.1152/physrev.00015.2007

15. Robson-Ansley PJ, Gleeson M, Ansley L. Fatigue management in the preparation of Olympic athletes. *J Sports Sci.* (2009) 27(13):1409–20. doi: 10.1080/02640410802702186

16. Chinzara TT, Buckingham G, Harris DJ. Transcranial direct current stimulation and sporting performance: a systematic review and meta-analysis of transcranial direct current stimulation effects on physical endurance, muscular strength and visuomotor skills. *Eur J Neurosci.* (2022) 55(2):468–86. doi: 10.1111/ejn.15540

17. Maudrich T, Ragert P, Perrey S, Kenville R. Single-session anodal transcranial direct current stimulation to enhance sport-specific performance in athletes: a systematic review and meta-analysis. *Brain Stimul.* (2022) 15(6):1517–29. doi: 10.1016/j.brs.2022.11.007

18. Kaushalya FS, Romero-Arenas S, García-Ramos A, Colomer-Poveda D, Marquez G. Acute effects of transcranial direct current stimulation on cycling and running performance. A systematic review and meta-analysis. *Eur J Sport Sci.* (2022) 22(2):113–25. doi: 10.1080/17461391.2020.1856933

19. Machado DGDS, Unal G, Andrade SM, Moreira A, Altimari LR, Brunoni AR, et al. Effect of transcranial direct current stimulation on exercise performance: a systematic review and meta-analysis. *Brain Stimul.* (2019) 12(3):593–605. doi: 10.1016/j.brs.2018.12.227

20. Alix-Fages C, Romero-Arenas S, Castro-Alonso M, Colomer-Poveda D, Río-Rodriguez D, Jerez-Martínez A, et al. Short-term effects of anodal transcranial direct current stimulation on endurance and maximal force production. A systematic review and meta-analysis. *J Clin Med.* (2019) 8(4):536. doi: 10.3390/jcm8040536

21. Angius L, Hopker J, Mauger AR. The ergogenic effects of transcranial direct current stimulation on exercise performance. *Front Physiol.* (2017) 8:90. doi: 10.3389/fphys.2017.00090

22. Nitsche MA, Paulus W. Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *J Physiol.* (2000) 527(Pt 3):633–9. doi: 10.1111/j.1469-7793.2000.t01-1-00633.x

23. Lattari E, Campos C, Lamego MK, Legey S, Neto GM, Rocha NB, et al. Can transcranial direct current stimulation improve muscle power in individuals with advanced weight-training experience? *J Strength Cond Res.* (2020) 34(1):97–103. doi: 10.1519/JSC.0000000000001956

24. Romero-Arenas S, Calderón-Nadal G, Alix-Fages C, Jerez-Martínez A, Colomer-Poveda D, Márquez G. Transcranial direct current stimulation does not improve countermovement jump performance in young healthy men. *J Strength Cond Res.* (2021) 35(10):2918–21. doi: 10.1519/JSC.0000000000003242

25. Vargas VZ, Baptista AF, Pereira GOC, Pochini AC, Ejnisman B, Santos MB, et al. Modulation of isometric quadriceps strength in soccer players with transcranial direct current stimulation: a crossover study. *J Strength Cond Res.* (2018) 32(5):1336–41. doi: 10.1519/JSC.0000000000001985

26. Moreira A, Machado DGDS, Moscaleski L, Bikson M, Unal G, Bradley PS, et al. Effect of tDCS on well-being and autonomic function in professional male players after official soccer matches. *Physiol Behav.* (2021) 233:113351. doi: 10.1016/j.physbeh.2021.113351

27. Erdfelder E, Faul F, Buchner A. GPOWER: a general power analysis program. *Behav Res Methods Instrum Comput.* (1996) 28(I):1–11. doi: 10.3758/BF03203630

28. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods.* (2007) 39(2):175–91. doi: 10.3758/bf03193146

29. Faul F, Erdfelder E, Buchner A, Lang A-G. Statistical power analyses using G*pPower 3. 1 : tests for correlation and regression analyses. *Behav Res Methods.* (2009) 41(4):1149–60. doi: 10.3758/BRM.41.4.1149

30. Warburton DER, Jamnik VK, Bredin SSD, Gledhill N. The physical activity readiness questionnaire for everyone (PAR-Q+) and electronic physical activity readiness medical examination (ePARmed-X+). *Health Fit J Can.* (2011) 4(2):3–17. doi: 10.14288/hfjc.v4i2.103

31. Angius L, Pageaux B, Hopker J, Marcora SM, Mauger AR. Transcranial direct current stimulation improves isometric time to exhaustion of the knee extensors. *Neuroscience.* (2016) 339:363–75. doi: 10.1016/j.neuroscience.2016.10.028

32. Valenzuela PL, Amo C, Sánchez-Martínez G, Torrontegi E, Vázquez-Carrión J, Montalvo Z, et al. Enhancement of mood but not performance in elite athletes with transcranial direct-current stimulation. *Int J Sports Physiol Perform.* (2019) 14 (3):310–6. doi: 10.1123/ijspp.2018-0473

33. Reis J, Robertson E, Krakauer JW, Rothwell J, Marshall L, Gerloff C, et al. Consensus: "can tDCS and TMS enhance motor learning and memory formation?". *Brain Stimul.* (2008) 1(4):363–9. doi: 10.1016/j.brs.2008.08.001

34. Prichard G, Weiller C, Fritsch B, Reis J. Effects of different electrical brain stimulation protocols on subcomponents of motor skill learning. *Brain Stimul.* (2014) 7(4):532–40. doi: 10.1016/j.brs.2014.04.005

35. Vollmann H, Conde V, Sewerin S, Taubert M, Sehm B, Witte OW, et al. Anodal transcranial direct current stimulation (tDCS) over supplementary motor area (SMA) but not pre-SMA promotes short-term visuomotor learning. *Brain Stimul.* (2013) 6 (2):101–7. doi: 10.1016/j.brs.2012.03.018

36. Vitor-Costa M, Okuno NM, Bortolotti H, Bertollo M, Boggio PS, Fregni F, et al. Improving cycling performance: transcranial direct current stimulation increases time to exhaustion in cycling. *PLoS One.* (2015) 10(12):e0144916. doi: 10.1371/journal.pone.0144916

37. Cantarero G, Tang B, O'Malley R, Salas R, Celnik P. Motor learning interference is proportional to occlusion of LTP-like plasticity. *J Neurosci.* (2013) 33(11):4634–41. doi: 10.1523/JNEUROSCI.4706-12.2013

38. Schambra HM, Abe M, Luckenbaugh DA, Reis J, Krakauer JW, Cohen LG. Probing for hemispheric specialization for motor skill learning: a transcranial direct current stimulation study. *J Neurophysiol.* (2011) 106(2):652–61. doi: 10.1152/jn.00210.2011

39. Foster C, Florhaug JA, Franklin J, Gottschall L, Hrovatin LA, Parker S, et al. A new approach to monitoring exercise training. *J Strength Cond Res.* (2001) 15 (1):109–15. PMID: 11708692.

40. Heller GZ, Manuguerra M, Chow R. How to analyze the visual analogue scale: myths, truths and clinical relevance. *Scand J Pain.* (2016) 13:67–75. doi: 10.1016/j.sjpain.2016.06.012

41. King G, Hassmén P. Overtraining and recovery. A conceptual model. *Sports Med.* (1998) 26(1):1–16. doi: 10.2165/00007256-199826010-00001

42. Laurent CM, Green JM, Bishop PA, Sjökvist J, Schumacker RE, Richardson MT, et al. A practical approach to monitoring recovery: development of a perceived recovery Status scale. *J Strength Cond Res.* (2011) 25(3):620–8. doi: 10.1519/jsc.0b013e3181c69ec6

43. de Villarreal ES, Suarez-Arrones L, Requena B, Haff GG, Ferrete C. Effects of plyometric and sprint training on physical and technical skill performance in adolescent soccer players. *J Strength Cond Res.* (2015) 29(7):1894–903. doi: 10.1519/JSC.0000000000000838

44. Ferreira JC, Carvalho RG, Szmuchrowski LA. Validade e confiabilidade de um tapete de contato para mensuração da altura do salto vertical. *Braz J Biol.* (2016) 17:39–45. Available at: http://citrus.uspnet.usp.br/biomecan/ojs/index.php/rbb/article/view/74 (Accessed July 13, 2022).

45. Claudino JG, Cronin JB, Mezêncio B, Pinho JP, Pereira C, Mochizuki L, et al. Autoregulating jump performance to induce functional overreaching. *J Strength Cond Res.* (2016) 30(8):2242–9. doi: 10.1519/JSC.0000000000001325

46. Alix-Fages C, Romero-Arenas S, Calderón-Nadal G, Jerez-Martínez A, Pareja-Blanco F, Colomer-Poveda D, et al. Transcranial direct current stimulation and repeated sprint ability: no effect on sprint performance or ratings of perceived exertion. *Eur J Sport Sci.* (2022) 22(4):569–78. doi: 10.1080/17461391.2021.1883124

47. Mesquita PHC, Lage GM, Franchini E, Romano-Silva MA, Albuquerque MR. Bi-hemispheric anodal transcranial direct current stimulation worsens taekwondo-related performance. *Hum Mov Sci.* (2019) 66:578–86. doi: 10.1016/j.humov.2019.06.003

48. Zhiqiang Z, Wei W, Yunqi T, Yu L. Effects of bilateral extracephalic transcranial direct current stimulation on lower limb kinetics in countermovement jumps. *Int J Environ Res Public Health.* (2023) 20(3):2241. doi: 10.3390/ijerph20032241

49. Lattari E, de Oliveira BS, Oliveira BRR, de Mello Pedreiro RC, Machado S, Neto GAM. Effects of transcranial direct current stimulation on time limit and ratings of perceived exertion in physically active women. *Neurosci Lett.* (2018) 662:12–6. doi: 10.1016/j.neulet.2017.10.007

50. Silver MD. Use of ergogenic aids by athletes. *J Am Acad Orthop Surg.* (2001) 9 (1):61–70. doi: 10.5435/00124635-200101000-00007

51. Bernstein A, Safirstein J, Rosen JE. Athletic ergogenic aids. *Bull Hosp Jt Dis.* (2003) 61(3-4):164–71. PMID: 15156821.

52. Maughan RJ. Legal ergogenic aids? *Curr Sports Med Rep.* (2009) 8(4):165–6. doi: 10.1249/JSR.0b013e3181ae0297

53. Burke LM. Caffeine and sports performance. *Appl Physiol Nutr Metab.* (2008) 33 (6):1319–34. doi: 10.1139/H08-130

54. De Almeida RF, da Costa IT, Machado G, Rinaldi NM, Aquino R, Tallis J, et al. The effect of acute caffeine ingestion on tactical performance of professional soccer players. *Nutrients.* (2022) 14(7):1466. doi: 10.3390/nu14071466

55. Cao N, Pi Y, Liu K, Meng H, Wang Y, Zhang J, et al. Inhibitory and facilitatory connections from dorsolateral prefrontal to primary motor cortex in healthy humans at rest-an rTMS study. *Neurosci Lett.* (2018) 687:82–7. doi: 10.1016/j.neulet.2018.09.032

56. Holgado D, Zandonai T, Ciria LF, Zabala M, Hopker J, Sanabria D. Transcranial direct current stimulation (tDCS) over the left prefrontal cortex does not affect time-trial self-paced cycling performance: evidence from oscillatory brain activity and power output. *PLoS One.* (2019) 14(2):e0210873. doi: 10.1371/journal.pone.0210873

57. Selmi O, Ouergui I, Muscella A, My G, Marsigliante S, Nobari H, et al. Monitoring psychometric states of recovery to improve performance in soccer players: a brief review. *Int J Environ Res Public Health.* (2022) 19(15):9385. doi: 10.3390/ijerph19159385

58. Clemente FM, Rabbani A, Araújo JP. Ratings of perceived recovery and exertion in elite youth soccer players: interchangeability of 10-point and 100-point scales. *Physiol Behav.* (2019) 210:112641. doi: 10.1016/j.physbeh.2019.112641

59. Goulart KNDO, Duffield R, Junior GOC, Passos Ramos G, Pimenta EM, Couto BP. Recovery timeline following resistance training in professional female soccer players. *Sci Med Footb.* (2020) 4:233–9. doi: 10.1080/24733938.2020.1737724

60. Fessi MS, Nouira S, Dellal A, Owen A, Elloumi M, Moalla W. Changes of the psychophysical state and feeling of wellness of professional soccer players during pre-season and in-season periods. *Res Sports Med.* (2016) 24(4):375–86. doi: 10.1080/15438627.2016.1222278

61. Hooper SL, Mackinnon LT, Howard A, Gordon RD, Bachmann AW. Markers for monitoring overtraining and recovery. *Med Sci Sports Exerc.* (1995) 27 (1):106–12. doi: 10.1249/00005768-199501000-00019

62. Nobari H, Alves AR, Haghighi H, Clemente FM, Carlos-Vivas J, Pérez-Gómez J, et al. Association between training load and well-being measures in young soccer players during a season. *Int J Environ Res Public Health.* (2021) 18(9):4451. doi: 10.3390/ijerph18094451

63. Haddad M, Chaouachi A, Wong D, Castagna C, Hambli M, Hue O, et al. Influence of fatigue, stress, muscle soreness and sleep on perceived exertion during submaximal effort. *Physiol Behav.* (2013) 119:185–9. doi: 10.1016/j.physbeh.2013.06.016

64. Novack LF, de Souza GC, Conde JHS, de Souza RO, Osiecki R. Quantification of match internal load and its relationship with physical fitness and recovery state of professional soccer athletes during the competitive period. *Hum Mov.* (2018) 19:30–7. doi: 10.5114/hm.2018.76077

65. Ihsan N. *Development of speed measurement system for pencaksilat kick based on sensor technology. IOP Conference Series: Materials Science and Engineering.* Vol 180, Bristol, UK: IOP Publishing: (2017). p. 012171.

66. Fernandes R, Brito JP, Vieira LHP, Martins AD, Clemente FM, Nobari H, et al. In-season internal load and wellness variations in professional women soccer players: comparisons between playing positions and Status. *Int J Environ Res Public Health.* (2021) 18(23):12817. doi: 10.3390/ijerph182312817

67. Angius L, Hopker JG, Marcora SM, Mauger AR. The effect of transcranial direct current stimulation of the motor cortex on exercise-induced pain. *Eur J Appl Physiol.* (2015) 115(11):2311–9. doi: 10.1007/s00421-015-3212-y

68. Angius L, Mauger AR, Hopker J, Pascual-Leone A, Santarnecchi E, Marcora SM. Bilateral extracephalic transcranial direct current stimulation improves endurance performance in healthy individuals. *Brain Stimul.* (2018) 11(1):108–17. doi: 10.1016/j.brs.2017.09.017

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A comparative study of 8-week complex training and resistance training on athletic performance of amateur futsal players

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Background: Despite the acknowledged importance of resistance training (RT) in enhancing physical performance in futsal players., the comparative effectiveness of RT and complex training (CT) on both physical and technical performance in futsal players remains underexplored. This study aimed to compare the effects of RT vs. CT on physical and technical performance in amateur futsal players.

Method: Players from two amateur futsal teams were assigned to RT (one team of 16 players; 18 years) and CT (one team of 16 players; 18 years) to perform an 8-week intervention with two weekly sessions. The RT performed the squat and deadlift (6 sets of 6–10 repetitions at 75%–85% one-repetition maximum (1RM), while the CT performed the squat + squat jump and deadlift + high pull (3 sets of 4–6 + 10–12 repetitions at 75%–85% 1RM). Pre- and post-intervention assessments included the Futsal Special Performance Test (FSPT), repeated sprint ability (RSA), sprint decrement (Sdec), sprint times at 10-m (T10), 10–20-m (T10-20), and 20-m (T20), 1RM back squat (1RM BS), isometric mid-thigh pull (IMTP), and countermovement jump (CMJ).

Results: At baseline, no significant differences between groups were observed for any variable analyzed ($p > 0.05$). After 8 weeks, there were significant differences between CT vs. RT on FSPT (–10.8% vs. –3.4%; $p < 0.05$), T10 (–5.2% vs. –0.1%; $p < 0.05$), IMTP (7.8% vs. 5.1%; $p < 0.05$), and CMJ (10.2% vs. 4.5%; $p < 0.05$). On the other hand, no significant differences between CT vs. RT were observed for RSA (–2.0% vs. –1.2%; $p > 0.05$), Sdec (–7.6% vs. –3.5%; $p > 0.05$), T10-20 (–0.9% vs. –0.9%; $p > 0.05$), T20 (–1.8% vs. –1.7%; $p > 0.05$), and 1RM BS (5.7% vs. 4.5%; $p > 0.05$) after the training program. Both groups significantly improved FSPT, T20, 1RM BS, and IMTP, while only CT significantly improved RSA, Sdec, T10, and CMJ.

Conclusion: The results suggest that CT may be valuable for improving specific performance parameters in amateur futsal players, with some advantages over RT in enhancing strength and power. These findings support tailored training protocols for futsal players to optimize performance.

KEYWORDS

performance enhancement, muscular strength, training efficacy, power, sprint

1 Introduction

Futsal is a multiple-sprint sport, with high-intensity movements dominating the majority of the game (Barbero-Alvarez et al., 2008; Dogramaci et al., 2011). The movement patterns and physical demands of futsal have been extensively studied. Studies have revealed that elite players perform approximately 400–500 high-intensity movements during a futsal match, primarily short accelerations, decelerations, sprints, and directional changes (Barbero-Alvarez et al., 2008; Makaje et al., 2012). These movements occur at regular intervals, typically every 7–9 s (Dogramaci et al., 2011). In a futsal match, sprint distances typically account for 5%–10% of the total distance, indicating the high physical demands of this challenging team sport (Barbero-Alvarez et al., 2008; Castagna et al., 2009; De Oliveira Bueno et al., 2014). However, A comparative analysis between elite and subelite players reveals significant differences in performance metrics. Elite futsal players demonstrated a higher number of sprints, longer sprinting durations, and covered more distance per sprint compared to subelite players (Dogramaci et al., 2011). In addition, a study involving elite futsal players found that the distance covered per minute, number of sprints, decelerations, and metabolic power are crucial physical factors that can differentiate the top elite futsal players (Ribeiro et al., 2020). These features can differentiate players at different levels and can be crucial physical qualities for achieving top performance in the game. Among these features, the capacity of players to consistently repeat high-intensity running without fatigue is a key determinant of successful performance in futsal (De Oliveira Bueno et al., 2014). Hence, emphasis should be placed on developing this particular capability (repeated-sprint ability, RSA) in training sessions.

Sports science and coaching have proposed various training methodologies (futsal injury prevention programs, visual feedback, high-intensity interval training and resistance training (RT)) to optimize the physical preparation of futsal athletes (Bayrakdaroğlu et al., 2022; Marques et al., 2022; Saryono et al., 2022; Gómez et al., 2023). RT is a typical training approach to enhance the maximal strength and power in athletes (Marques et al., 2019; Marques et al., 2022), ultimately aiming to improve RSA. However, RSA is a complex quality related to several factors, including anthropometry, endurance capacity (e.g., VO_{2max} and speed to reach VO_{2max}), and neuromuscular performance (e.g., vertical jump, sprinting speed, and muscle strength) (Bishop et al., 2003; Brocherie et al., 2014; Buchheit and Mendez-Villanueva, 2014). Over the past decade, scientific research examining the impact of various RT programs on RSA has intensified, with several studies highlighting RT's potential to enhance RSA (Edge et al., 2006; Paz-Franco et al., 2017a; Ramos-Campo et al., 2018; Torres-Torrelo et al., 2018). Despite these positive findings, further investigations reveal that RT, when applied as the sole training modality, may not uniformly improve all aspects of RSA in sports such as futsal and handball, particularly concerning average peak power or mean sprint time (RSAmean) (Hermassi et al., 2017; Torres-Torrelo et al., 2018). The effectiveness of RT in augmenting RSA, specifically RSAmean, appears to have its limitations. For example, Torres-Torrelo et al. (2018) demonstrated that while strength improvements (1RM) can enhance RSA, the benefits diminish with an increase in the number of sprints, suggesting that as the sprinting demand becomes more endurance-oriented, the aerobic system's contribution might play a more significant role (Torres-Torrelo et al., 2018).

Complex training (CT) combines high-load RT and plyometric training within a single session. Recent studies have highlighted the efficacy of CT in improving sprint performance, jump height, and back squat 1RM in various sports (Qiao et al., 2022; Scott et al., 2023). It is thought that CT's unique mix of heavy load resistance exercises followed by plyometric or speed exercises in the same session uses the post-activation potentiation (PAP) effect to improve sprint performance, while RSA was highly dependent on the sprint ability. Despite these promising findings, the application and impact of CT on RSA, specifically within the context of amateur futsal players, have not been thoroughly investigated.

Thus, this study aimed to compare the effects of CT vs. RT on physical and technical performance in amateur futsal players. It was hypothesized that both training interventions would improve physical and technical performance in amateur futsal players, with greater improvements observed after CT.

2 Materials and methods

2.1 Subjects

A minimum sample size of 24 participants was determined using GPower (version 3.1.9.7, Franz Faul, University of Kiel, Kiel, Germany), based on an alpha error probability (α) of 0.05, a power (1-β error probability) of 0.8, an effect size (ES) of 0.4, and including tests such as F-test and analysis of variance (ANOVA) for repeated measures and within-between interactions (Beck, 2013). For the study, 32 players from two amateur futsal teams within Jiangsu Province, China, were recruited, with a 20% anticipated dropout rate factored in to ensure an adequate sample size that compensates for potential participant attrition, aligning with the sample size requirements previously calculated. The recruitment phase spanned from August 1 to 1 September 2022, targeting individuals from collegiate backgrounds actively participating in regional competitions from March to August annually. The observational phase of the study was scheduled off-season, from October 1 to December 1, to preclude interference from official competitive engagements. This period of inactivity facilitated an undisturbed examination of the participants, who were stationed in Nanjing, Jiangsu Province, during the study duration. A detailed explanation was provided to the participants regarding the aims, benefits, and risks associated with the investigation. Participants were informed that their participation in this study would not affect their employment status. The study protocol complied with the Declaration of Helsinki and was approved by the Ethics Committee of Shandong Normal University (2023036).

2.2 Experimental design

This study employed a non-randomized control trial to examine the comparative effects of two distinct training modalities. Participants were allocated into two groups based on team

TABLE 1 The descriptive characteristics of the participants.

	Age (years)	Height (cm)	Weight (kg)	Training experience (years)
RT (n = 16)	18.93 ± 0.88	177.20 ± 4.49	68.53 ± 4.00	5.60 ± 0.83
CT (n = 16)	18.80 ± 0.68	177.80 ± 3.30	66.93 ± 3.99	5.80 ± 0.86

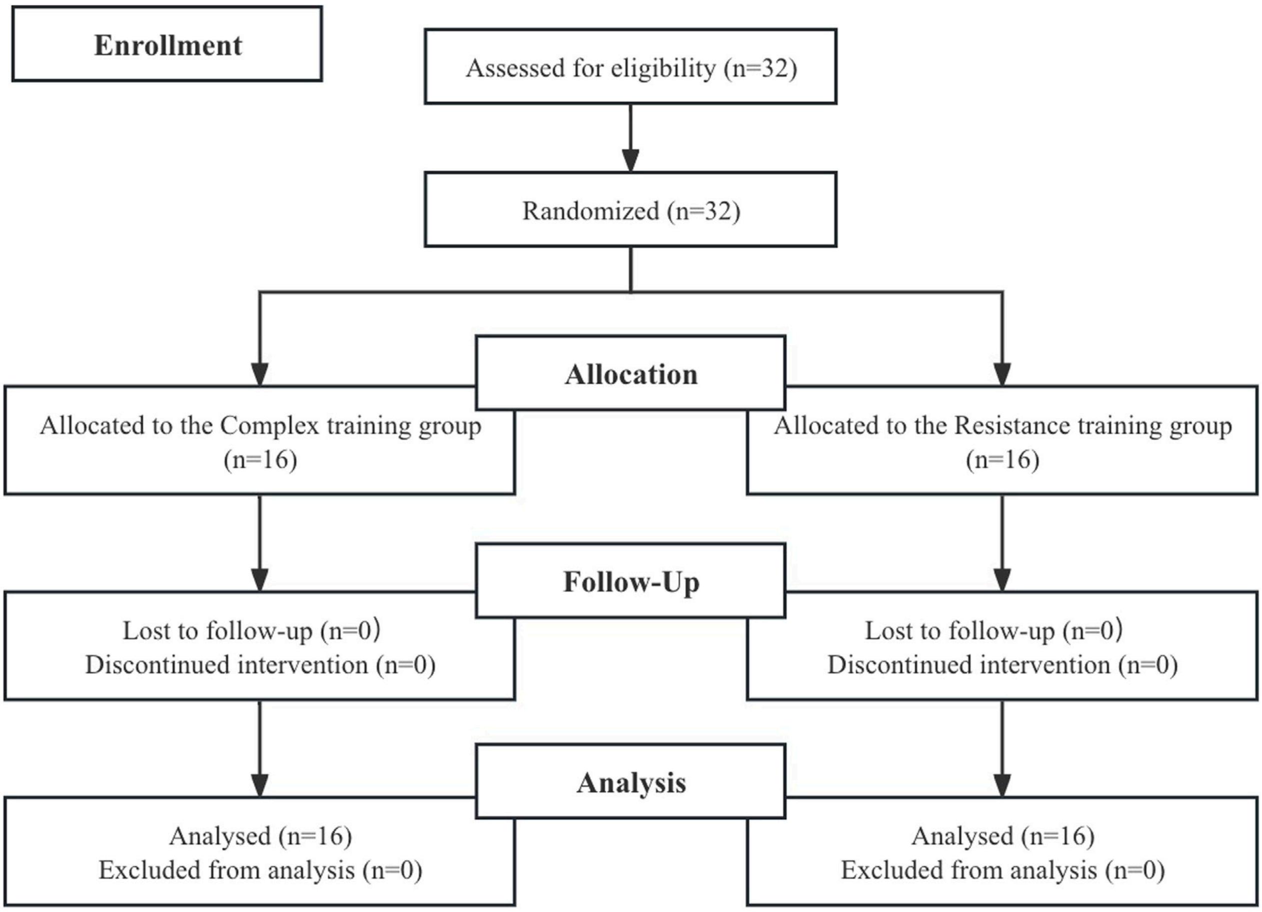

FIGURE 1
Flow chart of the progress through the phases of the study according to the CONSORT statements.

affiliation: the Resistance Training (RT) group (n = 16, age 18.93 ± 0.88 years) and the Complex Training (CT) group (n = 16, age 18.80 ± 0.68 years) (Table 1; Figure 1). An 8-week technical training regimen was systematically applied across all experimental protocols to ensure consistent progression and enable direct comparison between the CT and RT cohorts. Training sessions for both groups were scheduled concurrently on Mondays and Thursdays from 8:00 to 9:30 p.m. Evaluations to assess the impact of the interventions on futsal-related performance were conducted 1 week prior to and within 1 week following the conclusion of the training period. The testing conditions, including sequence, personnel, and location, remained uniform throughout the study. Pre- and post-intervention assessments included the Futsal Special Performance Test (FSPT), RSA, sprint decrement (Sdec), sprint times at 10-m (T10), 10–20-m (T10-20), and 20-m (T20), 1RM back squat (1RM BS), isometric mid-thigh pull (IMTP), and countermovement jump (CMJ).

2.3 Training programs

The characteristics of the CT and RT programs are detailed in Table 2, highlighting the progression and exercises used. To accommodate variations in participants' physical condition, a flexible range of repetitions was set for each exercise, aiming for a consistent workload across participants. In the CT protocol, participants performed an RT exercise (Squat or Deadlift, four to six reps) followed by a plyometric exercise (Squat Jump or High pull, 10–12 reps) within each pair, with a 4-min rest between exercises and pairs.

The RT group underwent an 8-week RT intervention, following the same schedule. Each session involved six sets of one RT exercise (Squat or Deadlift), with 6–10 reps per set and a 4-min rest between sets. Every 4 weeks, the 1RM for each exercise was assessed to adjust training intensity, based on Tomchuk (2010). If regular training

TABLE 2 Resistance training and plyometric training program.

		Training content	Intensity			Sets* repetitions	Rest (min)
			The first stage (1–2weeks)	The second stage (3–4 weeks)	The third stage (5–8 weeks)		
CT	The No.1 session of every week	Squat + Squat Jump	75%1RM + ME	80%1RM + ME	85%1RM + ME	3* (4–6 + 10–12)	4
	No.2 session every week	Deadlift + High pull	75%1RM+50%1RM	80%1RM+50%1RM	85%1RM+50%1RM	3* (4–6 + 10–12)	4
RT	The No.1 session of every week	Squat	75%1RM	80%1RM	85%1RM	6* (6–10)	4
	No.2 session every week	Deadlift	75%1RM	80%1RM	85%1RM	6* (6–10)	4

Note: CT, complex training; RT, resistance training; 1RM, 1-repetition maximum; ME, maximal effort.

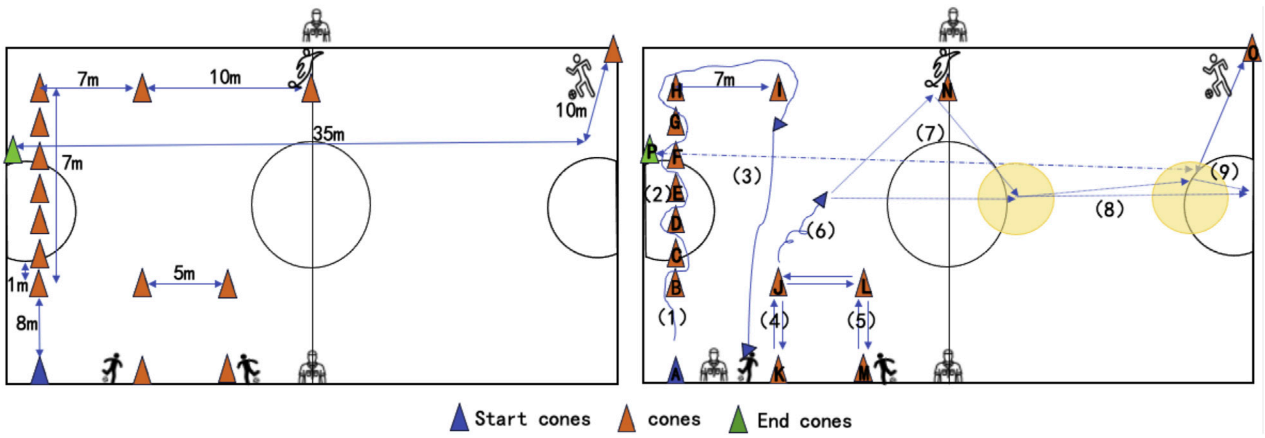

FIGURE 2
Schematic representation of Futsal Special Performance Test.

sessions were missed, make-up sessions were scheduled for Saturday from 8:00 to 10:00 a.m.

Both groups began each session with a standardized 8–15 min warm-up, including low-intensity running, coordination exercises, dynamic movements, sprints, and dynamic lower-limb stretching. A standard 8–15 min cooldown, consisting of static stretching, concluded each session. Researchers specialized in strength training, conditioning, and physical fitness oversaw the development and monitoring of all training protocols.

2.3.1 Futsal special performance test (FSPT)

The performance and skills of futsal players were assessed through nine steps, including running with the ball, dribbling, turning, long and short passes, catching passes, performing wall passes, and fast running without the ball. The time of each step was measured, and the total time was calculated(s). After warm-up, participant was located behind the purple cone. In steps 1 and 2, participant runs with the ball and dribbles. Afterward, the participant turns to cone I, sends a long pass, and goes near cone J (step 3). After repetition, steps 4 and 5 include receiving and sending short pass, and participant rotates and dribbles; then, he performs a wall pass and shoots the ball to the goal. Finally, in step 9, the participant receives long pass and shoots to the goal, and subsequently goes to the final cone (Figure 2). Time was calculated by two referees, and average of their records was considered as total time. The penalty time was also recorded during the test, and performance time is obtained by adding penalty time to the total time. The test is carried out following the recommendations of Farhani et al. (Farhani et al., 2019). The interval between each trial was 1 min, and the best result of three times was taken for subsequent analysis. The ICC for this test was 0.88.

2.3.2 RSA test

The test involved nine 20-m sprints with 25 s of active recovery between each repetition (jogging back to start within 20 s) to allow for 4–5 s of passive recovery (Torres-Torrelo et al., 2017). The times of the nine sprints taken by the athletes were recorded using the Polifemo Radio Light photocells from Microgate in Bolzano, Italy. The athletes started each sprint 1 m behind the timing lights and were verbally encouraged to run as fast as possible, and the RSAmean was calculated. Before the RSA, players performed a standardized warm-up consisting of a 5-min low-intensity run, three sets of 20-m progressive accelerations, and a maximum 10-m sprint with a 3-min break in between. The ICC was 0.87.

2.3.3 10-m and 20-m sprint test

Sprint times were recorded for a distance of 20 m on an indoor running track (Buchheit and Mendez-Villanueva, 2014). Each participant completed two 20-m sprints with a 3-min break in between. Photocell timing gates from Polifemo Radio Light (Microgate, Bolzano, Italy) were placed at 0, 10, and 20 m to determine the time spent for 0–10 m (T10), 0–20 m (T20), and 10–20 m (T10-20). Participants adopted a standing start with the lead-off foot placed 1 m behind the first timing gate and gave their fullest effort to sprint. The best time for each interval (best T10, T20, and T10-20 of both trials) was retained for analysis. The warm-up included sets of 30-m sprints with a gradual acceleration. The intra-class correlation coefficients (ICC) were 0.91 for T10, 0.93 for T20 and 0.86 for T10–20.

2.3.4 One-repetition maximum back squat

According to the protocol proposed by Tomchuk (2010) (Paz-Franco et al., 2017a), the back squat (BS) exercise was used to determine the maximal leg strength of each individual by a squat rack (Good Family, Shenzhen, China) To determine the maximum weight a participant can lift throughout the full range of motion (90° knee flexion), they first performed five to six repetitions with a relatively low weight (~40% of their last 1RM test), followed by three to four repetitions with a larger weight (~70% of their estimated 1RM). A single repetition was then performed with a load equivalent to 95% of the estimated 1RM. Afterward, the participant attempted a single repetition with the perceived 1RM load. When participants lifted the weight with the correct technique, they performed another attempt with an increase of 1.0–2.5 kg in weight. Failure was defined as a lift that did not reach the full range of motion on at least two trials with a 2-min break between trials. The test-retest reliability coefficient (ICC) for this test was 0.97 (Grgic et al., 2020).

2.3.5 Isometric mid-thigh pull test

The lower limb isometric strength was assessed by the isometric mid-thigh pull (IMTP) test (Comfort et al., 2015a). Before testing, the midpoint between the knee and hip joints was marked to determine the mid-thigh position of each participant. The participants could choose their preferred hip and knee angles for the deadlift. The height of the barbell was adjusted to touch the mid-thigh. The participants could use a two-handed grip, a mixed grip, or a hooked grip to pull the barbell upward as hard and fast as possible for 6 s, using the peak force in 6s for analysis. To avoid precontraction, participants were required to relax before the command "GO!" The force-time curve for each trial was recorded by a force plate (Kistler 9281CA, KISTLER, Winterthur, Switzerland) at a sampling rate of 1,000 Hz (Comfort et al., 2015b). The interval between each trial was 1 min, and the best result of three times was taken for subsequent analysis. The ICC for this test was 0.85.

2.3.6 Vertical-jump performance

The CMJ test was performed using the Ergo Jump Bosco System (Globus, Treviso, Italy) according to procedures proposed by Bosco et al. (Bosco et al., 1983). Jump height was determined based on flight time. Participants were requested to keep their bodies vertical throughout the jump, avoiding inappropriate lateral and frontal movements. The maximum vertical jump was performed from a standing position. The participants squatted to their self-selected depth and fully extended their knees on the ground. The interval between each trial was 1 min, and the best result of three times was taken for subsequent analysis. The hands of participants were placed on the hips during the jump to avoid any effect of arm-swing. The ICC for CMJ was 0.96.

2.4 Statistical analysis

Experimental data were processed by the IBM SPSS statistical software package (version 25.0, IBM, Chicago, IL, United States). All data were expressed as means and standard deviations (SD). The normality and homogeneity of variance were assessed by the Shapiro–Wilk and Levene's Test, respectively. Outliers, defined as studentized residuals greater than three standard deviations from zero, were identified and removed. The significance level for all tests was set at $p < 0.05$. To examine the effects of the CT on the athlete's performance in the futsal special performance test, RSA test, sprint test, and vertical-jump test, we first performed a two-way repeated-measure ANOVA (group × time). The dependent variables for each model were FSPT, RSAT, T10, T10–20, T20, 1RM BS, IMTP, and CMJ. The model factors were group, time, and their interactions. When significant interactions were observed, LSD *post hoc* corrections were performed to identify the location of significance. The intra-group effect size (ES) was also calculated using Hedge's g formula (29). The threshold values for assessing the magnitude of the standardized effects were 0.20, 0.60, 1.20, 2.00 for small, moderate, large, and very large, respectively (Hopkins et al., 2009). The analysis also included calculating probabilities to determine if the true (yet unknown) differences fell below, matched, or exceeded the smallest significant difference or change, defined as 0.2 times the between-subject standard deviation (SD) (Cohen, 1988). We assessed the quantitative chances of observing better or worse effects through a qualitative scale: less than 1% indicates it is almost certainly not going to happen; 1%–5% is very unlikely; 5%–25% is unlikely; 25%–75% suggests it is possible; 75%–95% means it is likely; 95%–99% is very likely; and over 99% is almost certain. If the probability of achieving either beneficial or detrimental outcomes was greater than 5%, we classified the true difference as unclear (Hopkins et al., 2009). To estimate the sensitivity to change, we calculated the calculated the minimal detectable change (MDC = $\sqrt{2}$ x SEM x 1.96) (Sainani, 2017) and MDC% ((MDC/mean of pretest) x 100) (Lexell and Downham, 2005). Furthermore, we calculated Pearson's correlation coefficients to explore the relationship between the percentage changes in all measured physical performance indicators. The significance of each correlation was classified using specific thresholds: below 0.1 as trivial; 0.1 to 0.3 as small; 0.3 to 0.5 as moderate; 0.5 to 0.7 as large; 0.7 to 0.9 as very large; and 0.9 to 1.0 as almost perfect (Hopkins et al., 2009). The relative reliability of the test was assessed using the intraclass correlation coefficient of the 1-way random-effects model with single

TABLE 3 Assessment results of the CT and RT groups before and after 8 weeks of training.

	MDC (%)	CT group					RT group				
		Pre	Post	Δ (%) (90% CI)	Percent changes of better/ Trivial/ Worse effect	ES	Pre	Post	Δ (%) (90% CI)	ES	Percent changes of better/ Trivial/ Worse effect
FSPT (s)	3.63	31.43 ± 1.78	28.01 ± 1.56*#	−10.84 (−12.13, −9.56)	100/0/0 Most likely positive	3.26	31.47 ± 2.72	30.35 ± 2.44*	−3.45 (−4.75, −2.16)	1.08	80/13.33/ 6.66 Unclear
$RSAT_{mean}$ (s)	1.27	3.22 ± 0.09	3.15 ± 0.090*	−1.96 (−3.25, −0.67)	73.33/6.66/ 6.66 Unclear	0.68	3.21 ± 0.06	3.17 ± 0.09	−1.23 (−2.53, 0.07)	0.41	26.66/60/ 6.66 Unclear
Sdec (%)	6.62	4.56 ± 0.65	4.17 ± 0.34*	−7.64 (−12.10, −3.17)	66.66/26.66/ 6.66 Unclear	0.69	4.54 ± 0.56	4.38 ± 0.54	−3.49 (−5.66, −1.32)	0.67	33.33/60/ 6.66 Unclear
T10 (s)	1.41	1.76 ± 0.04	1.66 ± 0.06*#	−5.18 (−6.75, −3.61)	100/0/0 Most likely positive	1.40	1.75 ± 0.06	1.74 ± 0.07	−0.08 (−1.11, 0.95)	0.05	40/33.33/ 26.66 Unclear
T10-20 (s)	1.79	1.24 ± 0.04	1.22 ± 0.03	−0.90 (−2.80, 1.01)	53.33/6.66/ 40 Unclear	0.23	1.24 ± 0.04	1.22 ± 0.03	−0.90 (-2.84, 1.03)	0.23	66.66/6.66/ 26.66Unclear
T20 (s)	0.96	2.95 ± 0.64	2.90 ± 0.66*	−1.82 (−2.94, −0.71)	73.33/13.33/ 13.33 Unclear	−0.69	2.95 ± 0.05	2.90 ± 0.08*	−1.67 (−3.20, −0.13)	−0.48	66.66/6.66/ 26.66Unclear
1RM BS (kg)	3.10	125.53 ± 9.13	132.53 ± 8.52*	5.67 (4.35, 7.00)	100/0/0 Most likely positive	1.90	125.53 ± 9.13	130.33 ± 5.86*	4.48 (2.19, 6.76)	0.83	80/13.33/ 6.66Unclear
IMTP (N)	2.64	1899.61 ± 102.70	2043.06 ± 55.31*#	7.80 (5.28, 10.31)	100/0/0 Most likely positive	1.47	1901.87 ± 99.09	1994.55 ± 48.82*	5.12 (2.56, 7.67)	0.94	80/13.33/ 6.66Unclear
CMJ (cm)	6.62	35.27 ± 2.86	38.66 ± 1.33*#	10.23 (6.38, 14.09)	100/0/0 Most likely positive	1.37	35.75 ± 1.21	37.33 ± 1.14	4.46 (3.17, 5.75)	0.29	86.66/0/ 3.33Unclear

Note: MDC: minimal detectable change; FSAT: futsal special performance test; RSATmean: mean sprint time of the nine sprints; Sdec: percent sprint decrement for the nine sprints; T10:10-m sprint time; T10–20: 10–20-m sprint time; T20: 20-m sprint time; 1RM BS: One-repetition maximum back squat; IMTP: Isometric Mid-thigh Pull; CMJ, countermovement jump. *Statistically significant difference between pre-and post-test, $p < 0.05$; # significant difference between the CT, and TT, groups in the post-test, $p < 0.05$. Δ: Percentage change; ES: Effect size Hedge´s *g*; CI: confidence interval.

measure ICC. The ICC of the FSPT, RSA, IMTP, and vertical jump tests was assessed by comparing the first two results obtained during the baseline test. A *p*-value of less than 0.05 was considered statistically significant for all tests.

3 Results

All the participants completed this study, and the data obtained from them were used in the analysis. All the data were normally distributed and homogeneity. At baseline, there were no significant differences between groups in any variable analyzed ($p > 0.05$). No significant correlation was observed between any measure and body weight for either CT or RT (Supplementary Table S1).

3.1 Futsal-specific performance test

After the 8-week training intervention, significant "time*group" interactions were observed for FSPT ($p < 0.001$). Intra-group comparisons revealed significant differences in the FSPT for the CT ($p < 0.001$, ES = 3.260) and RT ($p < 0.001$, ES = 1.079). Post-hoc analysis confirmed that the scores for FSPT ($p < 0.05$) was higher after the CT intervention than before and after the RT intervention. The CT showed a very likely effect in the FSPT, while the RT presented an unclear effect (Table 3).

3.2 RSA test

After the 8-week training intervention, no significant "time*group" interactions were observed for RSATmean and Sdec ($p > 0.05$). Intra-group comparisons revealed significant differences in the RSATmean ($p < 0.05$, ES = 0.678) and Sdec ($p < 0.05$, ES = 0.687) only in the CT. The CT and RT were showed unclear effect in the RSATmean and Sdec (Table 3).

3.3 Sprint test

After the 8-week training intervention, significant "time*group" interactions were observed for T10 ($p < 0.001$). Intra-group analysis showed significant improvements in the T10 ($p < 0.05$, ES = 1.400) and T20 ($p < 0.05$, ES = 0.687) only in the CT. Post-hoc analysis confirmed that the scores for T10 ($p < 0.05$) was higher after the CT intervention than before and after the RT intervention. The CT showed a very likely effect in the T10, while the RT presented an unclear effect. The CT and RT were showed an unclear effect in the

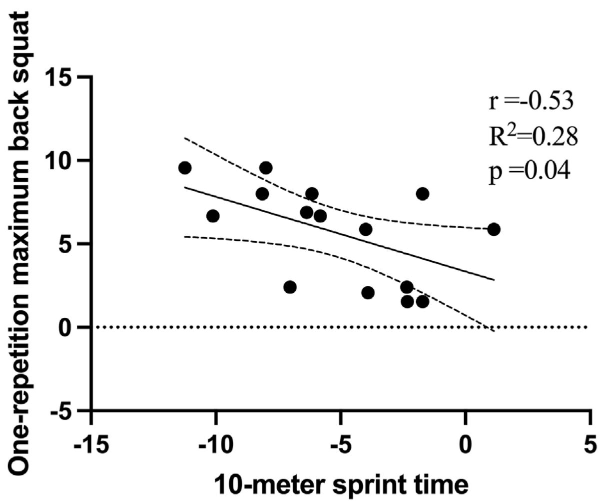

FIGURE 3
Relationship between percentage change in one-repetition maximum back squat and percentage change in 10-m sprint time performance.

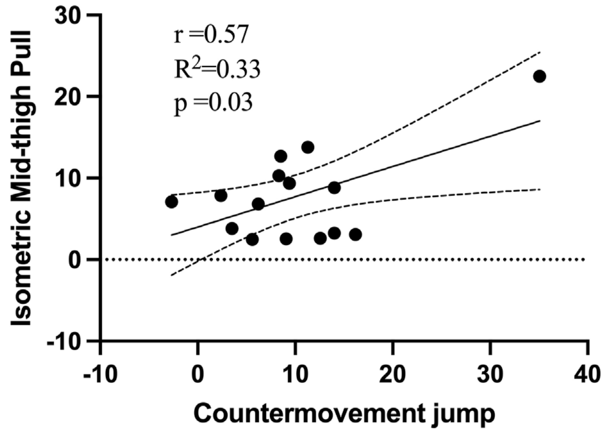

FIGURE 4
Relationship between percentage change in Isometric Mid-thigh Pull and percentage change in countermovement jump performance.

T20 and T10-20 (Table 3). Intra-group comparisons revealed significant differences in the FSPT for the T10 ($p < 0.001$, ES = 3.260) and RT ($p < 0.001$, ES = 1.079).

3.4 One-repetition maximum back squat

After the 8-week training intervention, no significant "time*group" interaction was observed for 1RM BS ($p > 0.05$). Intra-group comparisons revealed significant differences in the 1RM BS for the CT ($p < 0.05$, ES = 1.902) and RT ($p < 0.05$, ES = 0.826). The CT showed a very likely effect in the 1RM BS, while the RT presented an unclear effect (Table 3).

3.5 Isometric mid-thigh pull test

After the 8-week training intervention, no significant "time*group" interaction was observed for IMTP ($p > 0.05$). Intra-group comparisons revealed significant differences in the IMTP for the CT ($p < 0.05$, ES = 1.467) and RT ($p < 0.05$, ES = 0.944). The CT showed a very likely effect in the IMTP, while the RT presented an unclear effect (Table 3).

3.6 Vertical-jump performance

After the 8-week training intervention, significant "time*group" interactions were observed for CMJ ($p < 0.001$). Intra-group comparisons revealed significant differences in the CMJ for the CT ($p < 0.001$, ES = 1.372) and RT ($p < 0.001$, ES = 0.294). Post-hoc analysis confirmed that the scores for CMJ ($p < 0.05$) was higher after the CT intervention than before and after the RT intervention. The CT showed a very likely effect in the CMJ, while the RT presented an unclear effect (Table 3).

3.7 Correlations between changes in physical performance variables.

A negative correlation was observed between the percentage change in T10 and the 1RM BS ($p = 0.04$, r = −0.53), as shown in Figure 3, for the CT. And a positive correlation was observed between the percentage change in CMJ and the IMTP ($p = 0.03$, r = 0.57), as shown in Figure 4, for the CT. No significant correlations were observed for the RT.

4 Discussion

This study aimed to compare the effects of CT vs. RT on physical and technical performance in amateur futsal players. The results demonstrated that CT improved FSPT, T10, IMTP, and CMJ more than RT. On the other hand, no differences between groups were observed on RSA, Sdec, T10–20, T20, and 1RM BS. Overall, our study suggests that CT emerges as an effective method for augmenting performance in amateur futsal players.

4.1 Futsal-specific performance test

FSPT primarily assesses skills such as passing, dribbling, and shooting, in addition to abilities like speed and agility, which are crucial in futsal. Previous research has demonstrated the FSPT as a reliable measure for evaluating skill-related aspects in futsal (Farhani et al., 2019). These findings of this study suggest that CT could be an effective approach to enhance sports-related skills in futsal, especially in augmenting speed and agility. This is in line with our hypothesis that CT may be more effective than RT in enhancing movements involved in the stretch-shortening cycle function (Markovic and Mikulic, 2010). The CT regimen included exercises with both high loads (above 75% 1RM) to enhance the strength-speed segment and low loads (below 50% 1RM) to optimize the maximum velocity segment of the force-velocity curve (Haff and Nimphius, 2012). This approach aims to simultaneously improve maximal and explosive strength, thereby maximizing sport-specific performance. In contrast to CT, the higher loads employed in RT typically lead to slower muscle contractions, potentially making it less effective for enhancing explosive strength. Paz-Franco investigated the effects of different resistance training (RT) frequencies on professional futsal players over a 6-week period concluding that one or 2 RT sessions per week alongside regular futsal training significantly enhance physical performance, suggesting that RT once every second week is insufficient for improving physical fitness in professional futsal players (Paz-Franco et al., 2017b). Marques conducted over an 8-week in-season period with elite futsal players focused on evaluating the effects of a resistance training (RT) program on strength and power performance, observing that higher recovery quality could predict lower perceived exertion in training sessions (Marques et al., 2022). The study conducted over an 8-week in-season period with elite futsal players focused on evaluating the effects of a resistance training (RT) program on strength and power performance. It also examined the relationship between session perceived exertion (sRPE), total quality recovery (TQR), and the volume load of RT. Significant improvements were observed in isometric hip adduction strength (IHAS), with small yet significant enhancements in peak power and countermovement jump (CMJ). While our study utilized indirect measures of SSC function, future research would benefit from the inclusion of direct SSC assessments to more accurately evaluate the impact of training modalities on this crucial aspect of futsal athleticism. However, most changes did not exceed the minimal detectable change (MDC), suggesting that low-volume, low-to-moderate load RT might not sufficiently stimulate dynamic strength and power gains in elite players, although it can enhance isometric strength. Additionally, the study found a significant negative correlation between TQR and sRPE, indicating that higher recovery quality could predict lower perceived exertion in training sessions.

Consequently, CT might be a more effective training methodology for enhancing sport-specific performance, particularly during pre-season strength training.

4.2 Repeated sprint ability test

Previous research suggests that RSA is influenced by greater muscle power output (Okuno et al., 2013), indicating that CT could potentially improve RSA. Our findings partially corroborate this, which the result show that CT led to a significant reduction in RSATmean despite no significant group difference between CT and RT. The improved velocity in 10 m sprinting likely explains CT's effectiveness in improving the RSATmean. While sprinting velocity, a critical factor of RSA, has shown significant improvement through CT, RSA is also constrained by factors such as energy supply capacity, hydrogen ion (H+) removal, and muscle activity (Bishop et al., 2011). CT primarily focuses on neuromuscular aspects minimally impacting the metabolic system which explains the absence of significant differences observed between CT and RT. Torres-Torrelo found that a 6-week training intervention combining resistance training (RT) with loaded change of direction (CD) exercises significantly improved muscle strength and repeated sprint ability (RSA) in futsal players compared to RT alone and a control group with no training changes. The combined RT and CD group exhibited greater enhancements in RSA mean sprint times and ground contact time across multiple sprints, indicating the efficacy of combining RT with dynamic, sport-specific movements for futsal performance enhancement (Torres-Torrelo et al., 2018). Nevertheless, our results suggest that CT could be an effective approach to enhance RSA, warranting further investigation.

4.3 Sprinting performance

Both CT and RT demonstrated significant improvements in the T20, with no significant differences between the groups. However, CT showed a significant improvement in T10 compared to RT, while no significant difference in T10-20 in either group. In futsal, 10 m sprinting is a more relevant ability, as the majority of sprinting distances are between 10 and 20 m (Naser et al., 2017). Moreover, improvement in T10 may contribute to the improvement in RSA and FSPT, which partly explains the significant differences in CT instead of RT. Since sprint performance is heavily influenced by maximal strength, and both CT and RT involve high-intensity resistance training, both may have an effect on 20-m sprint performance. The study of Torres-Torrelo examined the impact of a 6-week training program on futsal players, indicating significant improvements in countermovement jump, ball throwing distance, and 30 m sprint performance with no significant changes observed in the control group. This suggests that incorporating resistance training with change of direction exercises can positively affect explosive power and speed in futsal players (Torres-Torrelo et al., 2017). The 10-m sprint, more dependent on the rate of force development (Naser et al., 2017), is significantly impacted by the plyometric training in CT. This might be re reason why CT effectively increases the rate of force development in the muscles, thus leading to more significant improvements in T10.

4.4 Strength and power test

1RM BS and IMTP were significantly increased after both CT and RT for IMTP, CT achieved a more significant improvement. Previous studies suggest that IMTP is more effective in detecting the positive effects of RSA (Bender et al., 2018), which is in line with the improvement of RSATmean in CT. Additionally, the peak force generation was significantly increased in IMTP, possibly an underlying mechanism of enhanced RSA due to improved efficiency of skeletal muscle contraction (Haider and Folland, 2014). Marques observed significant improvements in physical performance, including countermovement jump height, *t*-Test time, kicking ball speed, and maximum dynamic strength, indicating that such a training program can effectively enhance various performance parameters in young futsal players without prior RT experience (Marques et al., 2019). Overall, CT has more increased complexity and specificity than RT and may thus have more central nervous system stimulation, thereby promoting better neural adaptations such as greater intermuscular coordination and the synchronization of muscle fiber recruitment. In other words, CT is a more effective method to develop sports-specific ability and RSA compared to RT.

Importantly, the results of this study do not conclusively demonstrate the superiority of CT over RT in enhancing overall athletic performance. Both training programs contributed to performance improvements, with CT showing a trend for greater gains and effect sizes in some variables but not significantly different in RSA, Sdec, T10–20, T20, and 1RM BS. Our findings underscore the effectiveness of both CT and RT's effectiveness in augmenting amateur futsal players' athletic performance. While RT can provide the foundational strength necessary for athletic performance, CT's incorporation of plyometric exercises can further enhance power and technical performance, which is critical for futsal. Implementing periodization strategies, where the focus of training shifts between CT and RT across different phases of the season, can help optimize performance peaks and recovery. For instance, a pre-season focus on RT to build strength followed by a mid-season emphasis on CT to sharpen power and technical performance.

4.5 Correlations between Changes in Physical Performance Variables

In research examining the impact of CT, a notable negative correlation was found between gains in 10-m sprint times and 1RM BS performance, indicated by a correlation coefficient of −0.53. Conversely, a positive correlation emerged between lower limb power, as measured by the CMJ, and lower limb isometric strength, quantified through the IMTP), with a correlation coefficient of 0.57. These findings align with outcomes reported in previous studies after implementing CT programs (Mason et al., 2021; Liu et al., 2022; Qiao et al., 2022). For instance, Comfort and others, in their study with elite 17-year-old soccer players, identified a similarly strong negative correlation between maximal strength and 20-m sprint times, with a coefficient of −0.64 (Comfort et al., 2014). Additionally, a substantial correlation between IMTP and CMJ was documented in another investigation, reinforcing the theory that augmentations in lower-body strength positively influence sprint performance and lower limb power (Mason et al., 2021). Therefore, the CT approach, which emphasizes high-load resistance training combined with plyometric exercises, is increasingly recognized as an effective strategy for enhancing sprint performance and the power of the lower limbs.

The limitations of this study are multifaceted. Primarily, the findings presented herein necessitate verification through future investigations to bolster their validity. A significant limitation to acknowledge is the power analysis; although it adhered to established best practices. This acknowledgment serves not only to uphold transparency but also to guide and improve the methodological rigor in future research endeavors. Additionally, we recognize the omission of direct stretch-shortening cycle (SSC) measurements as a constraint in our evaluation. The SSC is pivotal to many futsal movements, and its assessment could provide a deeper understanding of the impact of CT on performance. This omission points to the need for a more comprehensive battery of tests in future studies, which should include SSC measures to offer a more complete picture of the interventions' effectiveness. The current study's focus on RSA may not fully represent the broad spectrum of functional adaptations that occur as a result of CT. Therefore, it is imperative to extend future assessments to encompass a wider range of performance indicators, including those that more directly reflect on-court demands. We also suggest that subsequent research should investigate the dose-response relationship between CT and performance outcomes in a more detailed manner. Employing a variety of assessments at multiple points throughout the intervention would yield valuable insights and enable a fine-tuning of training protocols to optimize athlete performance enhancements. Longitudinal studies are warranted to understand the long-term effects and sustainability of the benefits of CT. These should explore variations in CT program parameters, to identify the enduring effects of the training and to optimize session frequency and intensity for peak athletic outcomes.

5 Conclusion

The current study showed a tendency for greater physical and technical performance gains following CT compared to RT in amateur futsal players. Although both interventions may be valuable for improving specific performance parameters in amateur futsal players, CT may offer more advantages over RT in improving physical and technical performance. These findings support tailored strength and conditioning training programs for futsal players to optimize physical and technical performance.

Data availability statement

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

Ethics statement

The studies involving humans were approved by the Ethics Committee of Shandong Normal University (2023036). 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

YZ: Writing–original draft, Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization. GQ: Writing–review and editing.

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Conflict of interest

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

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2024.1360440/full#supplementary-material

References

Barbero-Alvarez, J. C., Soto, V. M., Barbero-Alvarez, V., and Granda-Vera, J. (2008). Match analysis and heart rate of futsal players during competition. *J. sports Sci.* 26 (1), 63–73. doi:10.1080/02640410701287289

Bayrakdaroğlu, S., Eken, Ö., Yagin, F. H., Bayer, R., Gulu, M., Akyildiz, Z., et al. (2022). Warm up with music and visual feedback can effect Wingate performance in futsal players. *BMC Sports Sci. Med. Rehabil.* 14 (1), 205. doi:10.1186/s13102-022-00601-3

Beck, T. W. (2013). The importance of *a priori* sample size estimation in strength and conditioning research. *J. Strength Cond. Res.* 27 (8), 2323–2337. doi:10.1519/JSC.0b013e318278eea0

Bender, D., Townsend, J. R., Vantrease, W. C., Marshall, A. C., Henry, R. N., Heffington, S. H., et al. (2018). Acute beetroot juice administration improves peak isometric force production in adolescent males. *Appl. physiology, Nutr. metabolism = Physiologie appliquee, Nutr. metabolisme* 43 (8), 816–821. doi:10.1139/apnm-2018-0050

Bishop, D., Girard, O., and Mendez-Villanueva, A. (2011). Repeated-sprint ability - part II: recommendations for training. *Sports Med.* 41 (9), 741–756. doi:10.2165/11590560-000000000-00000

Bishop, D., Lawrence, S., and Spencer, M. (2003). Predictors of repeated-sprint ability in elite female hockey players. *J. Sci. Med. sport* 6 (2), 199–209. doi:10.1016/s1440-2440(03)80255-4

Bosco, C., Komi, P. V., Tihanyi, J., Fekete, G., and Apor, P. (1983). Mechanical power test and fiber composition of human leg extensor muscles. *Eur. J. Appl. physiology Occup. physiology* 51 (1), 129–135. doi:10.1007/BF00952545

Brocherie, F., Girard, O., Forchino, F., Al Haddad, H., Dos Santos, G. A., and Millet, G. P. (2014). Relationships between anthropometric measures and athletic performance, with special reference to repeated-sprint ability, in the Qatar national soccer team. *J. sports Sci.* 32 (13), 1243–1254. doi:10.1080/02640414.2013.862840

Buchheit, M., and Mendez-Villanueva, A. (2014). Changes in repeated-sprint performance in relation to change in locomotor profile in highly-trained young soccer players. *J. sports Sci.* 32 (13), 1309–1317. doi:10.1080/02640414.2014.918272

Castagna, C., D'Ottavio, S., Granda Vera, J., and Barbero Alvarez, J. C. (2009). Match demands of professional Futsal: a case study. *J. Sci. Med. sport* 12 (4), 490–494. doi:10.1016/j.jsams.2008.02.001

Cohen, J. (1988). Statistical power ANALYSIS for the Behavioral sciences. *J. Am. Stat. Assoc.* 2nd (334). doi:10.2307/2283959

Comfort, P., Jones, P. A., McMahon, J. J., and Newton, R. (2015a). Effect of knee and trunk angle on kinetic variables during the isometric midthigh pull: test–retest reliability. *Int. J. Sports Physiology Perform.* 10 (1), 58–63. doi:10.1123/ijspp.2014-0077

Comfort, P., Jones, P. A., McMahon, J. J., and Newton, R. (2015b). Effect of knee and trunk angle on kinetic variables during the isometric midthigh pull: test-retest reliability. *Int. J. Sports Physiol. Perform.* 10 (1), 58–63. doi:10.1123/ijspp.2014-0077

Comfort, P., Stewart, A., Bloom, L., and Clarkson, B. (2014). Relationships between strength, sprint, and jump performance in well-trained youth soccer players. *J. Strength and Cond. Res.* 28 (1), 173–177. doi:10.1519/JSC.0b013e318291b8c7

De Oliveira Bueno, M. J., Caetano, F. G., Pereira, T. J., De Souza, N. M., Moreira, G. D., Nakamura, F. Y., et al. (2014). Analysis of the distance covered by Brazilian professional futsal players during official matches. *Sports Biomech.* 13 (3), 230–240. doi:10.1080/14763141.2014.958872

Dogramaci, S. N., Watsford, M. L., and Murphy, A. J. (2011). Time-motion analysis of international and national level futsal. *J. Strength Cond. Res.* 25 (3), 646–651. doi:10.1519/JSC.0b013e3181c6a02e

Edge, J., Hill-Haas, S., Goodman, C., and Bishop, D. (2006). Effects of resistance training on H+ regulation, buffer capacity, and repeated sprints. *Med. Sci. sports Exerc.* 38 (11), 2004–2011. doi:10.1249/01.mss.0000233793.31659.a3

Farhani, F., Rajabi, H., Negaresh, R., Ali, A., Amani Shalamzari, S., and Baker, J. S. (2019). Reliability and validity of a novel futsal special performance test designed to measure skills and anaerobic performance. *Int. J. Sports Physiol. Perform.* 14 (8), 1096–1102. doi:10.1123/ijspp.2018-0850

Gómez, E. M., Atef, H., Elsayed, S. H., Zakaria, H. M., Navarro, M. P., and Sulé, E. M. (2023). Effects of high-intensity interval training with an eccentric hamstring exercise program in futsal players: a randomized controlled trial. *Med. Baltim.* 102 (31), e34626. doi:10.1097/MD.0000000000034626

Grgic, J., Lazinica, B., Schoenfeld, B. J., and Pedisic, Z. (2020). Test–retest reliability of the one-repetition maximum (1RM) strength assessment: a systematic review. *Sports Med. - open* 6 (1), 31. doi:10.1186/s40798-020-00260-z

Haff, G., and Nimphius, S. (2012). *Training principles for power*.

Haider, G., and Folland, J. P. (2014). Nitrate supplementation enhances the contractile properties of human skeletal muscle. *Med. Sci. Sports Exerc* 46 (12), 2234–2243. doi:10.1249/MSS.0000000000000351

Hermassi, S., Chelly, M. S., Fieseler, G., Bartels, T., Schulze, S., Delank, K.-S., et al. (2017). Effects of in-season explosive strength training on maximal leg strength, jumping, sprinting, and intermittent aerobic performance in male handball athletes. *Sportverletzung· Sportschaden* 31 (03), 167–173. doi:10.1055/s-0043-103469

Hopkins, W., Marshall, S., Batterham, A., and Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Medicine+ Sci. Sports+ Exerc.* 41 (1), 3–13. doi:10.1249/MSS.0b013e31818cb278

Lexell, J. E., and Downham, D. Y. (2005). How to assess the reliability of measurements in rehabilitation. *Am. J. Phys. Med. rehabilitation* 84 (9), 719–723. doi:10.1097/01.phm.0000176452.17771.20

Liu, M., Zhou, K., Li, B., Guo, Z., Chen, Y., Miao, G., et al. (2022). Effect of 12 weeks of complex training on occupational activities, strength, and power in professional firefighters. *Front. physiology* 13, 962546. doi:10.3389/fphys.2022.962546

Makaje, N., Ruangthai, R., Arkarapanthu, A., and Yoopat, P. (2012). Physiological demands and activity profiles during futsal match play according to competitive level. *J. sports Med. Phys. Fit.* 52 (4), 366–374.

Markovic, G., and Mikulic, P. (2010). Neuro-musculoskeletal and performance adaptations to lower-extremity plyometric training. *Sports Med.* 40 (10), 859–895. doi:10.2165/11318370-000000000-00000

Marques, D. L., Ribeiro, J. N., Sousa, A. C., Travassos, B., and Marques, M. C. (2022). Strength and power performance changes during an in-season resistance training program in elite futsal players: a case study. *J. Hum. Kinet.* 84, 184–194. doi:10.2478/hukin-2022-0096

Marques, D. L., Travassos, B., Sousa, A. C., Gil, M. H., Ribeiro, J. N., and Marques, M. C. (2019). Effects of low-moderate load high-velocity resistance training on physical performance of under-20 futsal players. *Sports Basel, Switz.* 7 (3), 69. doi:10.3390/sports7030069

Mason, L., Kirkland, A., Steele, J., and Wright, J. (2021). The relationship between isometric mid-thigh pull variables and athletic performance measures: empirical study of English professional soccer players and meta-analysis of extant literature. *J. sports Med. Phys. Fit.* 61 (5), 645–655. doi:10.23736/S0022-4707.20.11205-2

Naser, N., Ali, A., and Macadam, P. (2017). Physical and physiological demands of futsal. *J. Exerc Sci. Fit.* 15 (2), 76–80. doi:10.1016/j.jesf.2017.09.001

Okuno, N. M., Tricoli, V., Silva, S. B., Bertuzzi, R., Moreira, A., and Kiss, M. A. (2013). Postactivation potentiation on repeated-sprint ability in elite handball players. *J. Strength Cond. Res.* 27 (3), 662–668. doi:10.1519/JSC.0b013e31825bb582

Paz-Franco, A., Rey, E., and Barcala-Furelos, R. (2017a). Effects of 3 different resistance training frequencies on jump, sprint, and repeated sprint ability performances in professional futsal players. *J. Strength and Cond. Res.* 31 (12), 3343–3350. doi:10.1519/JSC.0000000000001766

Paz-Franco, A., Rey, E., and Barcala-Furelos, R. (2017b). Effects of 3 different resistance training frequencies on jump, sprint, and repeated sprint ability performances in professional futsal players. *J. Strength Cond. Res.* 31 (12), 3343–3350. doi:10.1519/JSC.0000000000001766

Qiao, Z., Guo, Z., Li, B., Liu, M., Miao, G., Zhou, L., et al. (2022). The effects of 8-week complex training on lower-limb strength and power of Chinese elite female modern pentathlon athletes. *Front. Psychol.* 13, 977882. doi:10.3389/fpsyg.2022.977882

Ramos-Campo, D., Martínez-Guardado, I., Olcina, G., Marín-Pagán, C., Martínez-Noguera, F., Carlos-Vivas, J., et al. (2018). Effect of high-intensity resistance circuit-based training in hypoxia on aerobic performance and repeat sprint ability. *Scand. J. Med. Sci. sports* 28 (10), 2135–2143. doi:10.1111/sms.13223

Ribeiro, J. N., Gonçalves, B., Coutinho, D., Brito, J., Sampaio, J., and Travassos, B. (2020). Activity profile and physical performance of match play in elite futsal players. *Front. Psychol.* 11, 1709. doi:10.3389/fpsyg.2020.01709

Sainani, K. L. (2017). Reliability statistics. *PM&R* 9 (6), 622–628. doi:10.1016/j.pmrj.2017.05.001

Saryono, S., Irawan, A., Nopembri, S., Wiharja, A., and Zein, M. I. (2022). The effects of the FIVE futsal injury prevention program on lower limb muscle strength among young futsal players. *J. sports Med. Phys. Fit.* 62 (12), 1685–1692. doi:10.23736/S0022-4707.22.13498-5

Scott, D. J., Ditroilo, M., Orange, S. T., and Marshall, P. (2023). The effect of complex training on physical performance in rugby league players. *Int. J. Sports Physiol. Perform.* 18 (3), 240–247. doi:10.1123/ijspp.2021-0565

Torres-Torrelo, J., Rodríguez-Rosell, D., and González-Badillo, J. J. (2017). Light-load maximal lifting velocity full squat training program improves important physical and skill characteristics in futsal players. *J. sports Sci.* 35 (10), 967–975. doi:10.1080/02640414.2016.1206663

Torres-Torrelo, J., Rodríguez-Rosell, D., Mora-Custodio, R., Pareja-Blanco, F., Yañez-García, J. M., and González-Badillo, J. J. (2018). Effects of resistance training and combined training program on repeated sprint ability in futsal players. *Int. J. sports Med.* 39 (07), 517–526. doi:10.1055/a-0596-7497

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The effect of a 10-week TOCA Football System intervention program on sport-specific motor skills among junior footballers

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Introduction: The objective of our study was to examine, in addition to using the TOCA Football System tool and training method, the effect of a 10-week intervention on elite youth athletes in terms of their sport-specific motor skills and anthropometric variables.
Methods: The study covered a group of 32 young players practicing football (U14) (13.45 ± 0.64 years). The junior U14 footballers were randomly assigned to an intervention or TOCA group (TG, $N = 15$, 13.25 ± 0.58 years) and a control group (CG, $N = 17$, 13.63 ± 0.66 years). Before starting the test, we performed full anthropometric measurements and assessed the sample's agility with and without the ball and their sport-specific endurance. The measurements were then repeated after the 10-week intervention.
Results: Within-group analysis showed significant improvements in muscle mass ($p < 0.001$), sport-specific endurance ($p < 0.001$), ($p < 0.004$) and agility (in TG) both with and without the ball ($p = 0.002$), ($p = 0.004$) however, we did not find a significant change in body fat percentage in either group ($p = 0.988$, $p = 0.288$). In the CG, "agility with the ball" changed significantly only ($p = 0.023$). In the between-group analysis with a repeated-measures analysis of variance (mixed-design ANOVA), there was no significant interaction in any performance variables. The main findings of this study indicate that a TOCA Football training program in addition to normal training during the in-season period does not produce additional effects in anthropometric factors, sport-specific endurance and agility performance with the ball (dribbling) and without the ball in comparison with the control condition.
Discussion: From a practical point of view, the presented anthropometric and physical profiles of players can be useful for football coaches in optimizing soccer training. Overall, it also can be concluded that the device can be safely used in the sensitive age group in terms of the development of motor skills since we did not find any negative effects during the use of the device in terms of the parameters we examined. In addition to the expansion of the number of elements and the inclusion of other age groups, it is advisable to carry out further complex tests, as the TOCA Football System offers many research opportunities.

KEYWORDS
intervention study, junior football, TOCA Football System, motor skills, performance

1 Introduction

Football is the most popular sport and is played all over the world (1). In today's top football, the game is becoming faster and more physical, which demands exceptional skills from the players (2). According to Reilly et al. (3) and Davies (4), the modern game is primarily defined by power and speed. One-touch football, characteristic of modern football (5, 6), requires energy-demanding high-intensity movements from athletes (7, 8). As all elements of the game sped up, the sport-specific endurance (which means adapting to a large number of accelerations, decelerations and changes of direction and often repeated sprints) of the players also had to adapt to the increased expectations (9–12). If we add to this the number of matches held annually, which is approximately 45–55 on which they cover a total of 9–14 km on average, with high-intensity running accounting for 5%–15% of this distance, then we can conclude that the annual running volume of outstanding players at the international level requires amazing physical preparation. Due to the increased physical demands, athletes must have outstanding sport-specific skills (13–16). Based on a range of physical and biological characteristics (such as body mass, body composition, speed, agility, vertical jumping, power, repeated sprint ability, and endurance), researchers have differentiated more successful elite youth football players from those who were less successful at multiple age groups from U9-U21 (17–20). Therefore, in the world of football, more and more emphasis is being placed on training with a scientific approach.

The relationship between football and sports science began to strengthen approximately in the second half of the 20th century. By the 1980s, it became obvious that football could not rely on the traditional methods used in the previous decades in the long term. The effectiveness of scientific methods was proven by the fact that those clubs that changed their previous methods were more successful than those that stayed with the traditional methods used before (4). The early recognition of innovations and new training methods that appear in the sport can quickly give teams that apply them a step ahead. By the 2000s, the majority of elite Hungarian clubs founded their own academies. In recent years, further major great changes have taken place in Hungarian football, the economic environment has changed, which meant completely new funding through the introduction of the TAO support system. The aim of the operation was to prepare talented young footballers for professional football more effectively (17–19). According to international literature, these training workshops have become the most important talent development institutions in football (20). According to Rábai (18), the academic environment provides outstanding personal and infrastructural training opportunities for young footballers to become professional athletes. Among other things, this academic system enables the TOCA Football System to play a role in the preparation of young athletes. In Hungary, football academies are youth training institutions whose primary goal is to educate highly qualified and internationally competitive players (19). Currently, 19 such academies operate in Hungary, which work according to the operating conditions system used by the European Football Association (UEFA) by providing learning, housing, and professional and institutional conditions. In Hungary, the system of football academies is used primarily for the training and complex talent management of the sport, as well as the development of the careers of young footballers and the sport at the same time (21). Since the system has excellent conditions for selection and talent management (22), in recent years, academies have become prominent actors in the training of Hungarian youth (23). Despite all this, only a few of our young footballers make it to the best in Europe (24).

Thus, the methods, tools and tasks that promote the development of different physical and technical skills during football training should be given priority (25). The effect of the TOCA Football System has not been examined in this regard before. It can also be said that there are very few publications in English related to Hungarian football youth training methods. Given that its use is widespread in Hungary and many countries worldwide and that it is also readily used when providing training for junior footballers, the examination of the tool is of prime importance (26). Furthermore, sport for the health of young people is of prime importance in professional sport is also a strategic area of priority (27, 28). The novelty of the TOCA Football system lies in the fact that the sport-specific technical elements (first touch, passing, stops and starts, change of directions, etc.)—that form the basis of the technical toolkit of a footballer—can be practiced by the athlete with a higher repetition rate than it would be possible with traditional training methods (26). By changing the physical load in this way, the sport-specific technical elements can become a muscle memory action faster (29, 30). One of the most important goals of the various objective tests known and recognized by international research is to be able to monitor the effectiveness of the training and the defined physiological objective with the established periodization (31). Extensive examination of junior footballers can range from human biological values through lower-limb muscle strength and running speed to spiroergometric measurements. It evaluates the players in a complex manner (32), and its application is essential to create the possibility of conscious and progressive development. It has already been established that, in addition to laboratory tests, the results measured during field tests and match conditions are closer to the athletes' real performance; therefore, in our research, we preferred the use of field tests, as well (31, 33).

The objective of our study was to examine the effect of a 10-week intervention with the TOCA Football System tool and training method on elite youth athletes' sport-specific motor skills and anthropometric variables in a randomized controlled study.

2 Materials and methods

2.1 Selection and description of participants

In the spring of 2022, the U13-U14 junior football players of one of our country's elite academies in the Hungarian junior first division (NBI) are being examined. After eligibility assessment, 32 people were included in the study, which was randomly divided into two groups by www.randomizer.org, 15 people (13.25 years ± 0.58 years) made up the intervention group (hereafter TG) and 17 people (13.63 years ± 0.66 years) the control group (CG). The athletes included in the study all had more than five years of experience in football. They attended training sessions at an association football club six times a week, five of which were afternoon sessions, and one session was morning technical training. In the case of all participants, before the tests, the parents were provided information about the research, and they also had to fill out a written consent form. Exclusion criteria were defined as if the athlete suffered an injury during the previous two months or could not participate in at least 80% of the sessions.

2.2 Measurement tools

Measuring the physical ability of athletes is one of the most critical factors in modern football. Many tests are used to determine and analyze players' abilities and to examine the effectiveness of a training method (34, 35). To determine motor and physical performance, we used the tests of the measurement protocol preferred by the Hungarian Football Association (35), with which (31), also tested junior footballers. The body height of the tested sample was measured using the standard stadiometer technique, with their head in the Frankfort horizontal plane. We also determined the biological age of the examined sample. The calculation of morphological age can be summarized with the following formula:

$$\text{MA} = 0.25 * (\text{BH age} + \text{BW age} + \text{PLX age} + \text{CA} \pm C \text{ (years)}$$

where MA is morphological age, BH age is the age corresponding to the table value to which the subject's height is closest, BW age and PLX age are interpreted in the same way as for height, CA is calendar age, and C is any necessary correction (36, 37). A bioimpedance measurement method was used to measure body mass, muscle mass, and body fat percentage (InBody 770; InBody Co., Ltd., Seoul, South Korea).

2.2.1 Yo-Yo intermittent recovery test level 1

The Yo-Yo Intermittent Recovery Test Level 1 (YYIR1) was used to determine the sport-specific endurance, maximum oxygen uptake capacity and maximum pulse values. Many studies deal with the examination of the physical condition of junior footballers (13–18 years old), the process of physiological adaptations that occur as a result of different training sessions, and the analysis of the physical performance achieved in matches to find out which variables can be used to predict the expected motor performance in matches (38–42). The YYIR1 is one of the most widely used, internationally accepted, and reliable field tests relevant to junior players, and it is a predictor of expected endurance performance in matches (40, 43–46).

A YYIR1 and a laboratory exercise test (Bruce protocol) were chosen based on Fang et al.'s research (47)—were also performed on the athletes to assess accurate physiological characteristics and to determine the expected maximum heart rate (HRmax) and estimated aerobic capacity (VO2max) (48):

$$\text{VO2max} = (\text{Final distance (in meters)} \times 0.0084) + 36.4$$

Based on the exercise tests, it can be established that the examination group was homogeneous regarding expected endurance performance (49) and maximum aerobic capacity (50, 51).

The Illinois Agility Test assessed multidimensional speed, agility, acceleration, change of direction speed and maneuverability (52–54).

2.2.2 Illinois agility test

By performing the test, we determined the soccer players' agility, speed and deceleration ability, and ability to change direction by performing sequences of movements from different positions and angles. The players performed the survey in special soccer cleats. To measure performance, we used an infrared photocell gate (Fusion Sport Smartspeed, Australia), which was placed in a standard position at a height of 1 m at the start and finish lines. During the test, the test subjects start from a standing position behind the start line, and they start running when they hear the predetermined sound signal. The test subjects start sprinting from the start line; they run forward 10 m to run around a cone, then back 10 m to a cone placed at the height of the start line. Then, the test subjects weave in and out of the cones over a 10 m distance, complete a 180° turn and then weave back through the cones completing a 180° turn at the last cone. Then, the test subjects sprint forward 10 m to a cone, complete another 180° turn and sprint 10 m to the finish line. Finally, they cross the finish line by running between the infrared photocell gates placed at a height of 1 m (53, 55). The test subjects in the study had to complete the test as quickly as possible. Two options were provided to athletes to complete the course with a 3–5-min rest period between repetitions. During the statistical analysis, the fastest performance and the best time result were considered. The test was also performed by the players while dribbling a football.

2.3 Procedure

2.3.1 Preintervention

For a start, the team staff was informed about the objectives of the study, and the research team ensured that parents signed their informed consent. Then, the research team studied and planned every training structure with the coaches, physical trainers, and both teams. After defining the groups, we ran pre-defined field tests and laboratory tests on the players in training week zero, and then after ten weeks, all the tests were repeated. The athletes performed the tests following the same order and with a minimum of 3 min and a maximum of 5 min of rest between tests. The tests, in both cases, were conducted indoors on synthetic turf at the Dárdai Pál Labdarúgó Akadémia Utánpótlás Edzőközpont (Senior Pál Dárdai Football Academy Youth Training Center) and the TOCA Football Center-Garami József Utánpótlás Labdarúgó Képző Központ (TOCA Football Center-

József Garami Junior Football Training Center), at the constant temperature of 20°C–22°C.

2.3.2 The intervention protocol

The TG $n = 15$ was determined randomly from the total sample $N = 32$. The CG was $n = 17$ people. During the entire period of the investigation (10 weeks), the morning training of the TG was held at TOCA Football Center-Garami József Utánpótlás Labdarúgó Képző Központ (TOCA Football Center-József Garami Junior Football Training Center) where they used the TOCA Football System (TOCA Football Inc. California Costa Mesa, US.) throughout their training sessions. Due to the championship schedule, the morning training sessions for both groups took place on Thursday between 07:00 and 08:15. The CG was instructed to continue the team's original training plan. In contrast, the TG group continued the same training plan using the soccer ball delivery system. Before training, the same warm-up protocol was used for both groups. Before the first session, the TG was verbally and visually informed about the operation of the new training device and the method. After the warm-up, the training continued according to the original training plan with the help of the device. During the training sessions, the main part after the warm-up lasted 45–50 min for each training session, with the same rest period added. The training sessions were conducted by the team coach and a trainer with a qualification in the TOCA Touch Trainer.

2.3.3 Postintervention

After the intervention protocol, the TG and CG were evaluated at the same time of day as in the preintervention session, in a similar space with the same conditions.

2.4 Data analysis

For the treatment of the data, we used adequate statistical methods. Descriptive statistics were used to characterize the sample. Descriptive statistics are represented as mean ± standard deviation (SD) with standard mean difference data. Tests of normal distribution and homogeneity (Shapiro-Wilk's and Levene's, respectively) were conducted on all data before analysis. A paired sample *t*-test was used to determine differences as a repeated measures analysis (pre–post) within groups. When comparing normally distributed variables (anthropometry, Illinois agility test), we used a paired sample *T*-test where the significance level was set at $p < 0.05$. A non-parametric Wilcoxon test was used where the sample was not normally distributed (YOYO IR1 test- in the case of the TG), and the error limit was set at $p < 0.05$. The correlation coefficient (r) was the indicator of the effect size. To interpret the magnitude of the effect size, we adopted the following criteria: $r = 0.10$, small; $r = 0.30$, medium; $r = 0.50$, large. To discover between-group differences, a 2 (group: TG and CG) × 2 (time: pre, post) repeated-measures analysis of variance (mixed-design ANOVA) was calculated for each parameter. The delta percentage (Δ%) was calculated via the standard formula: $\Delta\% = [(\text{posttest score} - \text{pretest score})/\text{pretest score}] \times 100$. Partial eta-squared ($\eta p2$) effect sizes for the time × group interaction effects were calculated. An effect of $\eta p2 \geq 0.01$ indicates a small, ≥0.059 a medium, and ≥0.138 a large effect, respectively (56). Data were analyzed using the IBM SPSS Statistics 27 software.

2.5 Ethical considerations

The study was conducted in accordance with the Declaration of Helsinki and approved by the University of Pécs Regional Research Ethics Committee (No. 9119-PTE 2022).

3 Results

3.1 The results of the anthropometric tests

In the case of BF%, no significant difference was found within either group. However, in the case of BM and SMM, we found a significant change within both groups (BM: $p < 0.001$, $r = 0.804$; $p = 0.030$ $r = 0.511$; SMM: $p < 0.001$, $r = 0.812$; $p < 0.001$, $r = 0.716$). Data showed that participants improved significantly after ten weeks in most anthropometric variables, except BF% within both groups Table 1.

3.2 Results of the performance variables

The paired measures *t*-test with participant's performance variables (IAT, YYIR1, VO2max- in TG and CG) and Wilcoxon-test based on the variables normality test (YYIR1^{post} and VO2max^{post}- in TG) that showed significant difference for all variables within groups (IAT without ball: $p = 0.004$, $r = 0.675$; IAT with ball: $p = 0.002$, $r = 0.716$; $p = 0.023$, $r = 0.533$; YYIR1: $p = 0.001$, $r = 0.674$, $p = 0.004$, $r = 0.647$) except of the IAT without the ball test within control group which showed no significant differences (IAT without ball: $p = 0.675$, $r = 0.106$). Data showed that participants improved significantly after ten weeks within groups in most performance variables, except IAT without the ball in CG. Absolute values for each variable at the pre- and post-test, along with the repeated measured ANOVA, showed no significant group x time interactions were observed between training groups (TG and CG) in any variable ($p > 0.05$) Table 2.

4 Discussion

This research aimed to examine the effect of the TOCA Football System on the body composition and motor performance (agility and sport-specific endurance) of junior athletes within the framework of a 10-week intervention program. When evaluating the results, we do not deal with the change in body height separately since it is more likely that it stems from age characteristics rather than from the training performed. The main findings of this study indicate that a

TABLE 1 Anthropometric characteristics of the study sample before and after the 10-week intervention (mean ± SD).

	Young male football players (N = 32)							
	TG (n = 15)				CG (n = 17)			
	Pretest	Posttest	RM t-test (p)	Δ (%)	Pretest	Posttest	RM t-test (p)	Δ (%)
BH (cm)	163.2 ± 10.07	165.66 ± 9.2*	–	1.51	164.17 ± 12.19	166.11 ± 11.79*	–	1.18
BM (kg)	46.22 ± 8.6	48.19 ± 9.63*	p < 0.001 r = 0.804	4.26	50.4 ± 11.45	51.32 ± 11.37*	p = 0.030 r = 0.511	1.83
BF (%)	8.57 ± 4.01	8.59 ± 2.54	p = 0.988 r = 0.004	0.23	11.38 ± 4.94	10.79 ± 3.66	p = 0.288 r = 0.265	−5.18
SMM (kg)	23.05 ± 5.08	24.27 ± 5.27*	p < 0.001 r = 0.812	3.28	24.57 ± 6.62	25.25 ± 6.48*	p = 0.001 r = 0.716	2.77

BF%, body fat percentage; BH, body height; BM, body mass; SMM, skeletal muscle mass.
*significant differences (p < 0.05).

TABLE 2 Changes in the performance variables after the 10-weeks intervention (mean ± SD).

	Young male football players (N = 32)							
	TG (n = 15)				CG (n = 17)			
	pre	post	RM t-test (p)	Δ (%)	pre	post	RM t-test (p)	Δ (%)
IAT without ball (s)	15.82 ± 0.56	15.64 ± 0.59*	p = 0.004 r = 0.675	−1.14	15.85 ± 0.43	15.82 ± 0.42	p = 0.675 r = 0.106	−0.19
IAT with ball (s)	20.27 ± 1.14	19.92 ± 1.02*	p = 0.002 r = 0.716	−1.73	20.71 ± 1.14	20.40 ± 1.15*	p = 0.023 r = 0.533	−1.5
YYIR1. distance (m)	1,830.67 ± 333.71	2,073.33 ± 325.10*	p = 0.001 r = 0.674	13.26	1,435.29 ± 381.49	1,605.88 ± 381.49*	p = 0.004 r = 0.647	11.89
VO2max (ml/kg/min)	51.77 ± 2.8	53.81 ± 2.73*	p = 0.001 r = 0.674	3.94	48.45 ± 2.87	49.88 ± 3.20*	p = 0.004 r = 0.647	2.95
	ANOVA p values (ηp^2)							
	time		group			group × time		
IAT without ball (s)	p = 0.025, η^2 = 0.157		p = 0.527, η^2 = 0.013			p = 0.101, η^2 = 0.087		
IAT with ball (s)	p < 0.000, η^2 = 0.371		p = 0.254, η^2 = 0.043			p = 0.807, η^2 = 0.002		
YYIR1. distance (m)	p < 0.000, η^2 = 0.550		p = 0.001, η^2 = 0.311			p = 0.660, η^2 = 0.007		
VO2max (ml/kg/min)	p < 0.000, η^2 = 0.583		p = 0.001, η^2 = 0.309			p = 0.348, η^2 = 0.029		

RM, repeated measures (paired-samples t-test); IAT, Illinois agility test.
*significant differences (p < 0.05).

TOCA Football training program in addition to regular training during the in-season period does not produce additional effects in anthropometric factors, sport-specific endurance and agility performance with the ball (dribbling) and without the ball in comparison with the control condition. This may indicate that the adaptations obtained during training with one TOCA training per week for ten weeks were similar to players participating in traditional soccer training. Related to these findings (57, 58) reported that regular participation in soccer-specific training sessions can be a sufficient incentive to increase the performance of soccer-specific skills.

However, based on the results of the body composition tests, it can be concluded that the average body mass of both groups changed significantly, in the case of the TG by +1.97 kg (p < 0.001) and in the case of the CG by +0.92 kg, (p = 0.030). The increase in muscle mass was primarily responsible for the increase in body mass in both groups since, in terms of body fat percentage, no significant difference was found in either group, while the body fat percentage of the TG increased by an average of +0.02%; (p = 0.988), while the body fat percentage of the CG increased by 0.59% on average; (p = 0.288). After the t-test, the results indicate that the effect of the intervention on body composition is not significant, as we found that the muscle mass (SMM) increased significantly in both groups. In the case of the TG with +1.22 kg (p < 0.001) and the CG with 0.68 kg (p = 0.001). However, observing the results, it can also be stated that although the increase in muscle mass can be statistically demonstrated in both cases, in the case of the TG, the muscle mass increased approximately twice as much. Csáki et al. (35) examined 76 people in the same age group and documented the body composition results of Hungarian junior soccer players over 12 months. At the end of the study, they experienced an average increase in muscle mass of +1.48 kg. So, while in a similar study such a change in muscle mass was only detectable in 12 months, with the TOCA training, it was achieved in only ten weeks. This can be supported by the results of a previous study by Szabó and Ács (26), in which TOCA and traditional football technical training, with the same training goal, were compared based on locomotor and physiological parameters that Polar Team Pro could measure. Based on their results, the athletes trained at a significantly higher intensity during the TOCA training sessions. This increased intensity—shown in the number of micromovements (number of stops, starts, changes of direction, sprints) and the distance covered in proportion to time—can benefit the increase in skeletal muscle mass, which is extremely important, since in football, as established by Mohr et al. (59), to carry out 30–40 acceleration phases and frequent jumps with a high efficiency level, one requires outstanding lower limb strength (60, 61). Previous studies have also reported that faster running speed is affected by the force applied to the ground, in addition to a higher step frequency (62–64). This physical axiom—according to which the greater the ground force (action), the greater the reaction force (reaction)—also proves the importance of skeletal muscle in improving the speed of footballers, which makes the athlete suitable for coping with the extreme physical demands experienced on the field of international soccer.

The agility tests used in football, including a combination of accelerations, decelerations, change of direction, explosiveness and turns, are the most relevant objective sport-specific tracks. Carrying out the aforementioned abilities with a high level of efficiency is decisive in terms of the effectiveness of the matches and the game situations. During our investigation, we performed the Illinois Agility tests with and without a ball. The paired sample t-test results show that in the case of the results of the TG, we experienced a significant improvement both in the agility test with a ball ($p = 0.004$) and in the agility test without a ball ($p = 0.002$), in the case of the CG we only found an improvement in the agility test with a ball ($p = 0.023$). In contrast, no significant difference was found in the agility test without a ball ($p = 0.675$). However, based on the result of the mixed-design ANOVA test, it can also be said that no significant group × time interaction were found during the agility tests comparison between the groups. This also means that even before the first examination, the intervention group members achieved better results than the control group. Another study conducted on eighteen youth soccer players that analyzed the effects of a 6-week coordination training intervention on physical fitness revealed no significant differences between the pre-and post-tests in agility performance (65). Based on these, it can be assumed that a longer intervention process would show a more accurate view regarding the development of differences between groups. The higher the number of repetitions and the more frequent the execution of tasks, the more micro-movements the athletes require, which is shown in the development of agility. Taylor et al. (66) found that during football matches, athletes experience some rhythm change every 3–4 s. This can be categorized with up to 1,200 acyclic movements, where 30–40 acceleration-deceleration phases and jumps (59), more than 700 changes of direction (67) and other intensive sport-specific techniques such as shooting, dribbling, tackles and fully body collision can be found (9). Based on these, it can be stated that success in football is largely determined by movement without the ball. Running performance is best characterized by frequent and fast sprints and continuous changes of direction, which is nearly 10% of the total amount of running performed in matches (68). In various 1–1 game situations, quick starts, decelerations, and direction changes can result in a 1–2 m advantage over the opponent, which can determine the success of a game situation. It is essential to consider that, during a match, more time is spent running without the ball than with the ball. In the case of offensive players, during the game situations before scoring a goal, an almost minimal number of (1–3) touches can be determined, which can be explained by the high-intensity rapid movements and direction changes performed in the preceding 3–5 s (69). Another advantage of the TOCA Football System could be that it forces the athletes to move significantly more without the ball (27).

An extensive analysis of football matches determined that players show different running performances in various phases of the match, where more robust phases are generally followed by weaker periods (59, 70). These analyzes and the obtained data confirm the need for the development of continuous and intermittent high-intensity physical performance in training (71, 72). In our study, we found that based on the results of the sport-specific endurance test (YYIR1), both groups' performance improved significantly.

During the follow-up measurements after the 10th week, in the TG, the athletes ran an average of 242.66 m more ($p = 0.001$), while in the CG, they ran an average of 170.59 m more ($p = 0.004$). Based on these, it can be concluded that both groups' YYIR1 performance and oxygen uptake capacity improved significantly ($p = 0.001$) and ($p = 0.004$) during the ten weeks. Based on the mixed-design ANOVA test, the difference between the averages of the two groups shows no significant group × time interactions, but that the results of the TG were slightly better, which can also be explained by the higher intensity of the TOCA training (26), which is also reflected in the increase in muscle mass, micromovements without the ball and endurance indicators. This can also be explained by (57, 58) with the findings that regular participation in soccer-specific training can be a sufficient incentive to increase the performance of soccer-specific skills.

An analysis of VO2 max, which is regarded as one of the most critical components of endurance performance (73). The mean VO2max of elite soccer players generally ranges from 55 to 68 ml/kg/min (38), much higher than the values we measured, which can be between 49.9 and 53.8 ml/kg/min. Recently, at another Hungarian academy, the endurance parameters of youth soccer players were also examined, where a value of 57.6 ml/kg/min was measured, which is also higher than what we experienced (37).

Regarding the research, the tests were carried out in an age group that is a sensitive age for motor skill learning. At this age, the development of the bone and muscle system progresses by leaps and bounds, affecting adolescents' physical performance. This partially explains why the body height and body mass of the sample increased significantly until the 10-week intervention (BH: $p < 0.001$, $p < 0.001$; BM: $p < 0.001$, $r = 0.804$; $p = 0.030$ $r = 0.511$). Among the most critical morphological changes that can be observed at this time are the accelerated change in body sizes and internal organs, changes in body proportions, and changes in body composition. These small changes can affect performance and motor coordination. Through the quantitative and qualitative development of muscles, their strength improves significantly. They become not only stronger but their training load can also be increased. In boys, the absolute mass of the body fat can also decrease (74). During puberty, the favorable conditions for motor skill learning are temporarily reduced. The adolescent child's motor coordination deteriorates and becomes impaired, and previously successfully mastered movements may appear clumsy. These are usually related to the intense increase in body length dimensions typical of adolescence. In the case of adolescent athletes, the duration of motor skill learning and the number of repetitions of the exercises must be chosen carefully and according to a plan (75). Bearing in mind the above, it can be stated that training should aim not only to increase performance but also to maintain motor coordination for the affected age group. According to Dubecz (30) and Harsányi (29), the performance of athletes in the affected age group can also start to deteriorate due to the inappropriate use of training stimuli in training sessions. Furthermore, it can also be established based on own research and given the characteristics of soccer, implementing mixed approaches in the training process, as well as introducing strength and power training, for U14 players is of paramount importance to build more resilient athletes (76–78).

5 Conclusions

Overall, it can be concluded that the integration of the TOCA Football System into football training is safe, even for an age group that is sensitive to motor skill learning (U13-U14). The results confirmed that using the TOCA Football System does not negatively affect the athletes' performance in terms of the measured parameters. In the case of the sample we examined, we experienced a significant improvement in most of the parameters within groups. However, the comparison between the groups did not show a significant difference, so a positive interaction cannot be established during the intervention. It was also found that it is worth approaching the examination of football-related motor skills in a more complex manner and supplementing the research with other tests, such as sprint tests, tests measuring the dynamic strength of the lower limb, or sports psychology tests.

6 Limitations

The main limitation of our study is that we could get a more accurate view of the long-term effect of the tool if the study was carried out with a larger number of elements over a longer intervention period, including other age groups. We could also get a more accurate view of the athletes' estimated aerobic capacity if laboratory tests were used. In the present study, we only examined junior male athletes, so we could get more reliable results if the research were repeated with the involvement of female athletes.

Data availability statement

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

Ethics statement

The studies involving humans were approved by The study was conducted in accordance with the Declaration of Helsinki and approved by the University of Pécs Regional Research Ethics Committee (No. 9119-PTE 2022). 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

ZS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing. ED: Data curation, Investigation, Writing – review & editing. BD: Conceptualization, Resources, Writing – review & editing. VP: Conceptualization, Supervision, Visualization, Writing – review & editing, Data curation, Formal Analysis. LV: Writing – review & editing, Data curation. HP: Supervision, Writing – review & editing. PÁ: Conceptualization, Data curation, Formal Analysis, Resources, Supervision, Writing – review & editing.

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Conflict of interest

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

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References

1. Williams AM, Ford P, Reilly T, Drust B. *Science and Soccer*. 2nd ed London: Routledge (2003). p. 352.

2. Barnes C, Archer DT, Hogg B, Bush M, Bradley PS. The evolution of physical and technical performance parameters in the English premier league. *Int J Sports Med*. (2014) 35(13):1095–100. doi: 10.1055/s-0034-1375695

3. Reilly T. *The Science of Training—Soccer A Scientific Approach to Developing Strength, Speed and Endurance*. London: Routledge (2006). p. 208. Available online at: doi: 10.4324/9780203966662 (cited January 19, 2023).

4. Davies P. *Total Soccer Fitness*. 2005th ed Texas, USA: RIO Network LLC. Del Rio. (2005).

5. Dellal A, Chamari K, Wong DP, Ahmaidi S, Keller D, Barros R, et al. Comparison of physical and technical performance in European soccer match-play: FA premier league and La Liga. *Eur J Sport Sci*. (2011) 11(1):51–9. doi: 10.1080/17461391.2010.481334

6. Stojanović E, Stojiljković N, Stanković R, Scanlan AT, Dalbo VJ, Milanović Z. Game format alters the physiological and activity demands encountered during small-sided football games in recreational players. *J Exerc Sci Fit*. (2021) 19(1):40–6. doi: 10.1016/j.jesf.2020.05.001

7. Pereira Da Silva N, Kirkendall DT, Leite De Barros Neto T. Movement patterns in elite Brazilian youth soccer. *J Sports Med Phys Fitness*. (2007) 47(3):270–5.

8. Schimpchen J, Skorski S, Nopp S, Meyer T. Are "classical" tests of repeated-sprint ability in football externally valid? A new approach to determine in-game sprinting behaviour in elite football players. *J Sports Sci*. (2016) 34(6):519–26. doi: 10.1080/02640414.2015.1112023

9. Bangsbo J. The physiology of soccer–with special reference to intense intermittent exercise. *Acta Physiol Scand Suppl*. (1994) 619:1–155.

10. Csáki I, Bognár J, Révész L, Géczi G. Elméletek és gyakorlatok a tehetséges labdarúgó kiválasztásához és beválásához. *Magyar Sporttudományi Szemle*. (2013) 14(53):12–8.

11. Mallo J, Mena E, Nevado F, Paredes-Hernández V. Physical demands of top-class soccer friendly matches in relation to a playing position using global positioning system technology. *J Hum Kinet*. (2015) 47:179–88. doi: 10.1515/hukin-2015-0073

12. Modric T, Versic S, Sekulic D, Liposek S. Analysis of the association between running performance and game performance indicators in professional soccer players. *Int J Environ Res Public Health*. (2019) 16(20):4032. doi: 10.3390/ijerph16204032

13. Modric T, Versic S, Sekulic D. Position specific running performances in professional football (soccer): influence of different tactical formations. *Sports*. (2020) 8(12):161. doi: 10.3390/sports8120161

14. Bradley PS, Di Mascio M, Peart D, Olsen P, Sheldon B. High-intensity activity profiles of elite soccer players at different performance levels. *J Strength Cond Res*. (2010) 24(9):2343. doi: 10.1519/JSC.0b013e3181aeb1b3

15. Andrzejewski M, Chmura J, Pluta B, Konarski JM. Sprinting activities and distance covered by top level Europa league soccer players. *Int J Sports Sci Coach*. (2015) 10(1):39–50. doi: 10.1260/1747-9541.10.1.39

16. Clemente JA A, Requena B, Jukic I, Nayler J, Hernández AS, Carling C. Is physical performance a differentiating element between more or less successful football teams? *Sports*. (2019) 7(10):216. doi: 10.3390/sports7100216

17. Orosz R. A labdarúgó tehetség kibontakoztatását befolyásoló pszichológiai tényezők vizsgálata. (2009). Available online at: http://hdl.handle.net/2437/88741 (cited March 18, 2024).

18. Rábai D. A Magyar sportpolitika legfőbb jellemzői, intézkedései 1945-től kezdődően a rendszerváltásig és napjainkig, különös tekintettel a labdarúgás sportágára. *Különleges Bánásmód—Interdiszciplináris folyóirat*. (2018) 4(1):19–33. doi: 10.18458/KB.2018.1.19

19. Varga D, Földesi G, Gombocz J. Declared pedagogical values of coaches at Hungarian football academies. *Physical Culture and Sport Studies and Research*. (2018) 77(1):17–24. doi: 10.2478/pcssr-2018-0002

20. Nerland E, Sæther SA. Norwegian football academy players—Players self-assessed competence, Perfectionism, Goal orientations and Motivational climate. 7-11. (2016). Available online at: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2646300 (cited March 18, 2024).

21. Kiss Z, Csáki I, Bognár J. Magyar és határon túli bentlakásos labdarúgó akadémia sajátosságai az edző szerepe és jellemzői tekintetében. *Különleges Bánásmód*. (2019) 5(2):7–18. doi: 10.18458/KB.2019.2.7

22. Kasuba M. Az edző–sportoló kapcsolat egy labdarúgó akadémián. *Educatio*. (2018) 27(1):121–8. doi: 10.1556/2063.27.2018.1.10

23. Kiss Z, Fózer-Selmeci B, Csáki I, Bognár J. Bentlakó labdarúgó-korosztályok pszichés-mentális jellemzői. *Mentálhigiéné és Pszichoszomatika*. (2015 Dec 1) 16 (4):331–47. doi: 10.1556/0406.16.2015.4.2

24. Vincze G, Bognár J, Csáki I, Géczi G. A labdarúgás szakmai elitjének véleménye a sportág jelenlegi helyzetéről. *Kalokagathia*. (2011) 2(4):264–77.

25. Little T, Williams AG. Measures of exercise intensity during soccer training drills with professional soccer players. *J Strength Cond Res*. (2007) 21(2):367–71.

26. Szabó Z, Ács P. The study of the TOCA football system for developing complex sport-specific skills among junior football players. *Health Probl Civiliz*. (2022) 16 (2):156–63. doi: 10.5114/hpc.2022.117023

27. Ács P, Bergier B, Bergier J, Niźnikowska E, Junger J, Salonna F. Students leisure time as a determinant of their physical activity at universities of the EU Visegrad group countries. *Health Probl Civiliz*. (2016) 10(4):31–41. doi: 10.5114/hpc.2016.63569

28. Ács P, Melczer C, Sávolt-Szabó T, Welker Z, Gyúró M, Baumann P, et al. Overview of the fitness parameters in the students of pécs university. *Health Probl Civiliz*. (2017) 11(3):150–7. doi: 10.5114/hpc.2017.70005

29. Harsányi L. Edzéstudomány [Internet]. Budapest-Pécs. Budapest-Pécs: Dialóg Campus Kiadó. (2001). Available online at: https://www.libri.hu/konyv/harsanyi_laszlo.edzestudomany.html (cited January 20, 2023).

30. Dubecz J. Általános edzéselmélet és módszertan. *Rectus, Budapest*. (2009) 43:161.

31. Zalai D. Multidisciplinary testing of motor skills to track junior footballers. Budapest: Semmelweis University, Doctoral School of Sports Science. (2016). Available online at: http://real-phd.mtak.hu/375/

32. Botek Z, Gába A, Lehnert M, Přidalová M, Vařeková R, Botek M, et al. Condition and body constitution of soccer players in category U19 before and after completing a preparatory period. *Acta Gymnica*. (2010) 40(2):47–54.

33. Bradley PS, Mohr M, Bendiksen M, Randers MB, Flindt M, Barnes C, et al. Sub-maximal and maximal Yo-Yo intermittent endurance test level 2: heart rate response, reproducibility and application to elite soccer. *Eur J Appl Physiol*. (2011) 111 (6):969–78. doi: 10.1007/s00421-010-1721-2

34. Norkowski H. Anaerobic power of handball players representing various sport levels. *J Hum Kinet*. (2002) 7:43–50.

35. Csáki I, Mihály T. Labdarúgás és tudomány. Budapest. Puskás Akadémia—Testnevelési egyetem: Pro- Kvóta 2004 Kft. (2020).

36. Mészáros J, Mohácsi J. *Determination of Biological Development and Prediction of Adult Stature Based on the Developmental Profile of Urban Youth*. Hungary: Hungarian Science Academy (1983).

37. Soós I, Borysławski K, Boraczyński M, Ihasz F, Podstawski R. Anthropometric and physiological profiles of Hungarian youth male soccer players of varying ages and playing positions: a multidimensional assessment with a critical approach. *Int J Environ Res Public Health*. (2022) 19(17):11041. doi: 10.3390/ijerph191711041

38. McMillan K, Helgerud J, Macdonald R, Hoff J. Physiological adaptations to soccer specific endurance training in professional youth soccer players. *Br J Sports Med*. (2005) 39(5):273–7. doi: 10.1136/bjsm.2004.012526

39. Malina RM, Ribeiro B, Aroso J, Cumming SP. Characteristics of youth soccer players aged 13–15 years classified by skill level. *Br J Sports Med*. (2007) 41 (5):290–5. doi: 10.1136/bjsm.2006.031294

40. Castagna C, Impellizzeri F, Cecchini E, Rampinini E, Alvarez JCB. Effects of intermittent-endurance fitness on match performance in young male soccer players. *J Strength Cond Res*. (2009) 23(7):1954. doi: 10.1519/JSC.0b013e3181b7f743

41. Castagna C, Manzi V, Impellizzeri F, Weston M, Barbero Alvarez JC. Relationship between endurance field tests and match performance in young soccer players. *J Strength Cond Res*. (2010) 24(12):3227. doi: 10.1519/JSC.0b013e3181e72709

42. Aandstad A, Simon EV. Reliability and validity of the soccer specific INTER field test. *J Sports Sci*. (2013) 31(13):1383–92. doi: 10.1080/02640414.2013.781667

43. Bangsbo J, Mohr M, Poulsen A, Perez-Gomez J, Krustrup P. Training and testing the elite athlete. *J Exerc Sci Fitness*. (2006) 4(1):1–14.

44. Castagna C, Impellizzeri FM, Chamari K, Carlomagno D, Rampinini E. Aerobic fitness and Yo-Yo continuous and intermittent tests performances in soccer players: a correlation study. *J Strength Cond Res*. (2006) 20(2):320–5.

45. Rampinini E, Sassi A, Azzalin A, Castagna C, Menaspà P, Carlomagno D, et al. Physiological determinants of Yo-Yo intermittent recovery tests in male soccer players. *Eur J Appl Physiol*. (2010) 108(2):401. doi: 10.1007/s00421-009-1221-4

46. Rebelo A, Brito J, Seabra A, Oliveira J, Krustrup P. Physical match performance of youth football players in relation to physical capacity. *Eur J Sport Sci*. (2014) 14 (sup1):S148–56. doi: 10.1080/17461391.2012.664171

47. Fang B, Kim Y, Choi M. Effect of cycle-based high-intensity interval training and moderate to moderate-intensity continuous training in adolescent soccer players. *Healthcare*. (2021) 9(12):1628. doi: 10.3390/healthcare9121628

48. Bruce RA, Blackmon JR, Jones JW, Strait G. Exercising testing in adult normal subject and cardiac patients. *Pediatrics*. (1963) 32(4):742–56. doi: 10.1542/peds.32.4.742

49. Bradley PS, Sheldon W, Wooster B, Olsen P, Boanas P, Krustrup P. High-intensity running in English FA premier league soccer matches. *J Sports Sci*. (2009) 27(2):159–68. doi: 10.1080/02640410802512775

50. Wong PL, Chaouachi A, Castagna C, Lau PWC, Chamari K, Wisløff U. Validity of the Yo-Yo intermittent endurance test in young soccer players. *Eur J Sport Sci*. (2011) 11(5):309–15. doi: 10.1080/17461391.2010.521579

51. Ulupınar S, Özbay S, Gençoğlu C, Franchini E, Kishalı NF, İnce İ. Effects of sprint distance and repetition number on energy system contributions in soccer players. *J Exerc Sci Fit*. (2021) 19(3):182–8. doi: 10.1016/j.jesf.2021.03.003

52. Chamari K, Hachana Y, Ahmed YB, Galy O, Sghaïer F, Chatard JC, et al. Field and laboratory testing in young elite soccer players. *Br J Sports Med*. (2004) 38 (2):191–6. doi: 10.1136/bjsm.2002.004374

53. Sheppard JM, Young WB. Agility literature review: classifications, training and testing. *J Sports Sci*. (2006) 24(9):919–32. doi: 10.1080/02640410500457109

54. Mendez-Villanueva A, Buchheit M, Kuitunen S, Douglas A, Peltola E, Bourdon P. Age-related differences in acceleration, maximum running speed, and repeated-sprint performance in young soccer players. *J Sports Sci*. (2011) 29(5):477–84. doi: 10.1080/02640414.2010.536248

55. Nyberg CC, Penpraze V. Determination of anthropometric and physiological performance measures in elite Scottish female rugby union players. *Int J Res Exerc Physiol*. (2016) 12(1):10–6.

56. Cohen J. *Statistical Power Analysis for the Behavioral Sciences*. 2nd ed New York: Routledge (1988). p. 567.

57. Cortis C, Tessitore A, Perroni F, Lupo C, Pesce C, Ammendolia A, et al. Interlimb coordination, strength, and power in soccer players across the lifespan. *J Strength Cond Res*. (2009) 23(9):2458. doi: 10.1519/JSC.0b013e3181bc1b39

58. Tessitore A, Perroni F, Cortis C, Meeusen R, Lupo C, Capranica L. Coordination of soccer players during preseason training. *J Strength Cond Res*. (2011) 25(11):3059. doi: 10.1519/JSC.0b013e318212e3e3

59. Mohr M, Krustrup P, Bangsbo J. Match performance of high-standard soccer players with special reference to development of fatigue. *J Sports Sci*. (2003) 21 (7):519–28. doi: 10.1080/0264041031000071182

60. Almuzaini KS, Fleck SJ. Modification of the standing long jump test enhances ability to predict anaerobic performance. *J Strength Cond Res*. (2008) 22(4):1265. doi: 10.1519/JSC.0b013e3181739838

61. Deprez D, Valente-Dos-Santos J, Coelho E, Lenoir M, Philippaerts R, Vaeyens R. Multilevel development models of explosive leg power in high-level soccer players. *Med Sci Sports Exerc*. (2015) 47(7):1408–15. doi: 10.1249/MSS.0000000000000541

62. Weyand PG, Sternlight DB, Bellizzi MJ, Wright S. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. *J Appl Physiol*. (2000) 89(5):1991–9. doi: 10.1152/jappl.2000.89.5.1991

63. Zalai D, Gyimes Z, Bobák P, Csáki I, Hamar P. Gondolatok a modern labdarúgó mérk\Hozések futóteljesítményér\Hol. *Testnevelés, Sport, Tudomány*. (2016) 1 (1):21–6. doi: 10.21846/TST.2016.1.2

64. Pavillon T, Tourny C, Ben Aabderrahman A, Salhi I, Zouita S, Rouissi M, et al. Sprint and jump performances in highly trained young soccer players of different chronological age: effects of linear VS. CHANGE–OF–DIRECTION sprint training. *J Exerc Sci Fitness*. (2021) 19(2):81–90. doi: 10.1016/j.jesf.2020.10.003

65. Padrón-Cabo A, Rey E, Kalén A, Costa PB. Effects of training with an agility ladder on sprint, agility, and dribbling performance in youth soccer players. *J Hum Kinet*. (2020) 73(1):219–28. doi: 10.2478/hukin-2019-0146

66. Taylor JB, Wright AA, Dischiavi SL, Townsend MA, Marmon AR. Activity demands during multi-directional team sports: a systematic review. *Sports Med*. (2017) 47(12):2533–51. doi: 10.1007/s40279-017-0772-5

67. Bloomfield J, Polman R, O'Donoghue P, McNaughton L. Effective speed and agility conditioning methodology for random intermittent dynamic type sports. *J Strength Cond Res*. (2007) 21(4):1093–100.

68. Valente-dos-Santos J, Coelho-e-Silva MJ, Severino V, Duarte J, Martins RS, Figueiredo AJ, et al. Longitudinal study of repeated sprint performance in youth soccer players of contrasting skeletal maturity Status. *J Sports Sci Med*. (2012) 11 (3):371–9.

69. Little T, Williams AG. Specificity of acceleration, maximum speed, and agility in professional soccer players. *J Strength Cond Res*. (2005) 19(1):76–8.

70. Krustrup P, Mohr M, Nybo L, Jensen JM, Nielsen JJ, Bangsbo J. The Yo-Yo IR2 test: physiological response, reliability, and application to elite soccer. *Med Sci Sports Exerc*. (2006) 38(9):1666–73. doi: 10.1249/01.mss.0000227538.20799.08

71. Reilly T, Williams AM, Nevill A, Franks A. A multidisciplinary approach to talent identification in soccer. *J Sports Sci*. (2000) 18(9):695–702. doi: 10.1080/02640410050120078

72. Vaeyens R, Lenoir M, Williams AM, Philippaerts RM. Talent identification and development programmes in sport. *Sports Med*. (2008) 38(9):703–14. doi: 10.2165/00007256-200838090-00001

73. Hoff J, Helgerud J. Endurance and strength training for soccer players: physiological considerations. *Sports Med*. (2004) 34(3):165–80. doi: 10.2165/00007256-200434030-00003

74. Humánbiológia BÉ. *Fejlődés: növekedés és érés*. Budapest: ELTE Eötvös Kiadó kft (2006).

75. Mozgástanulás IC. *mozgáskészség, mozgásügyesség, Budapest: Plantin-Print Bt*. Budapest: Plantin-Print Kiadó (2006).

76. Sander A, Keiner M, Wirth K, Schmidtbleicher D. Influence of a 2-year strength training programme on power performance in elite youth soccer players. *Eur J Sport Sci*. (2013) 13(5):445–51. doi: 10.1080/17461391.2012.742572

77. Makhlouf I, Chaouachi A, Chaouachi M, Ben Othman A, Granacher U, Behm DG. Combination of agility and plyometric training provides similar training benefits as combined balance and plyometric training in young soccer players. *Front Physiol*. (2018) 9:1611. doi: 10.3389/fphys.2018.01611

78. Uzelac-Sciran T, Sarabon N, Mikulic P. Effects of 8-week jump training program on sprint and jump performance and leg strength in pre- and post-peak height velocity aged boys. *J Sports Sci Med*. (2020) 19(3):547–55.

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Effects of variable intensity and constant intensity flywheel resistance training programs on specific soccer players' performance

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Resistance training programs play a crucial role in optimizing soccer performance. The aim of this study is to compare performance outcomes in sport-specific tasks after implementing two different flywheel resistance training (FRT) programs: variable intensity (VI) and constant intensity (CI). Seventeen (n = 17) amateur footballers were divided into VI and CI groups with the same training volume. For the VI group, a decrease in inertial load was implemented every four sessions, whereas the CI group maintained a constant load during the entire program. After different familiarization sessions and testing (sprint, change of direction, jump, one-repetition maximum and flywheel strength variables), ten sessions of FRT were performed over 5 weeks. Both groups showed similar improvements in the one-repetition maximum (p < 0.01) but the CI group had significant improvements in the 10-m sprint (p = 0.04; ES = 0.72), emphasizing the potential benefits of medium inertial loads to maximize power and specificity in sport tasks. However, no significant differences were observed in the countermovement jump, change of direction and 30-m sprint, possibly attributed to neuromuscular fatigue from a high-volume training schedule and friendly matches. The study highlights the importance of considering training load distribution in FRT programs. The findings emphasize the need for complementary training to maximize the jump and change of direction abilities and caution against high-volume training and friendly match scenarios. In conclusion, FRT programs, whether varying in intensity or not, can yield medium-term performance improvements for soccer players.

KEYWORDS

flywheel resistance training, soccer, training program, strength training, performance

Introduction

Resistance training programs should consider various training variables over time (Kraemer and Ratamess, 2000) and there are different programming strategies to optimize the force–time relationship and consequently increase performance in sport-specific tasks (Suchomel et al., 2016). For this reason, programs should thoroughly control variables such as intensity, volume, density, frequency or exercise selection (Zatsiorsky et al., 2020). Training volume and training intensity have received the greatest attention in strength training programs. Intensity can be expressed as a percentage of the one-repetition maximum (1RM), velocity of the bar, repetitions in reserve or rating of perceived effort (RPE) (Suchomel et al., 2021). On the other hand, training volume is represented by the total session workload performed, which influences the magnitude of metabolic stress and muscle damage (Schoenfeld, 2010). Intensity and volume manipulation dictate the physiological and biomechanical resistance training demands. Therefore, a combination of training variables is essential for optimizing training outcomes, achieving fitness goals and reducing the risk of overtraining (Kraemer and Ratamess, 2004).

Over the last few years, flywheel resistance training (FRT) has gained a lot of relevance in the world of strength and conditioning (Maroto-Izquierdo et al., 2017). This technology involves the use of a rotating mass that stores and releases energy during exercise (de Keijzer et al., 2022). Furthermore, practitioners can maximize the training effect of flywheel resistance technology by generating greater eccentric than concentric power outputs, a phenomenon referred to as eccentric overload (Beato et al., 2020). In addition, flywheel devices offer the possibility of performing specific and multi-planar exercises, replicating sport actions (Raya-González et al., 2021). These characteristics have caused flywheel technology to be widely used in sports, most commonly in football (Beato et al., 2021). Research has proven the effectiveness of FRT in enhancing strength (Raya-González et al., 2021; Allen et al., 2023), power (Raya-González et al., 2021; Allen et al., 2023), change of direction (COD) (Coratella et al., 2019; Fiorilli et al., 2020), countermovement jump (CMJ) (Allen et al., 2023) and sprint performance (de Hoyo et al., 2015). In addition to the classical training variables, FRT requires the management of other variables, such as strap rewind height (Sabido et al., 2020), rope length (Sabido et al., 2020) and loading conditions (Asencio et al., 2022).

Despite the effectiveness of FRT at improving athletes' performance, supported by previous research (Beato et al., 2021), only a few programming variables (mainly intensity/inertial load) have been studied in the scientific literature. This scarcity of research signifies a lack of knowledge about the optimal manipulation of basic variables during a FRT program. Most studies (de Hoyo et al., 2015; Sabido et al., 2018; Pecci et al., 2022) used a constant load approach (same inertial load during FRT), finding improvements in different performance variables such as the CMJ, sprint performance or 1RM squat. To the authors' knowledge there is only one study (Sabido et al., 2017) that compared the effect of FRT on performance variables in rugby players who were divided into two training groups with different intensity during the intervention (0.075 kg m^2 and 0.025 kg m^2, respectively). The study reported 1RM squat and CMJ improvements in both groups but no improvement in COD and a possible decrease in sprint performance at 0.075 kg m^2. However, for the 0.025 kg m^2 group there were small changes in linear sprint and positive effects on the agility T-test. Recently, Beato et al. (2021) proposed methodological bases of flywheel periodization in team sports and the distribution of training variables along the microcycle. Nevertheless, there is a need to compare the effect between different types of FRT programs in medium- and long-term adaptations.

Due to the lack of research on the possible effects of different FRT programs, it is important to determine whether a change of training intensity over time is needed during an FRT program. The objective of this study is to compare two types of training programs in sport performance tasks: variable intensity (VI) and constant intensity (CI). We hypothesized that varying the intensity is necessary to achieve medium-term performance adaptations and, consequently, that the VI group will achieve higher levels of performance than the CI group.

Materials and methods

Study design

This experimental study was carried out during 7 weeks of the pre-season period (see Table 2). In Weeks 1 and 7, performance assessments were performed. After a familiarization procedure and testing, participants were divided into two groups differing in the type of intensity distribution (VI and CI). For the VI group, inertial load was changed from higher to lower (see Table 1), whereas for the CI group, the inertial load was constant during all training periods. Both groups trained with the same density and total volume.

Participants

Seventeen (n = 17) amateur footballers in the Spanish third division team took part in this study. Participants had at least 2 years of experience in resistance training. Previous power analysis was conducted to determine the appropriate sample size using G* Power (version 3.1.9.3, Dusseldorf, Germany). According to the study design (2 groups, 2 repeated measures), a medium effect size f = 0.8, a correlation between measurements of r = 0.6, an α = 0.05, a required power 1-β = 0.95, a sample of 16 participants was required (actual power = 0.95).

Participants were assessed for their 1RM and subsequently assigned to one of two homogeneous groups according to player's role and strength level based on their 1RM/body mass (Haff and Triplett, 2021).

The VI group (n = 8; age = 22.00 ± 5.71 years; height = 1.82 ± 0.08 m; body mass = 76.20 ± 6.40 kg; 1RM = 132.48 ± 18.90; ratio 1RM/body mass = 1.74 ± 0.29) trained with decreasing inertial load every four training sessions (0.12 kg·m^2; 0.10 kg·m^2; 0.08 kg·m^2) and the CI group (n = 9; age = 22.9 ± 7.2 years; height = 1.80 ± 0.04 m; body mass = 75.66 ± 6.13 kg; 1RM 130.41 ± 19.87 kg; ratio 1RM/body mass 1.80 ± 0.04) trained with 0.08 kg·m^2 during the entire training period. Participants provided written informed consent in accordance with the Declaration of Helsinki and the study was approved by the ethics committee of the host institution (Code: ADH. DES.RSS.PAV.23).

Procedures

During the first week, participants were tested on three separate sessions, with 72 h of recovery between sessions. On the first day, descriptive (e.g., age, training level) and anthropometric data were recorded for each participant. After that, jump tests and a 1RM back-squat test were performed and participants completed a

TABLE 1 Training volume and intensity for the two groups. CI: constant intensity; VI: variable intensity; S: sets; R: repetitions; T: total repetitions.

				Squat			HORIZONTAL lunge (total sets)		
CI group	VI group			S	R	T	S	R	T
Inertia 0.08 kg·m^2	Inertia 0.12 kg·m^2	Week 1	*Session 1*	3	6	18	2	6	12
			Session 2	3	6	18	4	6	24
		Week 2	*Session 3*	4	6	24	4	6	24
			Session 4	4	7	28	4	6	24
	Inertia 0.10 kg·m^2	Week 3	*Session 5*	4	8	32	4	8	32
			Session 6	4	8	32	4	8	32
		Week 4	*Session 7*	4	8	32	4	8	32
			Session 8	4	8	32	4	8	32
	Inertia 0.08 kg·m^2	Week 5	*Session 9*	4	8	32	4	8	32
			Session 10	4	11	44	4	11	44
						292			288
								T:	**580**

flywheel familiarization protocol (Sabido et al., 2020). On the second day, participants conducted speed and COD tests and another flywheel familiarization protocol. On the last day, a flywheel squat exercise test was performed (see Figure 1).

Testing session 1: CMJ and 1RM

Data on the CMJ and 1RM back-squat test were collected from the participants. A contact platform (Chronojump Boscosystem) was used to assess the CMJ. Participants were instructed to achieve their maximum jump height, with hands on their hips, and to execute the descending phase at their preferred depth. Three attempts were assessed and the best trial was used for analysis.

Data on the 1RM back-squat exercise were obtained using a linear encoder (T-Force System, Ergotech, Murcia, Spain) and a software application was used to calculate the relevant kinetic and kinematic parameters. For 1RM estimation, participants performed a protocol previously described by Loturco et al. (Loturco et al., 2016). Briefly, this consisted of starting from a shoulder-width stance with the barbell positioned on the upper back near the acromion and with the knees and hips fully extended. Each participant descended until the thighs were parallel to the ground and then they ascended to an upright position. Participants started with a load representing 50% of their body mass and thereafter the load was gradually increased until the mean propulsive velocity was <0.5 m s. Using this submaximal load, participants performed three maximal repetitions and with the linear position transducer attached it was possible to automatically estimate the 1RM of the athletes. A 4-min rest interval separated each test and the 1RM was estimated based on movement velocity, as previously described.

Testing session 2: speed and COD

Acceleration, speed capacity and COD were evaluated on a grass soccer field. To assess speed, the 10-m sprint and 30-m sprint were performed. Participants stood 1 m behind the start line in a starting position with the body leaned forward. Timing gates (Microgate, Bolzano, Italy) were placed at the start (0 m), middle (10 m) and end (30 m), with reflectors at 1 m height (Tous-Fajardo et al., 2016). Participants were instructed to sprint at maximum speed for the entire distance. Each participant performed three attempts, with 2 min of passive recovery. The best score was used for the analyses.

COD was tested using the modified 505 test (M505), which involved two attempts of a 5-m sprint followed by a 180º COD and return to the starting point, which is a common maneuver in many sports (Raya-González et al., 2021). Timing gates (Microgate, Bolzano, Italy) were positioned at the starting and finishing points. Tests started on the "Go" command from a standing position, with the front foot 0.2 m from the photocell beam (Chaouachi et al., 2012).

Testing session 3: flywheel squat

On the last testing day, participants completed a flywheel squat test with the flywheel device (VersaPulley, Iberian Sportech, Seville, Spain), carrying out a maximum set of eight repetitions, with an additional two initial repetitions needed to build momentum. The inertial load used during the test was 0.08 kg·m^2. Participants performed two sets to warm up with a 2-min rest interval, a protocol recommended by Sabido et al. (2017). During each repetition the concentric and eccentric power (and their ratio) were recorded using a linear encoder and subsequently analyzed (SmartCoach Power Encoder, Europe AB, Stockholm, Sweden). The

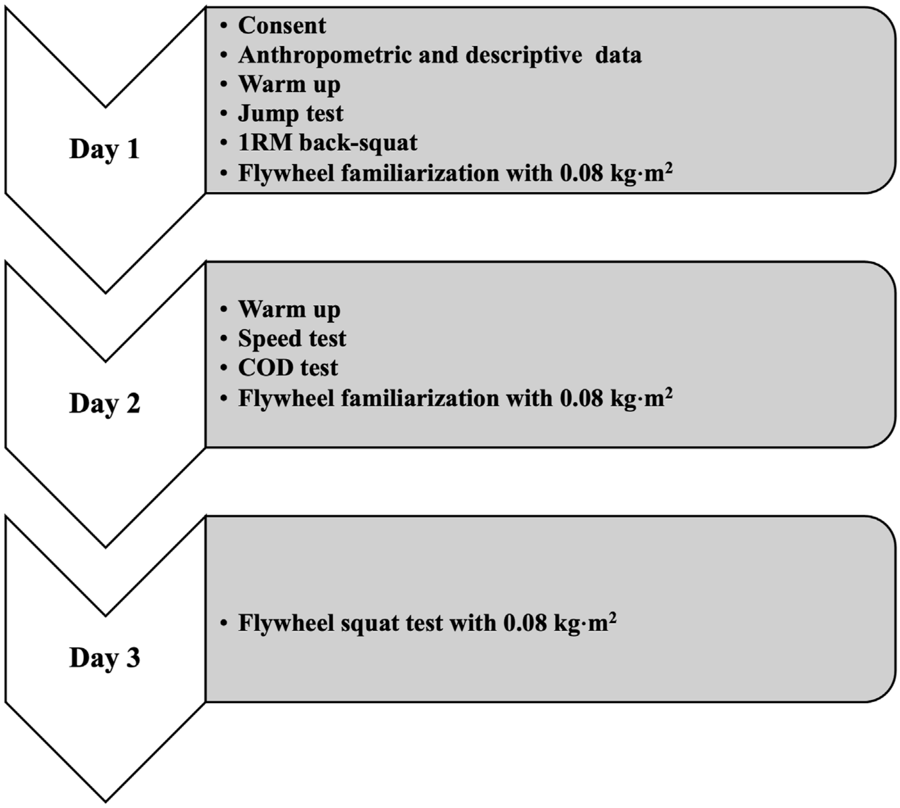

FIGURE 1
Scheme of the pretest.

variables used for data analysis were peak concentric power (PP_{con}), peak eccentric power (PP_{ecc}) and the eccentric overload (EO) ratio.

Training program

One week after the pre-test, participants started the training program using a flywheel device. Both groups engaged in two training sessions per week. The total volume of the training program was equated and the widest part of the conical pulley was chosen for setting the strap rewind height, aiming to maximize movement velocity (Sabido et al., 2020) (see Table 1). The program consisted of two exercises with different force vectors (vertical squat and horizontal lunge; see Table 1) twice a week. After a general warm up, each training session encompassed flywheel resistance exercises and a general soccer injury prevention program (e.g., core stability, balance and proprioceptive and hamstring eccentric exercises; see Table 2). During each set, two initial repetitions were needed to build inertia momentum and participants were instructed to perform each repetition as fast as possible and to delay braking action until the last third of the eccentric phase (Sabido et al., 2017). Rest intervals were standardized at 2 min, as specified by Sabido et al. (Sabido et al., 2018). The training protocols exhibited variations in training intensity, with a focus on either a conventional training block from high to low loads (G1) or constant load (G2) approaches (see Table 1). After Week 6, participants completed the post-test procedure.

Statistical analysis

Statistical analyses were performed using SPSS statistics package version 25.0 (IBM, New York, NY, United States of America). Following the size of the sample, confirmation of data normality using Shapiro-Wilk test was performed. Levene's test for homogeneity of variances was employed to assess the equality of variances across groups or conditions. To assess the assumption of sphericity in repeated measures or within subjects, Mauchly's sphericity test was employed. The effectiveness of each program (VI and CI) on the time was evaluated using a mixed model (time per group) ANOVA. A Bonferroni *post hoc* test for pairwise comparisons was conducted and the level of statistical significance was set at $p < 0.05$. Individual data analysis was presented using 2*SEM (Standard Error of the Mean) to establish individual changes between responders and non responders athletes. To assess the magnitude of the changes, Cohen's d effect size (ES) calculation was performed, with interpretations as trivial (<0.2), small (0.2–0.5), moderate (0.5–0.8) and large (>0.8) (Ferguson, 2009).

Results

After confirm data normality, Levene's test indicated homogeneity of variances ($p > 0.05$). To present the results more precisely according to the Mauchly's test, Greenhouse-Geisser criterion was selected to control Type I error rates.

TABLE 2 Weekly training plan for the training period. LSG: long side games; MSG: medium side games; SSG: small side games.

	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Week 1		Testing	Testing	Strength exercises technique LSG–MSG 2x (5vs5) + 3	Strength exercises technique LSG (11vs11) 3 × 12’	REST	REST
Week 2	AM: Testing PM: Flywheel training–Injury prevention SSG-MSG (7vs7) 4 × 8’	LSG (11vs11) 3 × 12’ Upper body strength work	AM: Flywheel training–Injury prevention PM: Friendly match	Upper body strength work	LSG–MSG 2 × 12’	Friendly match	REST
Week 3	AM: SSG–MSG 4 × 6’ PM: Flywheel training–Injury prevention	LSG–MSG 2 × 12’ Upper body strength work	AM: LSG (11vs11) 3 × 13’ PM: Flywheel training–Injury prevention	MSG - SSG	LSG–MSG 2 × 12’	Friendly match	REST
Week 4	LSG–MSG 4 × 6’ Flywheel training–Injury prevention	Friendly match	MSG–SSG Flywheel training–Injury prevention Upper body strength work	MSG 4 × 6’ (5vs5)	Friendly match	REST	REST
Week 5	SSG (4vs4)/(3vs3) 2 × 6 × 1’/1’ Flywheel training–Injury prevention	LSG–MSG Upper body strength work	MSG 4 × 6’ (5vs5) + 3 Flywheel training–Injury prevention	LSG–MSG Upper body strength work 2 × 12’	Friendly match	Friendly match	REST
Week 6	SSG (4vs4)/(3vs3) 2 × 6 × 1’/1’ Flywheel training–Injury prevention	LSG–MSG 2 × 12’ Upper body strength work	Friendly match	LSG–MSG Upper body strength work 2 × 12’	SSG (4vs4)/(3vs3) 2 × 6 × 1’/1’ Flywheel training–Injury prevention	Friendly match	REST
Week 7	Testing						

TABLE 3 Changes in performance after the variable intensity (VI) and constant intensity (CI) programs. CMJ: countermovement jump; M505-D: modified 505-Dominant side; M505-ND: modified 505 non-dominant side; 1RM: one-repetition maximum; PP_{con}: concentric peak power; PP_{ecc}: eccentric peak power; EO: eccentric overload; %: percentage change; ES: effect size; CI: confidence interval; *: $p < 0.05$.

	VI group (n = 8)					CI group (n = 9)				
Variable	Pretest	Posttest	ES	CI	%	Pretest	Posttest	ES	CI	%
CMJ (cm)	39.39 ± 4.29	37.94 ± 5.28	−0.30	(-0.58, −0,02)	−3.68	42.20 ± 5.30	41.57 ± 4.90	−0.11	(-0.33, 0.11)	−1.49
M505-D (s)	2.51 ± 0.06	2.61 ± 0.13*	−1.29	(0.07, 2.51)	3.98	2.49 ± 0.06	2.62 ± 0.09*	−1.83	(1.07, 2.60)	5.37
M505-ND (s)	2.58 ± 0.13	2.69 ± 0.23	−0.73	(-0.16, 1.62)	4.26	2.52 ± 0.06	2.62 ± 0.16	−1.32	(-0.42, 3.06)	3.79
SPRINT 10 m (s)	1.83 ± 0.09	1.80 ± 0.09	0.36	(-1.09, 0.36)	−2.06	1.81 ± 0.09	1.74 ± 0.07*	0.72	(-1.34, −0.11)	−4.02
SPRINT 30 m (s)	4.24 ± 0.17	4.30 ± 0.18	−0.31	(-0.09, 0.71)	1.41	4.16 ± 0.19	4.15 ± 0.16	0.05	(-0.38, 0.28)	−0.24
1RM (kg)	134.47 ± 20.84	141.12 ± 26.17*	0.28	(0.11, 0.46)	4.94	132.23 ± 20.41	140.68 ± 21.53*	0.37	(0.07, 0.68)	6.39
PP_{con} (W)	1488.21 ± 338.14	1628.54 ± 312.85	0.37	(-0.13, 0.87)	9.42	1635.11 ± 443.37	1808.24 ± 395.62	0.35	(0.08, 0.63)	10.50
PP_{ecc} (W)	1866.67 ± 531.74	2120.32 ± 573.33	0.42	(-0.08, 0.93)	13.58	1988.74 ± 448.68	2299.68 ± 465.61	0.63	(0.13, 1.12)	15.60
EO	25.18 ± 24.52	30.03 ± 19.13	0.18	(-0.43, 0.79)	19.26	29.68 ± 34.26	28.40 ± 15.42	−0.03	(-0.59, 0.53)	−4.31

The group factor showed that there were no significant differences between groups in initial conditions, indicating two homogeneous groups in all measured variables after balanced assignment.

No significant differences were observed in the time × group interaction ($p > 0.05$). The Time factor reported that there were pre-to post-changes in performance variables (see Table 3). Positive improvement in performance variables is shown by the positive values of effect size. Both groups showed no changes in CMJ height, M505-ND or 30-m sprint time. Furthermore, both groups showed significant decreases in M505-D.

However, in the 10-m sprint, the CI group showed significant improvements ($p = 0.04$). There were also significant improvements in the 1RM values for both groups ($p < 0.01$).

Finally, for the flywheel performance variables, both groups showed increases in PP_{con} (VI: 9.42%; CI: 10.50%) and PP_{ecc} (VI: 13.80%; CI: 15.60%). Due to small sample size, to confirm the results, individual target has been contrasted with an individual analysis using 2xSEM (see Figure 2).

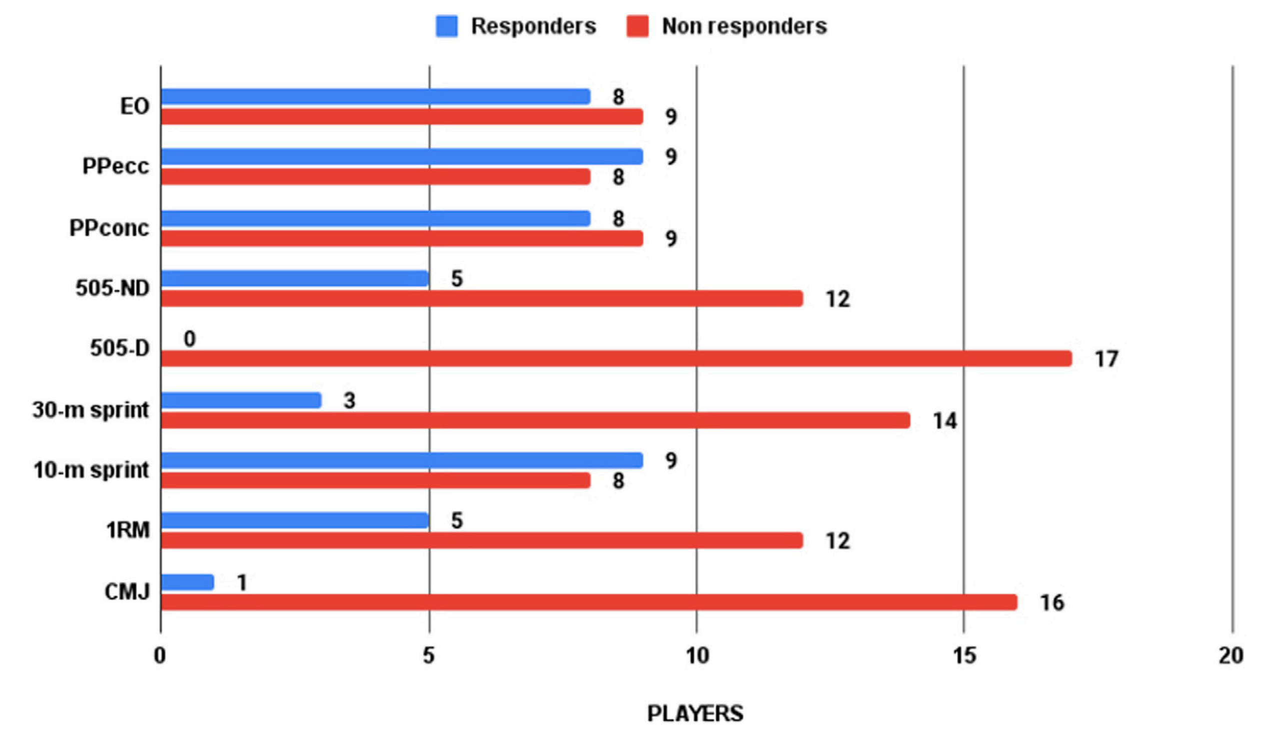

FIGURE 2
Individual results of different fitness testing. Athletes were divided into responders and non-responders based on 2xSEM criteria.

Discussion

This study aimed to compare the effects of VI and CI FRT programs on soccer players' fitness performance. The main findings of this research are: the VI and CI groups have similar improvements in the 1RM variable; the CI group shows significant improvement for the 10-m sprint; and no difference was observed in the other variables apart from a significant decrease in M505-D.

Previous studies have reported the relationship of the 1RM squat with different performance tests in soccer (Requena et al., 2009; Comfort et al., 2014) and its influence on players' performance (Owen et al., 2015; Wing et al., 2020). The benefits of FRT obtained in our study are similar to previous works (Fernandez-Gonzalo et al., 2014; Sabido et al., 2017; Sagelv et al., 2020). Thus, the inclusion of FRT can be an optimal way to improve maximal strength in lower limbs, optimizing sprinting (De Hoyo et al., 2016) and jumping (Wisløff et al., 2004), as a tool to improve match actions (Wing et al., 2020) or as an indicator of fatigue recovery after competition (Owen et al., 2015). The benefits mentioned for sprint performance have been observed in our results over short distances and are very important in soccer (Chelly et al., 2010). Individual outcomes surpassing twice the value of SEM for the 10-m sprint test and flywheel squat power values indicate substantial performance changes according to the previous statistical analysis. These results agree with previous studies using FRT (Núñez et al., 2018; Suarez-Arrones et al., 2018; Coratella et al., 2019; Sagelv et al., 2020; Raya-González et al., 2021). Although the trend to improve the 10-m sprint test is observed in both groups, only the CI group obtained a significant difference after training. This finding could be due to the CI group using lower inertial loads. These results are relevant because sprint ability is one of the most important performance variables in soccer (Castillo et al., 2020), being linked to soccer-specific tasks both in defensive and offensive actions (Mara et al., 2017; Cochrane and Monaghan, 2021). According to Sabido et al. (Sabido et al., 2018), lower inertial loads are a better option for eliciting high concentric peak power output values, and, according to our results, a low load where high power is produced can be the best choice to optimize short-sprint ability. For this reason, the increases in PP_{con} and PP_{ecc} are greater in the CI group compared to the VI group (10.50% vs. 9.42% and 15.60 vs. 13.58 in PP_{con} and PP_{ecc}, respectively). Accordingly, recent research (Asencio et al., 2024) shows that lower inertial loads can be optimal for trained subjects to obtain the maximal power values in the concentric and eccentric phases during squat exercises in FRT.

Studies on FRT have reported that this methodology can be very useful for improving jumping ability, COD and sprint tasks in soccer players (Gonzalo-Skok et al., 2017; Coratella et al., 2019; Fiorilli et al., 2020). Nevertheless, our results show that the CMJ, COD and 30-m sprint did not improve in any of the groups after ten sessions of FRT, and even worse values were found for M505-D. These results are in line with individual analysis, showing a similar or high number of non-responders for several tests. Two reasons may explain the results obtained in our study. On the one hand, the absence of complementary training to improve jump ability has been proposed by Pecci et al. (Pecci et al., 2022), who also did not find significant differences with female soccer players in CMJ height after 6 weeks of FRT. Thus, complementary tasks must be combined with FRT to obtain possible benefits in jump or COD abilities. On the other hand, the main hypothesis for these results is neuromuscular fatigue due to the high number of friendly matches (Hernández-Davo et al., 2022). The purpose of investigating in an ecological context implied different changes in the FRT program and the impossibility of resting at 72 h from the last match to the final tests (De Hoyo et al., 2016; Romagnoli et al., 2016).

To the authors' knowledge, this is the first study to compare the effects of two different FRT programs (VI and CI) on sports performance. Despite this, our study has some limitations. Firstly, the training volume and friendly matches calendar were very high, so it may not be possible to minimize post-match fatigue levels (Nédélec et al., 2012). Secondly, even though each player completed at least ninety percent of the sessions, the player role and external training load may be influencing the results. Thirdly, no control group was included because FRT was considered an important variable not only for optimizing strength in players but also for reducing the probability of injury. For this reason, and to have a greater number of players in each group, a control group was not considered in this study. Finally, after training protocol no anthropometrical mesurements (i.e., body mass) were recorded. As previous research shown, the values of post-test can be conditioned by anthropometric changes (Koźlenia et al., 2020; Popowczak et al., 2021).

The findings of this study have a number of practical implications. Present findings suggest that VI and CI training improved strength levels. In addition, CI group showed significant improvements in the 10-m sprint. However, probably another type of training load (e.g., lower intensity and volume or complementary training) is needed to maximize performance in specific tasks such as the CMJ or COD test. Furthermore, it is necessary to control the fatigue levels and friendly matches calendar in pre-season periods in order to achieve functional overreaching. Thus, strength and conditioning coaches of soccer players with high 1RM/body mass ratio should to individualize FRT programs using CI (medium and lower inertias) and perform complementary training in promoting specific soccer performance improvements. Due to competitive density of most team-sports with short pre-season periods, this study concludes how to optimize performance outcomes using FRT in short periods of time (i.e., ten sessions during 5 weeks).

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 Miguel Hernández University. Code: ADH. DES.RSS.PAV.23. 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

PA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. FM: Conceptualization, Formal Analysis, Project administration, Supervision, Validation, Writing–review and editing. JLH-D: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. RS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

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Conflict of interest

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

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References

Allen, W. J., De Keijzer, K. L., Raya-González, J., Castillo, D., Coratella, G., and Beato, M. (2023). Chronic effects of flywheel training on physical capacities in soccer players: a systematic review. *Res. Sports Med.* 31 (3), 228–248. doi:10.1080/15438627.2021.1958813

Asencio, P., García-Valverde, A., Albaladejo, C., Beato, M., Moreno-Hernández, F. J., and Sabido, R. (2024). Analysis of concentric and eccentric power in flywheel exercises depending on the subjects' strength level and body mass. *J. Strength Cond. Res.* (under review).

Asencio, P., Hernández-Davó, J. L., García-Valverde, A., and Sabido, R. (2022). Effects of flywheel resistance training using horizontal vs vertical exercises. *Int. J. Sports Sci. Coach.* 19, 410–416. doi:10.1177/17479541221135372

Beato, M., Maroto-Izquierdo, S., Hernández-Davó, J. L., and Raya-González, J. (2021). Flywheel training periodization in team sports. *Front. Physiol.* 12, 732802. doi:10.3389/fphys.2021.732802

Beato, M., McErlain-Naylor, S. A., Halperin, I., and Iacono, A. D. (2020). Current evidence and practical applications of flywheel eccentric overload exercises as postactivation potentiation protocols: a brief review. *Int. J. Sports Physiol. Perform.* 15 (2), 154–161. doi:10.1123/ijspp.2019-0476

Castillo, D., Raya-González, J., Manuel Clemente, F., and Yanci, J. (2020). The influence of offside rule and pitch sizes on the youth soccer players' small-sided games external loads. *Res. Sports Med.* 28 (3), 324–338. doi:10.1080/15438627.2020.1739687

Chaouachi, A., Manzi, V., Chaalali, A., Wong, D. P., Chamari, K., and Castagna, C. (2012). Determinants analysis of change-of-direction ability in elite soccer players. *J. Strength Cond. Res.* 26 (10), 2667–2676. doi:10.1519/JSC.0b013e318242f97a

Chelly, M. S., Chérif, N., Amar, M. B., Hermassi, S., Fathloun, M., Bouhlel, E., et al. (2010). Relationships of peak leg power, 1 maximal repetition half back squat, and leg muscle volume to 5-m sprint performance of junior soccer players. *J. Strength Cond. Res.* 24 (1), 266–271. doi:10.1519/JSC.0b013e3181c3b298

Cochrane, D. J., and Monaghan, D. (2021). Using sprint velocity decrement to enhance acute sprint performance. *J. Strength Cond. Res.* 35 (2), 442–448. doi:10.1519/JSC.0000000000002707

Comfort, P., Stewart, A., Bloom, L., and Clarkson, B. (2014). Relationships between strength, sprint, and jump performance in well-trained youth soccer players. *J. Strength Cond. Res.* 28 (1), 173–177. doi:10.1519/jsc.0b013e318291b8c7

Coratella, G., Beato, M., Cè, E., Scurati, R., Milanese, C., Schena, F., et al. (2019). Effects of in-season enhanced negative work-based vs traditional weight training on change of direction and hamstrings-to-quadriceps ratio in soccer players. *Biol. Sport* 36 (3), 241–248. doi:10.5114/biolsport.2019.87045

De Hoyo, M., Cohen, D. D., Sañudo, B., Carrasco, L., Álvarez-Mesa, A., Del Ojo, J. J., et al. (2016). Influence of football match time–motion parameters on recovery time course of muscle damage and jump ability. *J. Sports Sci.* 34 (14), 1363–1370. doi:10.1080/02640414.2016.1150603

de Hoyo, M., Pozzo, M., Sañudo, B., Carrasco, L., Gonzalo-Skok, O., Domínguez-Cobo, S., et al. (2015). Effects of a 10-week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. *Int. J. Sports Physiol. Perform.* 10 (1), 46–52. doi:10.1123/ijspp.2013-0547

de Keijzer, K. L., Gonzalez, J. R., and Beato, M. (2022). The effect of flywheel training on strength and physical capacities in sporting and healthy populations: an umbrella review. *PLoS One* 17 (2), e0264375. doi:10.1371/journal.pone.0264375

Fernandez-Gonzalo, R., Lundberg, T. R., Alvarez-Alvarez, L., and de Paz, J. A. (2014). Muscle damage responses and adaptations to eccentric-overload resistance exercise in men and women. *Eur. J. Appl. Physiol.* 114, 1075–1084. doi:10.1007/s00421-014-2836-7

Ferguson, C. J. (2009). An effect size primer: a guide for clinicians and researchers. *Prof. Psychol. Res. Pract.* 40, 532–538. doi:10.1037/a0015808

Fiorilli, G., Mariano, I., Iuliano, E., Giombini, A., Ciccarelli, A., Buonsenso, A., et al. (2020). Isoinertial eccentric-overload training in young soccer players: effects on strength, sprint, change of direction, agility and soccer shooting precision. *J. Sports Sci. Med.* 19 (1), 213–223.

Gonzalo-Skok, O., Tous-Fajardo, J., Valero-Campo, C., Berzosa, C., Bataller, A. V., Arjol-Serrano, J. L., et al. (2017). Eccentric-overload training in team-sport functional performance: constant bilateral vertical versus variable unilateral multidirectional movements. *Int. J. Sports Physiol. Perform.* 12 (7), 951–958. doi:10.1123/ijspp.2016-0251

Haff, G. G., and Triplett, N. T. (2021) *Essentials of strength training and conditioning*. 4th ed.

Hernández-Davo, J. L., Pérez, V. M., and Navarro, P. M. (2022). Effects of playing 1 vs 3 matches in a one-week period on physical performance in young soccer players. *Biol. Sport* 39 (4), 819–823. doi:10.5114/biolsport.2022.108700

Koźlenia, D., Domaradzki, J., Trojanowska, I., and Czermak, P. (2020). Association between speed and agility abilities with movement patterns quality in team sports players. *Med. Sport* 73, 176–186. doi:10.23736/S0025-7826.20.03662-5

Kraemer, W. J., and Ratamess, N. A. (2000). Physiology of resistance training: current issues. *Orthop. Phys. Ther. Clin. North Am.* 9 (4), 467–513.

Kraemer, W. J., and Ratamess, N. A. (2004). Fundamentals of resistance training: progression and exercise prescription. *Med. Sci. Sports Exerc* 36 (4), 674–688. doi:10.1249/01.mss.0000121945.36635.61

Loturco, I., Pereira, L. A., Abad, C. C. C., Gil, S., Kitamura, K., Kobal, R., et al. (2016). Using bar velocity to predict the maximum dynamic strength in the half-squat exercise. *Int. J. Sports Physiol. Perform.* 11 (5), 697–700. doi:10.1123/ijspp.2015-0316

Mara, J. K., Thompson, K. G., Pumpa, K. L., and Morgan, S. (2017). Quantifying the high-speed running and sprinting profiles of elite female soccer players during competitive matches using an optical player tracking system. *J. Strength Cond. Res.* 31 (6), 1500–1508. doi:10.1519/JSC.0000000000001629

Maroto-Izquierdo, S., García-López, D., and de Paz, J. A. (2017). Functional and muscle-size effects of flywheel resistance training with eccentric-overload in professional handball players. *J. Hum. Kinet.* 60, 133–143. doi:10.1515/hukin-2017-0096

Nédélec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., and Dupont, G. (2012). Recovery in soccer: part I—post-match fatigue and time course of recovery. *Sports Med.* 42, 997–1015. doi:10.2165/11635270-000000000-00000

Núñez, F. J., Santalla, A., Carrasquila, I., Asian, J. A., Reina, J. I., and Suarez-Arrones, L. J. (2018). The effects of unilateral and bilateral eccentric overload training on hypertrophy, muscle power and COD performance, and its determinants, in team sport players. *PLoS One* 13 (3), e0193841. doi:10.1371/journal.pone.0193841

Owen, A., Dunlop, G., Rouissi, M., Chtara, M., Paul, D., Zouhal, H., et al. (2015). The relationship between lower-limb strength and match-related muscle damage in elite level professional European soccer players. *J. Sports Sci.* 33 (20), 2100–2105. doi:10.1080/02640414.2015.1064155

Pecci, J., Muñoz-López, A., Jones, P., and Sañudo, B. (2022). Effects of 6 weeks in-season flywheel squat resistance training on strength, vertical jump, change of direction and sprint performance in professional female soccer players. *Biol. Sport* 40 (2), 521–529. doi:10.5114/biolsport.2023.118022

Popowczak, M., Cichy, I., Rokita, A., and Domaradzki, J. (2021). The relationship between reactive agility and change of direction speed in professional female basketball and handball players. *Front. Psychol.* 12, 708771. doi:10.3389/fpsyg.2021.708771

Raya-González, J., Prat-Luri, A., López-Valenciano, A., Sabido, R., and Hernández-Davó, J. L. (2021). Effects of flywheel resistance training on sport actions. A systematic review and meta-analysis. *J. Hum. Kinet.* 77 (1), 191–204. doi:10.2478/hukin-2021-0020

Requena, B., González-Badillo, J. J., de Villareal, E. S. S., Ereline, J., García, I., Gapeyeva, H., et al. (2009). Functional performance, maximal strength, and power characteristics in isometric and dynamic actions of lower extremities in soccer players. *J. Strength Cond. Res.* 23 (5), 1391–1401. doi:10.1519/JSC.0b013e3181a4e88e

Rhea, M. R. (2004). Determining the magnitude of treatment effects in strength training research through the use of the effect size. *J. Strength Cond. Res.* 18, 918–920. doi:10.1519/14403.1

Romagnoli, M., Sanchis-Gomar, F., Alis, R., Risso-Ballester, J., Bosio, A., Graziani, R. L., et al. (2016). Changes in muscle damage, inflammation, and fatigue-related parameters in young elite soccer players after a match. *J. Sports Med. Phys. Fit.* 56 (10), 1198–1205.

Sabido, R., Hernández-Davó, J. L., Botella, J., Navarro, A., and Tous-Fajardo, J. (2017). Effects of adding a weekly eccentric-overload training session on strength and athletic performance in team-handball players. *Eur. J. Sport Sci.* 17 (5), 530–538. doi:10.1080/17461391.2017.1282046

Sabido, R., Hernández-Davó, J. L., García-Valverde, A., Marco, P., and Asencio, P. (2020). Influence of the strap rewind height during a conical pulley exercise. *J. Hum. Kinet.* 74 (1), 109–118. doi:10.2478/hukin-2020-0018

Sabido, R., Hernández-Davó, J. L., and Pereyra-Gerber, G. T. (2018). Influence of different inertial loads on basic training variables during the flywheel squat exercise. *Int. J. Sports Physiol. Perform.* 13 (4), 482–489. doi:10.1123/ijspp.2017-0282

Sagelv, E. H., Pedersen, S., Nilsen, L. P. R., Casolo, A., Welde, B., Randers, M. B., et al. (2020). Flywheel squats versus free weight high load squats for improving high velocity movements in football. A randomized controlled trial. *BMC Sports Sci. Med. Rehabil.* 12 (1), 61–13. doi:10.1186/s13102-020-00210-y

Schoenfeld, B. J. (2010). The mechanisms of muscle hypertrophy and their application to resistance training. *J. Strength Cond. Res.* 24 (10), 2857–2872. doi:10.1519/JSC.0b013e3181e840f3

Suarez-Arrones, L., Saez de Villarreal, E., Núñez, F. J., Di Salvo, V., Petri, C., Buccolini, A., et al. (2018). In-season eccentric-overload training in elite soccer players: effects on body composition, strength and sprint performance. *PLoS One* 13 (10), e0205332. doi:10.1371/journal.pone0205332

Suchomel, T. J., Nimphius, S., Bellon, C. R., Hornsby, W. G., and Stone, M. H. (2021). Training for muscular strength: methods for monitoring and adjusting training intensity. *Sports Med.* 51 (10), 2051–2066. doi:10.1007/s40279-021-01488-9

Suchomel, T. J., Nimphius, S., and Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports Med.* 46, 1419–1449. doi:10.1007/s40279-016-0486-0

Tous-Fajardo, J., Gonzalo-Skok, O., Arjol-Serrano, J. L., and Tesch, P. (2016). Enhancing change-of-direction speed in soccer players by functional inertial eccentric overload and vibration training. *Int. J. Sports Physiol. Perform.* 11 (1), 66–73. doi:10.1123/ijspp.2015-0010

Wing, C. E., Turner, A. N., and Bishop, C. J. (2020). Importance of strength and power on key performance indicators in elite youth soccer. *J. Strength Cond. Res.* 34 (7), 2006–2014. doi:10.1519/jsc.0000000000002446

Wisløff, U., Castagna, C., Helgerud, J., Jones, R., and Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Br. J. Sports Med.* 38 (3), 285–288. doi:10.1136/bjsm.2002.002071

Zatsiorsky, V. M., Kraemer, W. J., and Fry, A. C. (2020) *Science and practice of strength training*. USA: Human Kinetics.

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The association between unilateral and bilateral performance-related measures in elite female soccer players: a multifaceted investigation

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Purpose: The present study aimed to investigate a) the associations between bilateral performance utilizing countermovement jump (CMJ), squat jump (SJ), speed and unilateral CMJ, isokinetic peak torque in knee extension and flexion with angular velocities of 60°/s and 180°/s and tensiomyography (TMG) parameters; b) whether the asymmetries derived from unilateral tests are associated with bilateral CMJ, SJ and speed in elite female soccer players.

Methods: Thirty-five elite female soccer players (average age: 20 ± 5 years) completed CMJ, SJ, speed, isokinetic muscle strength and TMG tests.

Results: Compared to the non-dominant leg, the dominant leg demonstrated greater peak torque output in both knee flexion (7.4%) and knee extension (5.6%) isokinetic tasks, as well as m. vastus medialis contraction time (7.6%), and soccer-specific agility test (4.1%). Conversely, the hamstring to quadriceps peak torque ratio at 180°/s (8.5%) was significantly greater in the non-dominant leg. The associations between CMJ, SJ and speed performance were positive and ranged from weak (r = 0.350) to high (r = 0.710). For speed and TMG-derived variables, correlations were negative and ranged from weak (r = −0.345, p = 0.042, for vastus medialis contraction time) to moderate (r = −0.530, p = 0.001, for biceps femoris contraction time). Furthermore, both bilateral CMJ and SJ negatively correlated with TMG-derived variables, ranging from weak (r = −0.350, p = 0.039, for vastus lateralis contraction time) to moderate (r = −0.537, p = 0.003, for rectus femoris contraction time).

Conclusion: The overall significant, albeit inconsistent, correlations between the diverse performance scores obtained highlight the necessity for a multifaceted and thorough diagnostic strategy in female soccer players.

KEYWORDS

TMG, neuromuscular function, physical function, strength, women's football, power, running speed and agility, muscle contractile properties

1 Introduction

Muscle power is an important factor in successful rapid movement performance like jumping, sprinting, and kicking (Newton and Kraemer, 1994). Such movements generally require optimal inter-limb balance (Bishop et al., 2018), regardless of lateral preference. Previous authors found >10% asymmetry in peak power tended to decrease jumping ability (Bell et al., 2014). Lateral preference, common among the vast majority of individuals (Annett, 1972), and repeated unilateral sporting activities can lead to muscle asymmetry (Heil et al., 2020). In recent years, an increasing number of studies have examined the relationship between muscle characteristics and their asymmetries and also between sprint and jumping ability (Gil et al., 2015; Bishop et al., 2021; Loturco et al., 2019; Bishop, Coratella, et al., 2021).

Many authors have sought to determine different muscle characteristics and the relationship between different testing methods but have come to different conclusions. For example, several studies (Binet et al., 2005; Almuzaini and Fleck, 2008; Križaj et al., 2019) found weak to high significant positive correlation coefficients (ranging 0.31–0.71) between isokinetic knee extension peak torque and vertical jump performance whilst others reported none (Atabek et al., 2009) or weak insignificant negative correlation coefficients (−0.12) (Maly et al., 2013). Similar discrepancies are present in studies using tensiomyography (TMG) with the same objective (Gil et al., 2015; Loturco et al., 2018; Pereira et al., 2018; Lewis et al., 2022). TMG is a recent method for evaluating the contractile properties of superficial skeletal muscles (Paravlić et al., 2017). It assesses radial muscle deformation caused by electrical stimuli (Paravlić et al., 2020) and provides valuable parameters related to muscle function and structure (Macgregor et al., 2018). One of the mostly reported and clinically important TMG-derived variables are presented through the time of contraction (Tc) and displacement measure (Dm) (Pišot et al., 2008; Šimunic et al., 2011; Paravlić et al., 2022). In contrast to established methods like isokinetic dynamometry and force plates, TMG's neuromuscular assessment is not influenced by factors like motivation or voluntary effort, which can influence athletic performance (Macgregor et al., 2018; Paravlic et al., 2022). For example, Loturco et al., 2015 and Pereira et al., 2018 found a significant moderate negative correlation between TMG parameters and vertical jump performance. In contrary, Gil et al., 2015 and Lewis et al., 2022 found non-significant correlation between aforementioned variables. These variations may be due to differences in the population evaluated, the TMG measurement technique including measuring point and the electrode positioning, and, most likely, evaluated muscles. Consequently, Loturco et al., 2015 claimed that TMG can discriminate endurance and power athletes whereas Lewis et al., 2022 state the opposite. Consequently, unclear findings in team sports and limited evidence in female soccer players emphasize a need for further investigation in this area.

Although the investigation of inter-limb asymmetry is not a new concept in sports science, researchers have recently intensified their efforts to explore the relationship between asymmetries and athletic performance. A systematic review (Bishop et al., 2018) reported inconsistent findings regarding asymmetry prevalence and its effects on athletic performance. Nevertheless, the literature as a whole indicates there is a high prevalence of muscle asymmetry. This has been measured and found using sports specific tasks (Lockie et al., 2014), dynamometry (Križaj et al., 2019), tensiomyography (Gil et al., 2015), anthropometry (Trivers et al., 2014), in general population (Maloney, 2019) and in the physically active individuals (Lockie et al., 2014).

Athletes in team sports such as soccer primarily use their dominant leg for technical actions like ball control, dribbling, passing, and shooting. Consequently, numerous studies have investigated how inter-limb asymmetry relates to bilateral performance in this population, aiming to enhance understanding and inform strength and conditioning practices (Križaj et al., 2019; Beato et al., 2021; Bishop, Coratella, et al., 2021; Fox et al., 2023). These athletes were required to perform activities demanding maximal lower body strength and power exertion, including jumps, sprints, twists, and rapid and frequent changes of direction. While soccer involves diverse motor skills, strength and power-related measures are deemed the most critical for successful play (Wisløff et al., 2004) and consequently the most frequently evaluated. It has been suggested that asymmetries in strength seem to negatively affect sport-specific performance like change of direction, sprinting, cycling and kicking (Ličen and Kozinc, 2023). Additionally, an increasing number of studies underline the importance of evaluating asymmetry in the realm of injury prevention. It has been shown that inter-limb asymmetry and injury risk might be related (Helme et al., 2021).

Within the body of soccer asymmetry studies, female soccer players participated in just a few of them. Considering the existence of gender differences (Haizlip et al., 2015) it is clear that the lack of asymmetry studies involving female soccer players precludes clear information regarding asymmetry and performance association. The lack of studies on high-performance female athletes limits the ability to apply research findings to the real world and consequently practitioners are often failing to maximize the performance potential of females because applying findings observed on male athletes to female athletes may be erroneous (Emmonds et al., 2019). Nevertheless, few published papers showed asymmetry direction appears highly variable (Bishop et al., 2020), task-specific (Raya-González et al., 2021), and reported a negative association between asymmetry and sprinting and jumping performance (Bishop, Read, et al., 2021). These findings emphasize the need for further research in this field.

Therefore, the present study aim was twofold. Firstly, to investigate the associations between different bilateral and unilateral power/strength-related performance tests and TMG-derived parameters. Secondly, to investigate whether the asymmetries in countermovement jump (CMJ) height, isokinetic strength testing (knee flexion and knee extension at 60°/s and 180°/s) and TMG are associated with bilateral CMJ height, squat jump (SJ) height and speed in elite female soccer players.

2 Methods

In the conceptualization phase of the study, we conducted a power analysis using the G*Power (Faul et al., 2007). Based on previous study with similar design (Gil et al., 2015) we expected to find medium correlation between TMG derived parameters and jumping performance (0.5) with power of 0.90 and α = 0.05, two-tailed, which calculated a sample size of 34 participants.

Thirty-five female soccer players (average age: 20 ± 5 years; body height 169.2 ± 6.9 cm; body mass 63.4 ± 7.0 kg; body mass index 22.1 ± 1.4 kg/m^2) members of the Slovenian National Football Team (Tier 4: Elite level) (McKay et al., 2022) were assessed at the beginning of the new 2021/2022 soccer season. They were advised not to have strenuous workouts for at least 48 h before the assessment, which was monitored by the team staff. Before the initial assessment, a brief meeting was held to explain the study protocol in detail where the written consent of each athlete was obtained. Based on data collection performed by physician, all players were physically healthy, without acute pain, and serious lower limb injuries for at least 1 year. All the participants were informed of the study procedures and provided written informed consent prior to participation. All procedures were approved by an institutional Human Research Ethics Committee (approval decision number: 25:2021) and research was conducted according to Helsinki declaration. Procedures.

A cross-sectional cohort study examined neuromuscular performance and limb differences with corresponding asymmetries in elite female soccer players. Athletes arrived at the testing facility at 8 a.m. and abstained from alcohol and caffeine consumption for at least 24 h prior to testing. All measurements were performed in the following order: basic anthropometry, TMG assessment, SJ, CMJ, speed, agility test, and maximal isometric strength. After the TMG assessment, athletes performed a standardized warm-up protocol by an experienced kinesiologist. For all tests, leg dominance was defined as the kicking leg. All athletes were familiar with the study procedures, having undergone the same battery of tests once per year for a minimum of 2 years before they were recruited for the current investigation. These assessments were conducted as part of regular, periodic measurements at the Institute of Sport, Faculty of Sport, University of Ljubljana.Body mass and height were measured using a stadiometer and scale anthropometer (GPM, Model 101, Zurich, Switzerland) to the nearest of 0.1 cm and 0.05 kg, respectively.

The contractile properties of the individual muscles were assessed by the non-invasive TMG method. We measured knee flexor and extensor muscles bilaterally. Therefore, *m.biceps femoris* (BF) assessment was performed while prone at rest at a knee angle set at 5° knee flexion; whereas the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) were measured while supine at rest at a knee angle set at 30° knee flexion. The well-established methodology was used as previously described (Paravlic et al., 2022). Briefly, following an electrically induced isometric twitch, the radial displacement of the muscle belly was recorded at the skin surface using a sensitive digital displacement sensor (TMG-BMC, Ljubljana, Slovenia). The sensor was set perpendicular to the skin normal plane above the muscle belly as recommended previously (Delagi et al., 2011). The rounded (5-cm diameter) self-adhesive cathode and anode (Axelgaard, Aarhus, Denmark) were set 5 cm distally and 5 cm proximally to the measuring point, on all muscles assessed. Electrical stimulation was applied through a TMG-100 System electro stimulator (TMG-BMC d.o.o., Ljubljana, Slovenia) with a pulse width of 1 ms and an initial amplitude of 20 mA. During each measurement, the amplitude was progressively increased by 20 mA increments until there was no further increase in the amplitude of the TMG response (Dm), which was usually accompanied by the maximal stimuli of 110 mA. Rest periods of 30 s were given between each stimulus in order to minimize the effects of fatigue and potentiation. More detailed testing procedures were previously described elsewhere (Paravlić et al., 2017). From two maximal twitch responses, several TMG parameters were calculated, as follows: delay time (Td) as time from an electrical impulse to 10% of the maximal displacement amplitude (Dm); contraction time (Tc) as time from 10% to 90% of Dm; sustain time (Ts) as time from 50% to 50% of Dm; and half-relaxation time (Tr) as time from 90% to 50% of Dm. Additionally, the index representing the velocity of contraction (Vc) was calculated using Eq. 1 (Loturco et al., 2016):

$$Vc = \frac{Dm}{Td + Tc}\ (\text{mm/ms}) \tag{1}$$

Moreover, the TMG proposed the algorithm for calculating the functional symmetries which was implemented in the current investigation was calculated using Eq. 2.

$$\begin{aligned} FS = {} & 0.1\,x\,\frac{MIN\,(AVERAGE\,(TdRF; TdVL; TdVM); TdBF)}{MAX\,(AVERAGE\,(TdRF; TdVL; TdVM); TdBF)} \\ & + 0.8\,x\,\frac{MIN\,(AVERAGE\,(TcRF; TcVL; TcVM); TcBF)}{MAX\,(AVERAGE\,(TcRF; TcVL; TcVM); TcBF)} \\ & + 0.1\,x\,\frac{MIN\,(AVERAGE\,(TrRF; TrVL; TrVM); TrBF)}{MAX\,(AVERAGE\,(TrRF; TrVL; TrVM); TrBF)} \\ & x\,100 \end{aligned} \tag{2}$$

where FS represents a functional symmetry, MIN—the minimum and MAX–the maximum.

A 30-m distance was selected to evaluate sprint performance. Participants performed 2 maximal sprint efforts over the distance of 30 m in an indoor sports hall with a 3-min rest period between trials. The fastest trial was used for further analyses. Players were verbally encouraged to sprint as fast as possible during each trial. Sprint times, and therefore maximal running speed was recorded to 0.001 mm/s accuracy by a laser distance measuring device (Artech LDM 301, Rostock, Germany).

The soccer-specific change of direction test (SSCOD) is recently newly developed agility assessment tool which showed to have high levels of reliability and discriminative validity (Krolo et al., 2020). In brief, a test is performed on the 10 m square field. It starts with the players running with maximal effort to the first cone placed at 1 m distance from the start, following which they need to run at maximal speed in the direction of the second cone placed diagonally (left and right), 3 m away. Then, the players need to kick the ball on the goal with the inside foot and turn back through the starting gate as quickly as possible. All the players were tested on the same pattern and performed two trials for each side, whereas first running in the direction of the cone placed on the left side, and secondly to the right side. The change of direction (i.e., running to the left or right-side placed cone) was predetermined. The time was measured using one pair of electronic timing system sensors (Witty Timing System, MicroGate, Bolzano), with the nearest of 0.1 s, while the average of two trials was taken for further analysis.

Jumping ability was assessed by vertical jump tests, using bilateral force plate (model 9260AA6, Kistler, Winthertur, Switzerland) with Kistler MARS software to record ground reaction force data. Before the actual test a 2–3 warm-up squat jumps, bilateral countermovement jumps (CMJb), and unilateral CMJ (CMJu) with hands placed on the hips were executed, followed by actual maximal jump trials. Test execution was supervised and verbally encouraged by an experienced researcher to improve proficiency in jumping technique. Jumps were repeated after a 60-s rest period, until three valid SJ, CMJb and CMJu jumps were achieved. In total, the number of trials at each jumping condition ranged from three to five. Subjects were instructed and verbally encouraged to maximize their jump height. The depth position during both SJ and CMJ was self-preferred. Jump height was calculated by vertical velocity of the center of mass at take-off. Finally, the jump with the highest jump height was taken for further analysis (Moir, 2008).

Isokinetic strength testing was performed on an isokinetic dynamometer (Biodex 4, Medical System, NY, United States) with the Advantage software. Standard leg attachment was used. The test was performed with the participants in the sitting position, strapped with belts across the chest, pelvis and test leg thigh to minimize body movement and compensation of other muscles. The dynamometer axis of rotation was aligned with the knee's joint axis of rotations using lateral epicondyle as an anatomic mark. The range of motion was 60° (from 90° to 30° of knee flexion with full knee extension being 0°). Before the testing, each subject performed 5 to ten submaximal knee extension and flexion concentric contractions at 60°/s as part of a specific warm-up. The testing procedure consisted of 5 consecutive knee extension and flexion repetitions at 60°/s and 10 at 180°/s. There was a 2-min break between the velocities. Participants were verbally encouraged by the investigator to perform the test as hard and as fast as possible. Visual feedback was provided throughout the test on the dynamometer monitor. The isokinetic torques for the quadriceps and the hamstrings at each angular velocity (60°/s and 180°/s) were first normalized to the subject's body mass. We then calculated the isokinetic H:Q ratios at both angular velocities using Eq. 3.

$$H:Q = \frac{peak\,hamstrings\,torque}{peak\,quadriceps\,torque} \times 100 \tag{3}$$

3 Inter-limb asymmetry analysis

The mean inter-limb asymmetries were computed for CMJu, isokinetic strength, SSCOD test, and TMG variables by using the Eq. 4:

$$Inter - limb\,asymmetry = 100 - \left((MIN\,value) / (MAX\,value) \right) \times 100 \tag{4}$$

4 Statistical analysis

Statistical analyses were performed using SPSS statistical software (version 27.0, IBM Inc, Chicago, United States). All data are presented as mean ± SD. Descriptive statistics were used to summarize player general characteristics and all outcome measures. Normality was confirmed by visual inspection and using the Shapiro-Wilk test. Inter-limb differences were assessed by the Student t-test. Conversely, a Wilcoxon signed rank test was used for the comparison of variables not following a normal distribution. Hedges' g effect sizes (ES) with 95% confidence intervals were calculated to show practical differences between legs and were interpreted as: trivial: <0.20, small: 0.20–0.50, moderate: 0.50–0.80, or large: >0.80 (Lovakov and Agadullina, 2021). The Pearson correlation was used to analyze the relationship between the variables of interest that followed a normal distribution. If otherwise, the correlation was analyzed using nonparametric Spearman's rho. The following thresholds of the correlation coefficient were used to assess magnitude of the relationships analyzed: weak ≤0.35; 0.36≤moderate<0.67; 0.68≤ high <1 (Taylor, 1990). Statistical significance for all analyses was accepted at $p \leq 0.05$.

5 Results

A total of thirty-five players were measured, with the right leg defined as dominant in thirty players. On average, players jumped 29.0 ± 5.1 cm and 30.1 ± 5.8 cm from the CMJb and SJ, respectively, while maximum running speed was 7.7 ± 0.4 m/s.

5.1 Inter-limb comparisons

Table 1 shows comparisons between dominant and non-dominant legs with the resulting asymmetries for all measures assessed. A significant difference (*small* ES = 0.47, p = 0.008) was observed in the soccer-specific change of direction test, where players took less time to complete the test when they changed direction towards the dominant side. In addition, compared to the non-dominant leg, the dominant leg showed greater values for knee extension torque at 60°/s (small ES = −0.43, p = 0.014), peak knee flexion torques at both angular velocities 60°/s (small ES = −0,36, p = 0.038) and 180°/s (small ES = −0.47, p = 0.009), while the HQ peak torque ratio at 180°/s was lower for the dominant leg (small ES = −0.42, p = 0.018). As for the TMG variables, only the contraction time of the VM was shorter on the dominant side (small ES = −0.46, p = 0.011). A detailed inter-limb comparison of the CMJ-derived parameters between dominant and non-dominant legs are presented in Supplementary Table S1.

5.2 The interrelationship between countermovement jump, squat jump, maximum running speed, and different isokinetic peak torque testing parameters

Table 2 shows the correlations between CMJ, SJ, Maximum running speed on 30°m distance (MRS30), and various isokinetic peak torque test parameters performed with dominant and non-dominant legs. For CMJb, significant correlations were observed for most of the variables studied, ranging from weak (r = 0.354, p = 0.037, for dominant leg H/Q at 60°/s) to moderate (r = 0.482, p = 0.005, for dominant knee extension peak torque at 180°/s). For SJ, a

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TABLE 1 Inter-limb comparison of the soccer-specific change of direction test, countermovement jump, squat jump, isokinetic strength and tensiomyography-derived parameters between dominant and non-dominant legs in elite female soccer players.

Variables	Non-dominant leg		Dominant leg		Inter-limb asymmetries (%)		Inter-limb comparison				
Unilateral tests	Mean	SD	Mean	SD	Mean	SD	t or Z value	*p*-value	Hedges's g	LCI	UCI
Agility											
Soccer specific COD test (s)	2.67	0.16	2.61	0.14	4.02	2.59	2.838	**0.008**	0.47	0.12	0.82
Strength and power											
CMJ unilateral (cm)	14.1	3.5	14.3	3.3	8.55	5.59	−0.847	0.397	−0.10	−0.43	0.23
Knee extension peak torque at 60°/s (Nm/kg)	2.68	0.29	2.76	0.27	5.55	4.42	−2.586	**0.014**	−0.43	−0.77	−0.09
Knee flexion peak torque at 60°/s (Nm/kg)	1.36	0.19	1.41	0.20	7.36	6.06	−2.159	**0.038**	−0.36	−0.70	−0.02
HQ peak torque ratio at 60°/s (%)	51.33	7.64	51.04	7.33	6.96	5.56	−0.353	0.726	−0.06	−0.39	0.27
Knee extension peak torque at 180°/s (Nm/kg)	1.86	0.23	1.88	0.23	5.76	3.80	−0.622	0.538	−0.10	−0.43	0.23
Knee flexion peak torque at 180°/s (Nm/kg)	0.99	0.18	1.05	0.20	8.19	7.06	−2.788	**0.009**	−0.47	−0.81	−0.12
HQ peak torque ratio at 180°/s (%)	55.92	8.18	53.30	5.73	8.47	6.03	−2.375	**0.018**	−0.42	−0.76	−0.07
TMG parameters											
Biceps Femoris Tc (ms)	28.64	5.22	28.34	4.96	10.43	8.01	−0.033	0.974	0.07	−0.26	0.40
Rectus Femoris Tc (ms)	29.25	4.10	28.52	3.73	8.23	5.93	−1.245	0.213	0.22	−0.11	0.55
Vastus Lateralis Tc (ms)	20.59	1.74	20.86	1.92	6.57	4.49	−1.097	0.272	−0.15	−0.48	0.18
Vastus Medialis Tc (ms)	24.06	2.31	23.08	2.56	7.64	5.06	−2.539	**0.011**	0.46	0.11	0.81
Biceps Femoris Vc (mm/ms)	0.08	0.03	0.08	0.03	46.44	16.16	0.230	0.819	0.04	−0.29	0.37
Rectus Femoris Vc (mm/ms)	0.13	0.04	0.13	0.04	14.24	11.49	−0.974	0.337	−0.16	−0.49	0.17
Vastus Lateralis Vc (mm/ms)	0.12	0.03	0.12	0.02	12.00	6.58	−1.335	0.191	−0.22	−0.55	0.11
Vastus Medialis Vc (mm/ms)	0.14	0.03	0.15	0.02	9.56	6.68	−0.642	0.525	−0.11	−0.44	0.22
Functional Knee symmetry (%)	83.97	9.33	81.08	7.29	8.21	6.67	−1.933	0.053	0.32	−0.02	0.65

CMJ, countermovement jump; HQ, hamstring to quadriceps peak torque; LCI, lower confidence interval; UCI, upper confidence interval. Bold values represent significant difference.

TABLE 2 Correlation between countermovement jump, squat jump, maximum running speed and different isokinetic peak torque testing parameters performed with dominant (Dom) and non-dominant (Ndom) legs in elite female soccer players.

	CMJb	SJ	MRS30 m	CMJu Ndom	CMJu Dom	SSCOD Ndom	SSCOD Dom
SJ	**.795****						
MRS30m	**.649****	**.710****					
CMJu Ndom	**.837****	**.673****	**.654****				
CMJu Dom	**.776****	**.646****	**.583****	**.901****			
SSCOD Ndom	−0.33	−0.309	**−.521****	−0.264	−0.228		
SSCOD Dom	−0.243	**−.360***	**−.427***	−0.043	0	**.692****	
KET60 Ndom	0.213	0.134	0.193	0.272	0.285	−0.251	0.099
KET60 Dom	0.168	0.167	0.089	0.278	**.375***	−0.106	0.25
KF60 Ndom	**.454****	**.402***	0.313	.412*	**.422***	−0.294	−0.176
KF60 Dom	**.467****	**.493****	**.363***	**.498****	**.531****	−0.016	0.05
KET180 Ndom	**.448****	**.399***	**.524****	**.546****	**.463****	**−.377***	−0.108
KET180 Dom	**.482****	**.345***	**.437****	**.566****	**.588****	−0.329	0.043
KF180 Ndom	**.467****	**.532****	**.563****	**.558****	**.437****	**−.458****	−0.313
KF180 Dom	**.411***	**.402***	0.27	**.419***	**.375***	−0.293	−0.147
HQr60 Ndom	**.354***	**.368***	0.321	0.318	0.256	0.053	−0.142
HQr60 Dom	0.291	0.296	0.187	0.212	0.206	−0.091	−0.267
HQr180 Ndom	0.139	0.225	0.004	0.084	−0.002	−0.092	−0.21
HQr180 Dom	0.234	**.390***	0.303	0.263	0.176	−0.308	**−.389***

Dom, dominant leg; Ndom, Non-dominant leg; CMJb, bilateral countermovement jump; CMJu, unilateral countermovement jump; SJ, squat jump; MRS30 m, Maximum running speed on 30 m distance; SSCOD, soccer specific change of direction test; KET60, Knee extension peak torque at 60°/s; KET180, Knee extension peak torque at 180°/s; KF, knee flexion peak torque; HQr, Hamstring to quadriceps peak torque ratio. Bold values represent significant difference.

significant correlation was also observed, ranging from weak (r = 0.345, p = 0.042, for dominant knee extension peak torque at 180°/s) to moderate (r = 0.532, p = 0.001, for non-dominant knee flexion peak torque at 180°/s). Finally, for the maximal running speed, correlations ranged from slightly moderate (r = 0.363, p = 0.032, for dominant knee extension peak torque at 60°/s) to moderate (r = 0.563, $p < 0.001$, for non-dominant knee flexion peak torque at 180°/s).

5.3 The interrelationship between countermovement jump, squat jump, maximum running speed, and different tensiomyography-derived parameters

Table 3 and Table 4 shows the correlations between CMJ, SJ, MRS30 and various tensiomyography-derived parameters performed with dominant and non-dominant legs. For CMJb, significant correlations were observed only for a few variables studied, ranging from moderate (r = 0.337, p = 0.048, for dominant leg BF Vc) to moderate (r = 0.537, p = 0.001, for non-dominant leg RF Tc). For SJ, a significant correlation was also observed, ranging from weak (r = −0.354, p = 0.037, for non-dominant leg BF Tc) to moderate (r = −0.512, p = 0.002, for dominant leg BF Tc). Finally, for MRS30, correlations ranged from weak (r = −0.345, p = 0.042, for dominant leg VM Tc) to moderate (r = −0.530, p = 0.001, for non-dominant leg BF Tc). A comprehensive presentation of the association between bilateral CMJ-derived parameters and TMG-derived parameters are presented in Supplementary Figure S1, S2.

6 Discussion

The present study investigated associations between different bilateral and unilateral performance-related screening tests. Moreover, we addressed the question, whether the inter-limb asymmetries detected by CMJ, isokinetic strength and TMG are associated with bilateral performance assessed by CMJ, SJ and speed in elite female players. At first, we observed significant inter-limb asymmetries in favor of dominant side for peak torque output in both knee flexion (7.4%) and knee extension (5.6%) isokinetic tasks, as well as VM contraction time (7.6%), and soccer specific agility test (4.1%). On the other side, the H:Q peak torque ratio at 180°/s was significantly greater (8.5%) in non-dominant leg. Considering the "10% rule" suggested by Bishop and colleagues (Bishop, Coratella, et al., 2021), we may conclude asymmetries we found were in line with previous studies (Ruas et al., 2015; Loturco et al., 2019) supporting the fact that inter-limb asymmetries in football players of both sexes, are smaller than the borderline values

TABLE 3 Correlation between countermovement jump, squat jump, maximum running speed and different tensiomyography-derived parameters performed on dominant (Dom) and non-dominant (Ndom) legs in elite female soccer players.

	CMJb	*SJ*	*MRS30m*	BF Tc Ndom	BF Tc Dom	RF Tc Ndom	RF Tc Dom	VL Tc Ndom	VL Tc Dom	VM Tc Ndom	VM Tc Dom
SJ	**.795****										
MRS30m	**.649****	**.710****									
BF Tc Ndom	−0.33	**−.354***	**−.530****								
BF Tc Dom	**−.526****	**−.512****	**−.497****	**.660****							
RF Tc Ndom	**−.537****	**−.387***	−0.223	**.335***	0.29						
RF Tc Dom	**−.459****	**−.425***	**−.406***	**.353***	**.370***	**.667****					
VL Tc Ndom	−0.277	−0.105	−0.133	0.243	0.146	**.486****	**.353***				
VL Tc Dom	**−.350***	−0.198	−0.271	**.527****	**.473****	**.519****	**.535****	**.536****			
VM Tc Ndom	**−.519****	**−.439****	**−.392***	**.492****	**.396***	**.482****	**.432****	**.513****	**.401***		
VM Tc Dom	**−.487****	−0.289	**−.345***	0.291	0.278	0.317	0.243	0.274	0.214	**.637****	
BF Vc Ndom	0.113	0.115	0.076	0.145	0.087	0.072	0.231	0.017	0.024	0.01	0.039
BF Vc Dom	**.337***	0.272	0.219	−0.003	−0.008	−0.269	−0.092	−0.2	−0.146	−0.229	0.056
RF Vc Ndom	**.372***	0.312	0.203	−0.243	−0.058	−0.263	0.017	−0.087	−0.141	−0.311	−0.091
RF Vc Dom	0.321	0.28	0.113	**−.357***	−0.069	−0.201	0.075	−0.157	−0.004	−0.321	−0.004
VL Vc Ndom	0.328	0.241	0.245	−0.228	−0.225	−0.306	−0.023	0.164	−0.166	−0.087	0.029
VL Vc Dom	0.225	0.124	0.096	−0.184	−0.128	−0.241	0.141	0.006	−0.005	−0.292	−0.074
VM Vc Ndom	0.169	0.226	0.179	−0.207	−0.103	−0.065	0.192	0.129	0.046	−0.262	−0.32
VM Vc Dom	0.101	0.196	0.159	−0.202	−0.174	−0.021	0.194	0.133	0.071	−0.101	−0.038

Dom, dominant leg; Ndom, Non-dominant leg; CMJb, bilateral countermovement jump; SJ, squat jump; MRS30 m, Maximum running speed on 30 m distance; BF, Biceps femoris; RF, Rectus femoris; VL, Vastus Lateralis; VM, Vastus medialis; Tc, Contraction time; Vc, Contraction velocity. Bold values represent significant correlation.

proposed (Ruas et al., 2015). Interestingly, although similar asymmetry levels were observed in previous studies recruiting male soccer players (Daneshjoo et al., 2013; Menzel et al., 2013), we found that the preferred kicking leg outperformed contralateral leg in both knee extension and flexion strength task, which is opposite to aforementioned studies recruiting male soccer players (Daneshjoo et al., 2013; Menzel et al., 2013). This phenomenon has been observed elsewhere in female athletes (Risberg et al., 2018; Eustace et al., 2019) and identified as a potential risk factor for a more frequent occurrence of anterior cruciate ligament injuries in female soccer players (Brophy et al., 2010). The mechanics behind this adaptation has been previously described and include factors like anthropometric, physiological and gameplay differences between male and female soccer (Pedersen et al., 2019).

Another interesting observation in current study were variations in force-time strategies between the dominant and non-dominant legs, despite achieving similar jump performance (Supplementary Table S1). Specifically, the non-dominant leg exerted a higher maximal force relative to body weight (183.9% BW vs. 179.3% BW), greater average force (916.1 N vs. 900.6 N), and spent less time in the push-off phase (0.34 s vs. 0.36 s) than the dominant leg. This suggests that athletes may have reached a greater depth position during the CMJ with the non-dominant leg. This could be attributed to biomechanical and neuromuscular differences between the dominant and non-dominant legs which may have importance in

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TABLE 4 Correlation between countermovement jump, squat jump, maximum running speed and inter-limb asymmetries (a) derived from countermovement jump, agility, isokinetic and tensiomyography testing procedures performed with dominant and non-dominant legs.

	CMJb	*SJ*	*MRS30m*	aCMJ	aSSCOD	aKET60	aKFT60	aHQr60	aKET180	aKET180	a HQr180
SJ	**.773****	1									
MRS30m	**.664****	**.705****	1								
aCMJ	−0.283	−0.094	−0.235	1							
aSSCOD	−0.225	−0.242	−0.047	−0.114	1						
aKET60	−0.174	−0.164	−0.202	−0.004	−0.073	1					
aKFT60	−0.265	−0.052	−0.17	0.308	0.006	0.191	1				
aHQr60	−0.13	0.26	0.191	**.420***	−0.079	−0.003	**.412***	1			
aKET180	−0.081	−0.238	−0.247	0.053	0.091	0.287	0.138	−0.113	1		
aKET180	0.122	0.021	−0.069	**.341***	−0.182	−0.006	0.218	−0.181	0.023	1	
aHQr180	0.063	−0.1	−0.188	0.195	−0.276	0.015	0.002	−0.107	.398*	**.549****	1
aBFTc	−0.056	−0.08	−0.298	0.095	−0.208	−0.08	0.097	−0.082	0	0.206	0.236
aRFTc	−0.216	−0.154	−0.227	0.186	0.183	0.268	0.076	0.102	0.231	−0.088	−0.08
aVLTc	**−.419***	−0.286	−0.183	0.138	0.191	0.006	0.152	0.031	0.203	−0.107	0.004
aVMTc	0.037	−0.091	0.016	−0.148	−0.221	0.05	−0.152	**−.346***	0.102	−0.01	0.104
aBFVc	0.069	0.153	0.069	−0.067	0.017	−0.307	−0.01	0.227	−0.208	0.005	0.027
aRFVc	−0.296	−0.272	−0.047	−0.072	0.313	0.033	−0.027	0.113	−0.222	**−.402***	**−.337***
aVLVc	−0.177	−0.326	−0.213	0.265	0.191	0.021	0.003	−0.028	−0.003	0.087	0.178
aVMVc	−0.008	−0.029	0.123	0.133	**−.339***	−0.055	0.06	0.08	−0.002	−0.026	0.203
aFKSTMG	−0.021	−0.094	−0.243	0.147	−0.087	0.174	**.393***	0.055	0.003	0.093	0.004

CMJb, bilateral countermovement jump; SJ, squat jump; MRS30 m, Maximum running speed on 30 m distance; SSCOD, soccer specific change of direction test; KET60, Knee extension peak torque at 60°/s; KET180, Knee extension peak torque at 180°/s; KFE, knee flexion peak torque; HQr, Hamstring to quadriceps peak torque ratio; BF, Biceps femoris; RF, Rectus femoris; VL, Vastus Lateralis; VM, Vastus medialis; Tc, Contraction time; Vc, Contraction velocity; as, asymmetry. Bold values represent significant correlation.

players profiling and identification of athletes who were at risk of sustaining injury (Bishop, Read, et al., 2021; Mitchell et al., 2021; Roso-Moliner et al., 2023). A recent study (Mitchell et al., 2021) reported compromised performance in single-leg CMJ among athletes with a history of injury. This was characterized by significantly reduced eccentric and concentric peak force, lower rates of force development, and a deeper countermovement. Conversely, the players recruited in our study were physically healthy, without acute pain, and free from serious lower limb injuries for at least 1 year before recruitment. Thus, the observed differences in time-force characteristics may result from previous injuries that have been repaired (happened more than a year before the recruitment), or they may represent a risk factor for future injuries, which still warrants further investigation.

Further on, different bilateral and unilateral screening tests showed statistically significant and slightly moderate to large correlation. In detail, a weak to moderate correlation was found between highest height jumped and isokinetic variables, and slightly moderate to large correlation between highest height jumped and TMG-derived parameters. We also found moderate correlation between VL contraction time asymmetry and bilateral CMJ performance. These results support the fact that the isokinetic dynamometry test and the TMG, as well as the corresponding inter-limb asymmetries, are highly variable in indicating performance related to bilateral jumping ability and running speed-related tasks. This has also been shown in the recent study conducted by Loturco et al. (2019). Loturco and colleagues (Loturco et al., 2019) found that CMJ and SJ asymmetry index does not correlate or impair maximal running speed and bilaterally assessed jumping performance in professional female soccer players. The later study also found nonsignificant to slightly moderate significant correlation coefficients between performance tests and bilateral and unilateral vertical jump variables. However, no significant correlations were found between unilateral vertical jump asymmetries and other performance tests were found.

The overall significant, albeit inconsistent, correlations between the diverse performance scores obtained highlight the previously recognized necessity for a multifaceted and thorough diagnostic strategy in female soccer (Loturco et al., 2018; 2019) aiming at examining multiple performance aspects. These are further supported by the nonsignificant asymmetry-performance relationship indicating even the asymmetry evaluation requires multiple approaches. For example, some conflicting evidence found previously illustrated this issue. Namely, Loturco and colleagues (Loturco et al., 2018) found better performances in SJ and CMJ tests were associated with higher asymmetry levels whilst Bishop and colleagues (Bishop, Read, et al., 2021) found greater asymmetries being associated with reduced jump performance. Therefore, it is still unclear whether certain asymmetry parameters inevitably influence bilateral performance evaluated by maximal running speed and jumping performance. Considering the previously stated and the fact that injury types (Cross et al., 2013) and mechanisms (Brophy et al., 2010) differ between female and male athletes, there is need for the development of unique testing procedures sensitive enough for multidimensional purposes, including performance profiling, neuromuscular fatigue and performance monitoring, injury prevention and rehabilitation testing in female soccer players and female athletes in general.

7 Conclusion

The present study added a new knowledge on performance assessment in female soccer players. First, we found significant differences in several performance measures of interest when comparing dominant and non-dominant legs, that may have an important indices for training program optimization and prevention of future injuries. Second, the overall significant, albeit inconsistent, correlations between the diverse performance scores obtained highlight the necessity for a multifaceted and thorough diagnostic strategy in female soccer players. From the results observed it is difficult to choose a single test as a unique screening tool for performance profiling. We believe, it would be valuable to consider the implications of these findings on performance, injury risk, and training strategies, providing a more comprehensive understanding of the biomechanics involved in unilateral jumping movements.

8 Perspectives

The findings of the current study have implications for the training and assessment of elite female soccer players. A comprehensive diagnostic strategy that considers a variety of performance measures, including bilateral and unilateral assessments as well as TMG parameters, is essential for a thorough understanding of an athlete's capabilities. For future perspective, this study suggests that a more extensive longitudinal evaluation with a larger and diverse sample of female soccer players could help establish more robust and generalizable relationships between these performance-related measures. Additionally, examining how these associations evolve over time or in response to specific training interventions may aid in tailoring individualized training programs to enhance performance and reduce the risk of injury.

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 Faculty of Sport (University of Ljubljana, Slovenia, approval decision number: 25:2021). 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

AP: Writing–review and editing, Writing–original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal Analysis, Data curation, Conceptualization. EA: Writing–review and editing. ZM: Writing–review and editing. GV: Writing–review and editing. DS: Writing–review and editing. VH: Writing–review and editing. MP: Writing–review and editing. JV: Writing–review and editing.

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Conflict of interest

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

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2024.1298159/full#supplementary-material

References

Almuzaini, K. S., and Fleck, S. J. (2008). Modification of the standing long jump test enhances ability to predict anaerobic performance. *J. Strength Cond. Res.* 22 (4), 1265–1272. doi:10.1519/JSC.0b013e3181739838

Annett, M. (1972). The distribution of manual asymmetry. *Br. J. Psychol.* 63 (3), 343–358. doi:10.1111/j.2044-8295.1972.tb01282.x

Atabek, H. Ç., Sönmez, G. A., and Yilmaz, I. (2009). The relationship between isokinetic strength of knee extensors/flexors, jumping and anaerobic performance. *Isokinet. Exerc. Sci.* 17 (2), 79–83. doi:10.3233/IES-2009-0337

Beato, M., Young, D., Stiff, A., and Coratella, G. (2021). Lower-limb muscle strength, anterior-posterior and inter-limb asymmetry in professional, elite academy and amateur soccer players. *J. Hum. Kinet.* 77 (1), 135–146. doi:10.2478/hukin-2020-0058

Bell, D. R., Sanfilippo, J. L., Binkley, N., and Heiderscheit, B. C. (2014). Lean mass asymmetry influences force and power asymmetry during jumping in collegiate athletes. *J. Strength Cond. Res.* 28 (4), 884–891. doi:10.1519/JSC.0000000000000367

Binet, J., Lehance, C., Vandenbroek, G., Bury, T., and Croisier, J.-L. (2005). Isokinetic and functional muscle performances among football players: a transversal study. *Isokinet. Exerc. Sci.* 13 (1), 25–26.

Bishop, C., Coratella, G., and Beato, M. (2021). Intra-and inter-limb strength asymmetry in soccer: a comparison of professional and under-18 players. *Sports* 9 (9), 129. doi:10.3390/SPORTS9090129

Bishop, C., Pereira, L. A., Reis, V. P., Read, P., Turner, A. N., and Loturco, I. (2020). Comparing the magnitude and direction of asymmetry during the squat, countermovement and drop jump tests in elite youth female soccer players. *J. Sports Sci.* 38 (11–12), 1296–1303. doi:10.1080/02640414.2019.1649525

Bishop, C., Read, P., McCubbine, J., and Turner, A. (2021). Vertical and horizontal asymmetries are related to slower sprinting and jump performance in elite youth female soccer players. *J. Strength Cond. Res.* 35 (1), 56–63. doi:10.1519/JSC.0000000000002544

Bishop, C., Turner, A., and Read, P. (2018). Effects of inter-limb asymmetries on physical and sports performance: a systematic review. *J. Sports Sci.* 36 (10), 1135–1144. doi:10.1080/02640414.2017.1361894

Brophy, R., Silvers, H. J., Gonzales, T., and Mandelbaum, B. R. (2010). Gender influences: the role of leg dominance in ACL injury among soccer players. *Br. J. Sports Med.* 44 (10), 694–697. doi:10.1136/bjsm.2008.051243

Cross, K. M., Gurka, K. K., Saliba, S., Conaway, M., and Hertel, J. (2013). Comparison of hamstring strain injury rates between male and female intercollegiate soccer athletes. *Am. J. Sports Med.* 41 (4), 742–748. doi:10.1177/0363546513475342

Daneshjoo, A., Rahnama, N., Mokhtar, A. H., and Yusof, A. (2013). Bilateral and unilateral asymmetries of isokinetic strength and flexibility in male young professional soccer players. *J. Hum. Kinet.* 36 (1), 45–53. doi:10.2478/hukin-2013-0005

Delagi, E., Iazzetti, J., Perotto, A., and Morrison, D. (2011). Anatomical guide for the electromyographer: the limbs and trunk. *J. Anat.* doi:10.1093/ptj/86.7.1043

Emmonds, S., Heyward, O., and Jones, B. (2019). The challenge of applying and undertaking research in female sport. *Sports Med. - Open* 5 (1), 51. doi:10.1186/s40798-019-0224-x

Eustace, S. J., Page, R. M., and Greig, M. (2019). Isokinetic strength differences between elite senior and youth female soccer players identifies training requirements. *Phys. Ther. Sport* 39, 45–51. doi:10.1016/j.ptsp.2019.06.008

Faul, F., Erdfelder, E., Lang, A. G., and Buchner, A. (2007). G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav. Res. Methods* 39 (2), 175–191. doi:10.3758/BF03193146

Fox, K. T., Pearson, L. T., and Hicks, K. M. (2023). The effect of lower inter-limb asymmetries on athletic performance: a systematic review and meta-analysis. *PLoS ONE* 18 (6 June), 02869422–e287017. doi:10.1371/journal.pone.0286942

Gil, S., Loturco, I., Tricoli, V., Ugrinowitsch, C., Kobal, R., Cal Abad, C. C., et al. (2015). Tensiomyography parameters and jumping and sprinting performance in Brazilian elite soccer players. *Sports Biomech.* 14 (3), 340–350. doi:10.1080/14763141.2015.1062128

Haizlip, K. M., Harrison, B. C., and Leinwand, L. A. (2015). Sex-based differences in skeletal muscle kinetics and fiber-type composition. *Physiology* 30 (1), 30–39. doi:10.1152/physiol.00024.2014

Heil, J., Loffing, F., and Büsch, D. (2020). The influence of exercise-induced fatigue on inter-limb asymmetries: a systematic review. *Sports Med. - Open* 6 (1), 39. doi:10.1186/s40798-020-00270-x

Helme, M., Tee, J., Emmonds, S., and Low, C. (2021). Does lower-limb asymmetry increase injury risk in sport? A systematic review. *Phys. Ther. Sport* 49, 204–213. doi:10.1016/j.ptsp.2021.03.001

Križaj, J., Rauter, S., Vodičar, J., Hadžić, V., and Šimenko, J. (2019). Predictors of vertical jumping capacity in soccer players. *Isokinet. Exerc. Sci.* 27 (1), 9–14. doi:10.3233/IES-182138

Krolo, A., Gilic, B., Foretic, N., Pojskic, H., Hammami, R., Spasic, M., et al. (2020). Agility testing in youth football (Soccer)players; evaluating reliability, validity, and correlates of newly developed testing protocols. *Int. J. Environ. Res. Public Health* 17 (1), 294. doi:10.3390/ijerph17010294

Lewis, M., Young, W., Knapstein, L., Lavender, A., and Talpey, S. (2022). Countermovement jump variables not tensiomyography can distinguish between sprint and endurance focused track cyclists. *Biol. Sport*, 39, 67, 72. doi:10.5114/biolsport.2022.103572

Ličen, U., and Kozinc, Ž. (2023). The influence of inter-limb asymmetries in muscle strength and power on athletic performance: a review. *Montenegrin J. Sports Sci. Med.* 19 (1), 75–86. doi:10.26773/mjssm.230310

Lockie, R., Callaghan, S., Berry, S., Cooke, E., Jordan, C., Luczo, T., et al. (2014). Relationship between unilateral jumping ability and asymmetry on multidirectional speed in team-sport athletes. *J. Strength Cond. Res.* 28 (12), 3557–3566. doi:10.1519/JSC.0000000000000588

Loturco, I., Gil, S., Laurino, C. F. D. S., Kobal, H. R. R., Abad, C. C. C., Nakamura, F. Y., et al. (2015). Differences in muscle mechanical properties between elite power and endurance athletes: a comparative study. *J. Strength Cond. Res.* 29 (6), 1723–1728. doi:10.1519/JSC.0000000000000803

Loturco, I., Pereira, L. A., Kobal, R., Abad, C. C. C., Rosseti, M., Carpes, F. P., et al. (2019). Do asymmetry scores influence speed and power performance in elite female soccer players? *Biol. Sport* 36 (3), 209–216. doi:10.5114/biolsport.2019.85454

Loturco, I., Pereira, L. A., Kobal, R., Kitamura, K., Ramírez-Campillo, R., Zanetti, V., et al. (2016). Muscle contraction velocity: a suitable approach to analyze the functional adaptations in elite soccer players. *J. Sports Sci. Med.* 15 (3), 483–491.

Loturco, I., Pereira, L. A. R., Abad, K., Cal, C. C., Komatsu, W., Cunha, R., et al. (2018). Functional screening tests: interrelationships and ability to predict vertical jump performance. *Int. J. Sports Med.* 39 (3), 189–197. doi:10.1055/s-0043-122738

Lovakov, A., and Agadullina, E. R. (2021). Empirically derived guidelines for effect size interpretation in social psychology. *Eur. J. Soc. Psychol.* 51, 485–504. doi:10.1002/ejsp.2752

Macgregor, L. J., Hunter, A. M., Orizio, C., Fairweather, M. M., and Ditroilo, M. (2018). Assessment of skeletal muscle contractile properties by radial displacement: the case for tensiomyography. *Sports Med.* 48 (7), 1607–1620. doi:10.1007/s40279-018-0912-6

Maloney, S. (2019). The relationship between asymmetry and athletic performance: a critical review. *J. Strength Cond. Res.* 33 (9), 2579–2593. doi:10.1519/JSC.0000000000002608

Maly, T., Zahálka, F., Malá, L., Hrasky, P., Buzek, M., and Gryc, T. (2013). "Relationship between isokinetic knee strength, sprint and jump performance in young elite soccer players," in *Science and football VII 1st editio*. Editors H. Nunome, B. Drust, and B. Dawson (China: Routledge), 19, 6.

McKay, A. K. A., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., et al. (2022). Defining training and performance caliber: a participant classification framework. *Int. J. Sports Physiology Perform.* 17 (2), 317–331. doi:10.1123/ijspp.2021-0451

Menzel, H.-J., Chagas, M. H., Szmuchrowski, L. A., Araujo, S. R. S., de Andrade, A. G. P., and de Jesus-Moraleida, F. R. (2013). Analysis of lower limb asymmetries by isokinetic and vertical jump tests in soccer players. *J. Strength Cond. Res.* 27 (5), 1370–1377. doi:10.1519/JSC.0b013e318265a3c8

Mitchell, A., Holding, C., and Greig, M. (2021). The influence of injury history on countermovement jump performance and movement strategy in professional soccer players: implications for profiling and rehabilitation foci. *J. Sport Rehabilitation* 30 (5), 768–773. doi:10.1123/JSR.2020-0243

Moir, G. L. (2008). Three different methods of calculating vertical jump height from force platform data in men and women. *Meas. Phys. Educ. Exerc. Sci.* 12 (4), 207–218. doi:10.1080/10913670802349766

Newton, R. U., and Kraemer, W. J. (1994). Developing explosive muscular power: implications for a mixed methods training strategy. *Strength Cond.* 16 (5), 20–31. doi:10.1519/1073-6840(1994)016<0020:DEMPIF<2.3.CO;2

Paravlić, A., Zubac, D., and Šimunič, B. (2017). Reliability of the twitch evoked skeletal muscle electromechanical efficiency: a ratio between tensiomyogram and M-wave amplitudes. *J. Electromyogr. Kinesiol.* 37 (September), 108–116. doi:10.1016/j.jelekin.2017.10.002

Paravlic, A. H., Segula, J., Drole, K., Hadzic, V., Pajek, M., and Vodicar, J. (2022). Tissue flossing around the thigh does not provide acute enhancement of neuromuscular function. *Front. Physiology* 702. doi:10.3389/fphys.2022.870498

Paravlić, H., Pisot, R., and Simunic, B. (2020). Muscle-specific changes of lower extremities in the early period after total knee arthroplasty: insight from tensiomyography. *J. Musculoskelet. Neuronal Interact.* 20, 390–397.

Pedersen, A. V., Aksdal, I. M., and Stalsberg, R. (2019). Scaling demands of soccer according to anthropometric and physiological sex differences: a fairer comparison of men's and women's soccer. *Front. Psychol.* 10 (APR), 762–811. doi:10.3389/fpsyg.2019.00762

Pereira, L. A., Ramirez-Campillo, R., Martín-Rodríguez, S., Kobal, R., Abad, C. C. C., Arruda, A. F. S., et al. (2018). Is tensiomyography-derived velocity of contraction a sensitive marker to detect acute performance changes in elite team-sport athletes. *Int. J. Sports Physiology Perform.* 15 (1), 31–37. doi:10.1123/ijspp.2018-0959

Pišot, R., Narici, M. V., Šimunič, B., De Boer, M., Seynnes, O., Jurdana, M., et al. (2008). Whole muscle contractile parameters and thickness loss during 35-day bed rest. *Eur. J. Appl. Physiology* 104 (2), 409–414. doi:10.1007/s00421-008-0698-6

Raya-González, J., Clemente, F. M., and Castillo, D. (2021). Analyzing the magnitude of interlimb asymmetries in young female soccer players: a preliminary study. *Int. J. Environ. Res. Public Health* 18 (2), 475. doi:10.3390/ijerph18020475

Risberg, M. A., Steffen, K., Nilstad, A., Myklebust, G., Kristianslund, E., Moltubakk, M. M., et al. (2018). Normative quadriceps and hamstring muscle strength values for female, healthy, elite handball and football players. *J. Strength and Cond. Res.* 32 (8), 2314–2323. doi:10.1519/JSC.0000000000002579

Roso-Moliner, A., Lozano, D., Nobari, H., Bishop, C., Carton-Llorente, A., and Mainer-Pardos, E. (2023). Horizontal jump asymmetries are associated with reduced range of motion and vertical jump performance in female soccer players. *BMC Sports Sci. Med. Rehabilitation* 15 (1), 80–10. doi:10.1186/s13102-023-00697-1

Ruas, C. V., Minozzo, F., Pinto, M. D., Brown, L. E., and Pinto, R. S. (2015). Lower-extremity strength ratios of professional soccer players according to field position. *J. Strength Cond. Res.* 29 (5), 1220–1226. doi:10.1519/JSC.0000000000000766

Šimunic, B., Degens, H., Rittweger, J., Narici, M., Mekjavić, I. B., and Pišot, R. (2011). Noninvasive estimation of myosin heavy chain composition in human skeletal muscle. *Med. Sci. Sports Exerc. Sports Exerc. d(February)* 43, 1619–1625. doi:10.1249/MSS.0b013e31821522d0

Taylor, R. (1990). Interpretation of the correlation coefficient: a basic review. *J. Diagnostic Med. Sonogr.* 6 (1), 35–39. doi:10.1177/875647939000600106

Trivers, R., Fink, B., Russell, M., McCarty, K., James, B., and Palestis, B. G. (2014). Lower body symmetry and running performance in elite Jamaican track and field athletes. *PLoS ONE* 9 (11), e113106. doi:10.1371/journal.pone.0113106

Wisløff, U., Castagna, C., Helgerud, J., Jones, R., and Hoff, J. (2004). Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. *Br. J. Sports Med.* 38 (3), 285–288. doi:10.1136/bjsm.2002.002071