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Physical, physiological and technical development in youth athletes

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Evidence of weight loss in junior female judo athletes affects their development

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Purpose: The facile manipulation of body weight in junior athletes has the potential to pose significant risks to their lifelong health. In judo, which is a weight class sport, pre-competition weight loss is widespread even among juniors, but information on the current situation is scarce, especially for female athletes, for whom it is important to provide adequate nutrition and enhance bone mass during the growth period, and the details of the current situation are not clear. Therefore, the purpose of this study was to determine the actual weight loss during the growth period in junior female judo athletes and its subsequent impact on their health.
Methods: The survey was a cross-sectional survey of junior female judo athletes in Japan using a questionnaire. Participants were asked to respond via an online questionnaire about their weight, height, weight loss experience, menstruation, competition results, and other lifestyle.
Results: 51.8% of subjects experienced weight loss for competition during their junior high school years (ages 12–15). Those who experienced weight loss during secondary sexual characteristics were found to be significantly shorter in current height than those who did not ($p < 0.05$). Weight loss during secondary sexual characteristics did not affect current menstrual cycle. There was no significant difference in competition results due to the experience of weight loss during junior high school ($\chi^2 = 4.485$, df = 3, n.s.).
Conclusions: These findings suggest that weight loss during the growth spurt phase may adversely impact normal development. It also suggested that weight loss during the junior high school years may not be a strategy to bring about better competition results. These observations indicate the need for education on appropriate class selection and weight control for junior athletes in weight class competitions.

KEYWORDS

adolescence, female athlete, growth spurt, height, menstruation

1 Introduction

In judo, since the competition performance is likely to depend on the body weight (1), a weight class system is adopted to avoid such inequality, and athletes are required to weigh in and clear a delimited weight range before a match. It is known that the majority of senior judo athletes prefer to compete in a lower weight class than their normal weight and adjust their weight prior to competition by weight loss using gradual or rapid methods (2, 3). Gradual weight loss is achieved by dropping body fat by creating a negative energy balance through increased physical activity and decreased energy intake from food. Rapid weight loss is a weight loss technique in which water and carbohydrates are severely restricted or consumed, and extremely short-term, drastic weight loss is implemented in an attempt to temporarily clear the prescribed weight only at the weigh-in. In particular, rapid weight loss is of concern in terms of its safety aspects, psychological (4–6), decreased immune capacity (7), increased muscle damage (8), and impaired performance (9, 10). Despite all the health risks, rapid weight loss is very prevalent because of the potential for competitive advantage in cases of adequate recovery from post-weigh-in to competition (11). Furthermore, numerous athletes find themselves compelled to rapid lose weight in order to avoid being at a competitive disadvantage (12).

On the other hand, judo is now a sport that is popular among people of all ages (13), and international competitions for juniors are held every year. In most cases, weight limits are set for junior competitions as well, and, like senior judo athletes, they must weigh in and clear the weight limits prior to competition. Berkovich et al. reported that many (74%) of junior athletes experienced rapid weight loss before the age of 13 (14), indicating that even juniors practice weight adjustment for competition as a common practice it can be seen that. In addition, since losing a moderate amount of body fat in preparation for competition improves instantaneous force and other aspects of judo performance (15), weight adjustment is a fundamental aspect of athleticism, but junior athletes differ greatly from senior athletes in both mental and physical aspects. Weight loss (pressure to lose weight), such as weight manipulation and food restriction, is a risk factor for eating disorders (16, 17) and is also known to increase the risk of injury occurrence (18) Normally, children are at a time when nutritional accumulation is important for tissue growth. Even if it is gradual weight loss, going through weight loss with an immature body and mind is not only a transitory increase in burden, but also a risk to lifelong health.

Specific discussions and actions have been slow to address this widespread manipulation of junior athletes' body weight to compete. This may be due to the lack of research to elucidate the circumstances surrounding junior judo athletes and the accumulation of scientific evidence for the effects of subsequent health conditions. Little is known about the current status of weight loss and its effects specifically on female junior athletes (19). For female athletes, adequate hormone production during the growth period is important for the acquisition of sufficient bone mass and subsequent reduction of health risks (20). And the higher incidence of eating disorders compared to males should also be fully noted (21–23).

Therefore, this study was conducted with the aim of understanding the status of weight loss among Japanese junior female judo athletes during their developmental stages (elementary school, junior high school, and high school), and to clarify their past weight loss experiences and the effects of weight loss on their current development.

2 Material and methods

2.1 Research design

This survey was a cross-sectional study using an online questionnaire.

2.2 Subjects

In Japan, a system of school-based club activities has been established since around 1,880, and it was assumed that most athletes registered with the All Japan Judo Federation belonged to judo clubs in schools in Japan. Therefore, the target population was high school female judo players who belonged to judo clubs in high schools in Japan. Requests for participation in the questionnaire were extended to schools at all levels of competition, ranging from beginners to participants in national tournaments. The Japanese grade and age divisions are 6–12 for elementary school students, 12–15 for junior high school students, and 15–18 for high school students.

2.3 Survey period

The questionnaire was operational from January 6 to February 28, 2023.

2.4 Questionnaire request and methodology

The survey was conducted in an online format (Google Forms: Google LLC). Letters were mailed to 417 schools in Japan that were thought to have high school female judo players based on tournament lists of high school judo tournaments held in Japan over the past two years that were available on the Internet and on each school's website. The letters consisted of a request letter and a printed QR-coded survey link. After mailing the letters to each school, we asked each prefectural judo federation to disseminate the questionnaire and promote its collection.

2.5 Questionnaire contents

The survey encompassed inquiries regarding current habits and past experiences. The questionnaire consisted of (1) Basic information: grade, height, weight, weight class, results of elementary, junior high, and high school (Top 4 or more in the national competition, Participation in the national competition, Participation in the regional tournament, and Results not meeting the above criteria) (2) Current eating habits (3) Weight management (4) Sleeping time (5) Practice time (6) Past weight loss experience (7) Menstruation-related (age at menarche, current menstrual cycle, and menstrual symptoms).

All questions were administered in a recall method that relied on the respondent's memory. The questionnaire was developed with reference to several content areas. Specific content and considerations are listed next. Basic information was obtained from previous studies (24, 25). Competition results were combined for both individual and team competitions, and subjects were asked to select the best competition results. The Dietary Variety Square (DVS) (26, 27) developed by Kumagai was used to assess current eating habits. Subjects were asked to indicate their weekly frequency of consumption of 10 food groups: meat, seafood, eggs, milk, soy products, green and yellow vegetables, seaweed, fruits, potatoes, and fats and oils. The total score represents the food intake diversity, with "eat almost every day," received 1 point and "eat once every 2 days," "eat once or twice a week," and "rarely eat" received 0 point. The distribution of scores is from 0 to 10. The higher the score, the better the diversity of food intake. Weight management was created by referring to a previous study (25) for the options regarding information on consultants. Responses were made in a multiple-response format. Sleep time was taken from the Pittsburgh Sleep Quality Index (PSQI) up to question 4, which was differentiated from bedtime, and respondents were asked to specify the time they were actually asleep. The practice time question was asked with reference to previous studies (24, 25), distinguishing between weekdays and non-school days. "Weight loss" was defined as "intentional weight loss for the purpose of competing in a tournament, occurring within the period from one month before to the day of the competition." This definition included cases where the weight loss process started just a few days before the competition. And respondents were asked to indicate whether they had or had not lost weight in each of the elementary, junior high, and high school categories. Menstruation-related data were collected to examine the proportion of amenorrhea. Respondents were asked whether they had normal menstruation (approximately every month) or no menstruation. If they had no menstruation, they were presented with options to classify it as oligomenorrhea (irregular but within 3 months), secondary amenorrhea (irregular but between 3 and 6 months, or irregular and absent for more than 6 months), or Amenorrhea (no menstruation yet). Menstrual symptoms were evaluated using the Menstrual Distress Questionnaire (MDQ), consisting of 47 questions concerning physical and emotional changes associated with the menstrual cycle, in which participants report the degree of their symptoms on a scale of 0, 1, 2, or 3 per question. Higher scores indicate more intense symptoms. In this survey, respondents were asked to focus on symptoms during menstruation.

2.6 Questionnaire and analysis procedures

Figure 1 illustrated the overall grouping at the time of questionnaire administration and analysis. Focusing on the junior high school years, when the majority of the participants had experienced weight loss, the participants were divided into two groups: those who had experienced weight loss in junior high ($n = 247$) and those who had not experienced weight loss ($n = 190$). The current height, competitions result at that time, and current menstrual status were then compared.

2.7 Ethical consideration

Participation in this study was voluntary for the subjects. The printed text of the survey QR code and the start page of the online survey explained the purpose, content, and methods of the study, how the data will be stored, and that the data will be compiled, analyzed, and published in such a way that individuals cannot be identified. Participants voluntarily indicated their consent to participate and agreed to have their data analyzed. This study was conducted with the approval of the Toin University of Yokohama Ethics Committee (Approval No. I-66).

2.8 Statistical analysis

The obtained data were presented as mean ± standard deviation or value (percentage). The normality of the data was assessed using the Kolmogorov-Smirnov test. An unrepeated two-way analysis of variance (group × weight class) was conducted for height, where normality was observed, and a t-test was performed for MDQ score. For the diversity of food intake, where normality was not observed, the Mann-Whitney U test was employed to examine differences in score distribution, and the Kruskal-Wallis test was used to analyze differences in age at menarche between groups. The chi-square test was utilized to compare proportions between groups regarding weight loss experience in junior high school in relation to competition results and current menstrual cycle status. Relationships between variables were examined using Pearson's correlation analysis. Statistical processing was performed using SPSS ver. 29.0.1.1 (IBM Corporation). The respective statistical significance level was set at less than 5%.

3 Results

3.1 Valid responses

The total number of responses obtained for this study was 512, of which 477 were valid responses (valid response rate: 93.16%).

3.2 Subjects attributes and characteristics

The total number of respondents was 211 high school 1st-year students (44.2%), 193 high school 2nd-year students (40.6%), and 73 3rd-year students (15.3%). The distribution of the subjects' weight classes (i.e., the classes they will compete in the next

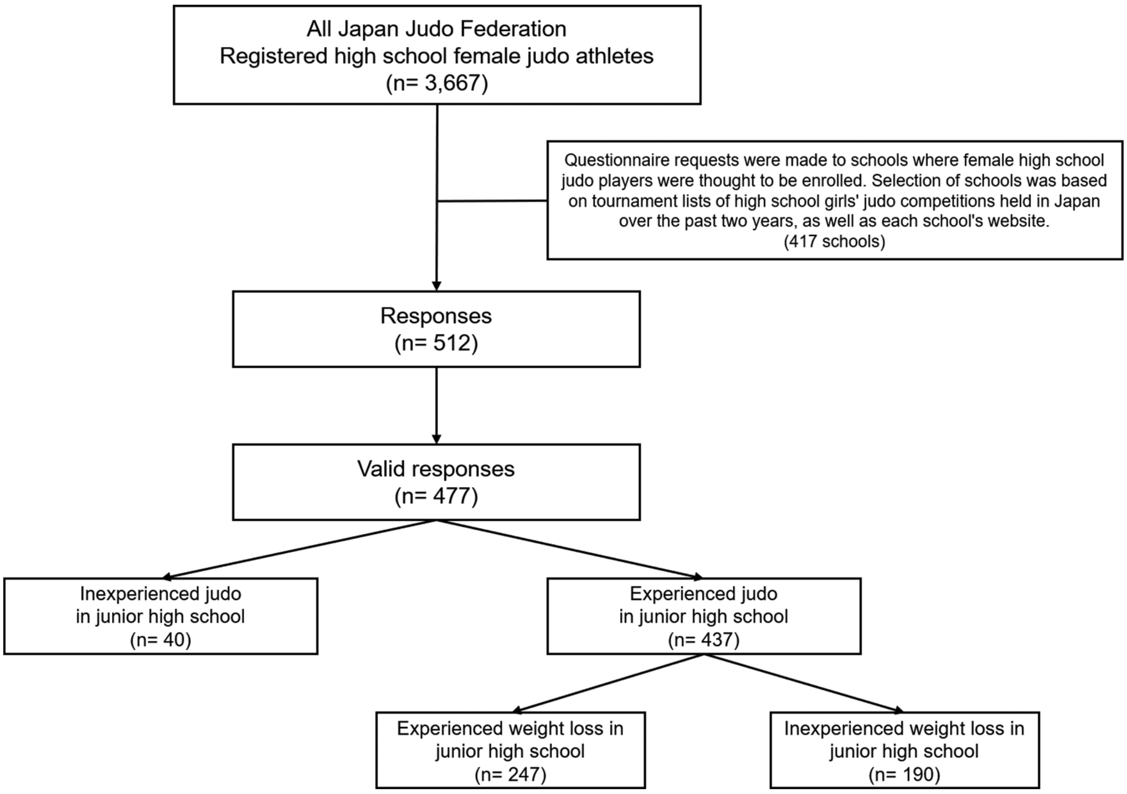

FIGURE 1
Questionnaire and analysis procedure.

competition) was as follows: 48 kg class: 82 (17.2%), 52 kg class: 95 (19.9%), 57 kg class: 109 (22.6%), 63 kg class: 79 (16.6%), 70 kg class: 48 (10.1%), 78 kg class: 33 (6.9%), 78+kg weight class: 31 (6.5%). The current weight of all ($n = 477$) was 60.5 ± 12.2 kg Current height was 158.9 ± 5.6 cm.

3.3 Weight loss experience

Figure 2 showed the percentage of subjects who had experienced weight loss in the past. More than 50% of the subjects had experienced weight loss as junior high school students.

3.4 Relationship between weight loss in junior high school and height

A comparison of current height based on the presence or absence of weight loss during junior high school revealed significant differences in height based on the factor of presence or absence of weight loss among subjects in the 48 kg, 52 kg, 57 kg, and 63 kg weight classes, with the group that experienced weight loss during junior high school being significantly shorter than the group that did not (Figure 3). No such differences were found in the 70 kg, 78 kg, and 78 kg + weight classes. Significant differences in height were found among the seven weight classes ($p < 0.01$), and the heavier the weight class, the taller the average height tended to be.

3.5 Effect of junior high school weight loss experience on competition result

A comparison of the competition results at that time between the group that experienced weight loss in junior high school and the group that did not show any significant difference ($\chi^2 = 4.485$, df = 3, n. s.) (Table 1).

TABLE 1 Weight loss experience in junior high school and competition results at that time.

	Experienced weight loss group *n* (%)		Inexperienced weight loss group *n* (%)	
Top 4 or more in the national competition	17	(6.9)	12	(6.3)
Participation in the national competition	64	(25.9)	51	(26.8)
Participation in the regional competition	75	(30.4)	42	(22.1)
Results not meeting the criteria above	91	(36.8)	85	(40.3)
Total number	247		190	

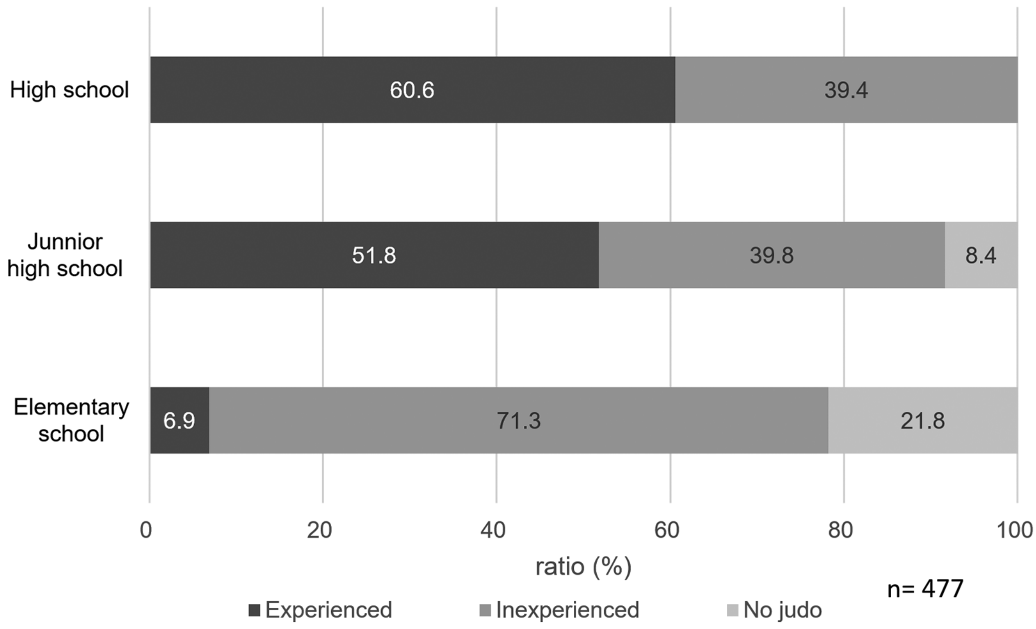

FIGURE 2
Percentage of elementary, junior high, and high school students who have experienced weight loss. "Experienced" indicates those who experienced weight loss, "Inexperience" indicates those who did not experience weight loss, and "No judo" indicates that they did not experience judo at the time.

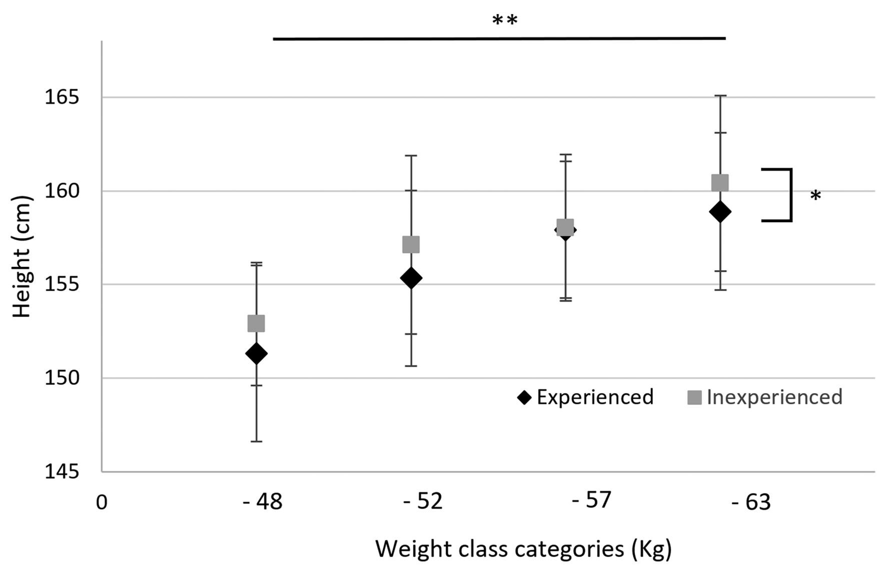

FIGURE 3
Difference between with and without weight loss in junior high school and current height.

3.6 Age at menarche, current menstrual cycle and associated menstrual symptoms

The age at menarche for all subjects was 12.21 ± 1.45 years ($n = 475$), with the age at menarche for each group detailed in Table 2. The current menstrual cycle distribution among all subjects was as follows: approximately 1 month for 338 (70.9%), irregular but within 3 months for 114 (23.9%), irregular but between 3 and 6 months for 19 (4.0%), irregular and absence for more than 6 months for 4 (0.8%), and not yet menstruated was reported by 2 subjects (0.4%). Comparisons were made between groups based on whether they had experienced weight loss during junior high school within the categories "approximately 1 month", "irregular but within 3 months", and "irregular but between 3 and 6 months", where comparisons were possible and no significant differences were found ($\chi^2 = 0.700$, df = 2, n.s.).

TABLE 2 Information on the age at menarche of the subjects.

Weight class categories	All	−48 kg	−52 kg	−57 kg	−63 kg	−70 kg	−78 kg	78 + kg	P value
All subjects	12.21 ± 1.45 (n = 475)	12.57 ± 1.57 (n = 81)	12.47 ± 1.46 (n = 95)	12.29 ± 1.34 (n = 108)	12.15 ± 1.47 (n = 79)	12.00 ± 1.35 (n = 48)	11.42 ± 1.10 (n = 33)	11.52 ± 1.34 (n = 32)	**
No judo	12.00 ± 1.45 (n = 40)	12.00 ± 1.61 (n = 10)	12.56 ± 1.83 (n = 9)	11.92 ± 1.07 (n = 13)	11.67 ± 1.25 (n = 3)	11.75 ± 0.43 (n = 4)	0.00 ± 0.00 (n = 0)	10.00 ± 0.00 (n = 1)	–
Played Judo	12.23 ± 1.45 (n = 435)	12.65 ± 1.55 (n = 71)	12.47 ± 1.41 (n = 86)	12.34 ± 1.37 (n = 95)	12.17 ± 1.47 (n = 76)	12.02 ± 1.41 (n = 69)	11.42 ± 1.10 (n = 33)	11.57 ± 1.33 (n = 30)	**
Experienced weight loss	12.39 ± 1.41 (n = 246)	12.63 ± 1.54 (n = 48)	12.52 ± 1.44 (n = 61)	12.32 ± 1.33 (n = 59)	12.46 ± 1.40 (n = 41)	12.38 ± 1.27 (n = 16)	11.40 ± 0.80 (n = 15)	11.83 ± 0.90 (n = 6)	n. s.
Inexperienced weight loss	12.02 ± 1.49 (n = 189)	12.70 ± 1.57 (n = 23)	12.32 ± 1.32 (n = 25)	12.36 ± 1.42 (n = 36)	11.83 ± 1.48 (n = 28)	11.82 ± 1.44 (n = 28)	11.40 ± 0.80 (n = 18)	11.50 ± 1.41 (n = 24)	*

"No judo" and "Played judo" based on judo experience in junior high school.
*p < 0.05, **p < 0.01, n. s.: not significant.

TABLE 3 Comparison of the distribution of diversity scores of current food intake in the experienced and inexperienced weight loss groups.

Score	0	1	2	3	4	5	6	7	8	9	10	Mean ± SD
Experienced weight loss group (n = 247)	10.9	13.0	13.8	11.7	13.8	12.6	9.7	4.0	5.3	1.2	4.0	3.7 ± 2.6 point
Inexperienced weight loss group (n = 190)	6.8	7.9	11.6	16.3	16.8	11.6	8.9	5.8	3.2	4.7	6.3	4.3 ± 2.7 point

The numbers in the table corresponding to scores 0–10 in the SCORE are percentages (%). Based on Mann-Whitney U-test.

Due to the small sample sizes, the categories "irregular and absence for more than 6 months" and "not yet menstruated" were not included in the analysis.

Comparison of MDQ scores showed no difference based on weight loss experience in junior high school, and menstrual MDQ scores were only significantly correlated with sleep duration in the past month (r = 0.10, p = 0.04, n = 475).

3.7 Lifestyle of the subjects

The subjects current practice time on weekdays was 168 ± 47 min, and on non-school days 212 ± 74 min. The average sleep duration over the past month was 396 ± 58 min.

The diversity score of current food intake, where a higher score indicates a better diversity of food intake, was found to be significantly lower in the group that experienced weight loss in junior high school compared to the group that did not experience (3.7 ± 2.6 vs. 4.3 ± 2.7 point, p = 0.04) (Table 3).

3.8 Weight management consultants

Figure 4 showed the sources of information on eating habits and weight management methods. The most common source was family (57.4%).

4 Discussion

The aim of this study was to ascertain the weight loss status of Japanese junior female judo athletes during their developmental stages (elementary school, junior high school, and high school), and to elucidate the effects of weight loss on their development. The survey results revealed that the majority of first- through third-year high school students who participated in the study had experience weight loss during their junior high school years. Furthermore, the findings suggested that weight loss during junior high school, a period characterized by the onset of growth spurts and critical nutritional requirements, may adversely affect bone development. This represents a novel discovery, as no previous reports have addressed the reality of weight loss among junior judo athletes in Japan. And it is imperative that appropriate measures be implemented to address these findings.

In aesthetic sports for females, among many other sports, previous studies have demonstrated that intense exercise and lack of energy during adolescence inhibit bone growth and prevent full height gain (28, 29). The present study indicates that a similar phenomenon was observed with weight loss in judo athletes. First, in subjects belonging to the 48 kg, 52 kg, 57 kg, and 63 kg weight classes, which are lightweight to medium weight classes, the current height was significantly shorter in the group that had experienced weight loss compared to the group that had not experienced weight loss in junior high school (Figure 3). In general, weight loss in martial arts is often achieved by maintaining a negative energy balance (2, 30). On the other hand, normal development in humans is achieved by adequate nutritional supplementation (31, 32). In particular, with regard to height growth, it is known that adequate nutrition and accompanying adequate hormone secretion are essential during the period before height growth stops due to complete fusion of the epiphyseal line, roughly around age 15 in females (31). The results of this study suggest that the one-month or shorter weight loss for judo competitions in junior high school, or the awareness and behavior of trying to maintain weight on a daily

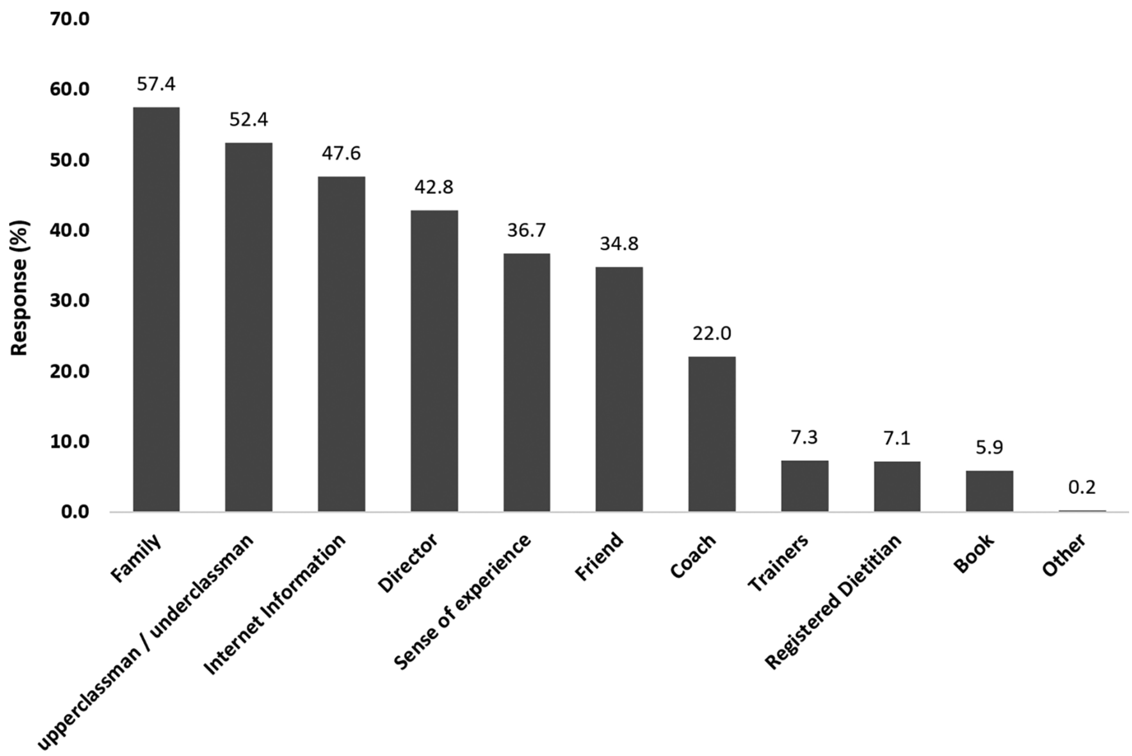

FIGURE 4
High school female judo athletes current weight advisors. Multiple responses were allowed.

basis despite the growth period, were factors that inhibited satisfactory bone growth for these females.

In the 70 kg, 78 kg, and 78 kg + weight classes, no height difference was observed between with and without weight loss. These results corroborate our previously stated hypothesis. Examining the age of menarche among respondents in this study by weight class revealed differences in the age of menarche across classes, with heavier weight classes associated with lower ages of menarche (Table 2). In general, women experience a rapid increase in the secretion of female hormones from around 8–9 years of age to 17–18 years of age, the appearance of secondary sexual characteristics, and rapid growth in height, followed by menarche. Menarche occurs 6 months after reaching "maximum height velocity (PHV)," when bone formation proceeds rapidly (33). Participants in this study experienced menarche approximately between the ages of 12 and 13 in the 48 kg, 52 kg, 57 kg, and 63 kg weight classes, while menarche occurred approximately between the ages of 11 and 12 in the 70 kg, 78 kg, and 78 kg + weight classes (Table 2). This difference in age at menarche is considered to represent a difference in the timing of rapid height growth. Among the heavyweight class athletes, most of them had already passed the period of maximum height velocity (PHV) even if they experienced weight loss within the age of 12∼15, which is the age of Japanese junior high school students, and it is possible that this did not have a significant effect on their current height. In addition, heavyweight class athletes generally have more body fat mass compared to lightweight and middleweight athletes (34, 35). Thus, it is possible that weight class athletes have a large amount of body fat reserves and that even if they reduced their food intake for weight loss, they were able to achieve weight loss while ensuring that they had enough nutrients for growth and did not have a significant impact on their growth. While we were unable to examine weight class changes from junior high school to high school in this study, junior high school students belong to the 40 kg, 44 kg, 48 kg, 52 kg, 57 kg, 63 kg, 70 kg, and 70kg + weight classes, while high school students belong to the 48 kg, 52 kg, 57 kg, 63 kg, 70 kg, 78 kg, and 78kg + weight classes. Considering the positive correlation between weight class and height for both junior high school students (34) and high school students, it is thought that the weight class an individual belonged to in junior high school and high school was generally similar, possibly dependent on the skeletal structure they were born with.

This is not to say that weight loss is acceptable for junior athletes based on their individual physique and growth level. The underlying reason for weight loss is to increase the probability of winning a tournament. However, when evaluating their best competition results in junior high school, there was no discernible difference in tournament outcomes between those who underwent weight loss and those who did not (Table 3). The results of this study suggest that the subjects' weight loss in junior high school may not have been strategic, scientific, and well-considered. In the present study, the menstrual cycle and menstrual symptoms, which are influenced by the nutritional intake, did not differ depending on whether the subjects had experienced weight loss in junior high school or not, suggesting that the intensity of symptoms may be influenced by current lifestyle habits. However, our data revealed a tendency toward delayed onset of menarche among individuals who had participated in judo during junior high school (Table 2). Notably, both women who had not experienced menarche by the time they reached high school were affiliated with the group that had engaged in judo during junior high school. The phenomenon of female athletes exhibiting delayed menarche compared to the general female population has been underscored in numerous studies (36, 37). For female's bodies, strenuous exercise is considered to have no small effect on the maintenance of reproductive development. Adding to this the burden of intentional undernutrition is undesirable. To begin with, it is important that children enjoy sports and compete in a healthy development (38, 39). The way they spend their growing years and their diet have a significant impact on future reproductive function, bone, muscle, and brain development (40–42). Therefore, weight manipulation strategies such as weight loss warrant special attention. Repeated weight loss can cause a decrease in basal metabolism and increase the likelihood of obesity in the future (43–46). And bone formation during school age and young adulthood is crucial for maintaining healthy bones throughout adulthood and beyond (47). Hence, it is very important that strengthening of children with promising futures also be done carefully and appropriately based on their stage of growth.

Note that because the questionnaire was designed to be answered from past memory, we did not use a detailed question focusing only on rapid weight loss, such as a weight loss of 5% or more in one week. The combat sports-specific rapid weight loss techniques that have been noted as generous health risks in senior athletes are probably prevalent in juniors (14), and special effects could also be observed if the number of experiences and actual weight loss ranges were closely examined and investigated.

Suggestions for addressing the current situation were derived from the data of this study. A diverse intake of food groups is typically essential to achieve adequate nutritional balance (48, 49). Scores indicating such food intake diversity were lower in the group that experienced weight loss during junior high school in this study compared to the group that did not undergo weight loss (Table 3). This suggests that the group that experienced weight loss during junior school may have previously lacked opportunities for nutrition education and environmental preparation in meal settings. In addition, it was found that the majority of the subjects would rely on family members and supervision, with very few relying on a nutrition specialist, a dietitian, as an advisor for diet and weight management (Figure 4). Therefore, addressing this issue may necessitate nutrition education aimed at promoting healthy eating habits, as well as education on the concept of appropriate weight class selection and weight control for children. This education should involve not only the individuals themselves but also their family members and supervisors.

In Japan, a measure was taken to abolish national judo tournaments for elementary school students in 2022, due to concerns about excessive coaching of children, such as prioritizing victory (50). However, before this problem becomes more serious, another comprehensive action/policy is needed by the association to address the problem. In terms of Japanese junior high school girls, weight gain of about 3–4 kg per year is usually desirable (51). Therefore, for athletes, especially those in the lightweight to middleweight classes whose height growth was affected this time, to compete in the same class for three years in junior high school would mean that they are competing against normal growth. Children should eat according to their appetites without fear of weight gain. It is not in our budget to have a dietitian on every team in the country. However, nutrition education, which has been limited to top athletes, could be improved by creating new materials and disseminating information widely, or by incorporating lectures on the concept of weight loss and other topics into leadership training sessions. Another possible measure would be to require athletes to submit a plot of their growth curves at the time of competition.

This study has limitations. First, this study was based on data that relied on the recall of survey respondents, not actual measurements. Also, because it is a cross-sectional study, it is not possible to distinguish whether the exposures occurred before or after the observed results. Nonetheless, our study's strength lies in obtaining over 500 responses (Figure 1). However, the population was not randomly selected from the 3,667 registered female high school student athletes of the All Japan Judo Federation in 2022 (52) which is considered the population size, using a rigorous methodology.

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 Toin University of Yokohama Ethics Committee. 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.

Author contributions

EY: Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Writing – original draft, Writing –

review & editing. HH: Conceptualization, Data curation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing. TS: Conceptualization, Data curation, Funding acquisition, Resources, Writing – review & editing. KK: Funding acquisition, Resources, 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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Norwegian male U14 soccer players have superior running capacity compared to Icelandic players

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The organisation and development strategies of youth soccer differ between Norway and Iceland. Whether this affect physical capacity is unknown. Thus, the first aim of the present study is to compare physical capacity between players from Iceland and Norway. Secondary aim is to assess associations between biological maturity and physical capacity in the Icelandic players since an association previously has been shown among the Norwegians. There were 48 U14 players from Iceland included and 103 players from Norway. Bone age (BA), measured with left-wrist x-ray, was used as an indicator of biological maturity. To measure physical capacity, 40 metre (m) linear sprint, standing long jump (SLJ), countermovement jump (CMJ), the Yo-Yo intermittent recovery test (IR1-test) and a maximal oxygen uptake test (VO_{2max}) were used. Training load was assessed by questionnaire. The results showed that the Norwegian players ran faster (5.90 ± 0.38 vs. 6.37 ± 0.44 s, $p < .001$), had better intermittent endurance capacity ($1{,}235 \pm 461$ vs. 960 ± 423 m, $p < .001$) and higher VO_{2max}, (60.3 ± 6.5 vs. 54.8 ± 5.3 ml·kg^{-1}·min^{-1}, $p < .001$) than the Icelandic players. The players from Norway reported a higher number of weekly organised soccer training hours than the Icelandic. We also found significant correlations between BA and performance on 40 m linear sprint ($r = -.566$, $p < .001$), SLJ ($r = .380$, $p = .008$) and CMJ ($r = .354$, $p = .014$) among the Icelandic players. Moreover, no correlations were found between BA and VO_{2max} or intermittent endurance capacity. In conclusion, the Norwegian players ran faster and had better VO_{2max} and intermittent endurance capacity than the Icelandic players. Biological maturity level was associated with speed and jumping performance in U14 soccer players in Iceland, but not with VO_{2max} or intermittent endurance capacity. Findings indicate that more research is needed to investigate the influence of different organisation and structure of youth soccer between the two countries on physical capacity.

KEYWORDS

youth athletes, Iceland, Norway, physical performance, biological maturity, selected and deselected players

1 Introduction

Soccer requires players to possess physical, technical, and tactical capabilities (1) due to its complexity. Despite the goal of developing successful soccer players at the elite senior level, the organisation and development strategies in youth soccer differ between countries (2–4). To succeed at the elite level, speed, intermittent endurance capacity and aerobic capacity at high level are required (5–9). The growth, biological maturity and physical capacity of male youth soccer players have received great attention in the literature (10–15). However, it remains unclear how various organizational and developmental strategies in youth soccer impact the development of physical capabilities among young athletes.

Both in Norway and Iceland, soccer is the most popular sport among children and youth. Players from both countries usually train with their local soccer club on teams with their schoolmates until the age of 13. After that age, the organisation differs between the countries. In Iceland, there is no strict differentiation between grassroots and elite youth soccer and the opportunity to join local soccer clubs is available for all youth soccer players regardless of their skills or training backgrounds, meaning that players at different levels are training together. The soccer clubs in Iceland do not have a traditional soccer academy for talent development, according to definitions from the Fédération Internationale de Football Association (FIFA) (16). Unlike in Iceland, most elite clubs in Norway recruit talented youth players from local soccer clubs to their academies at the age of 13–15 years, meaning that players at highest level train and play matches together as suggested by FIFA. Despite different organisational and developmental strategies for youth soccer, both Iceland and Norway have a strong passion for soccer and have achieved notable success on the international stage, making them interesting subjects for comparison. In 2023, both Iceland and Norway qualified for the male European U20 championship, showing that both countries have national junior teams at elevated levels.

Bone age (BA) is an important marker of biological maturation, in other words, puberty. In youth athletes, physical capacity is influenced by puberty, making talent identification and development challenging. Several studies have shown that biological maturity level is associated with physical capacities, indicating that more mature youth players have a physical advantage compared to their less mature peers (17–22). While the relationship between biological maturation and physical capacity has been established among Norwegian soccer players, it remains unexplored among Icelandic players. Thus, it is imperative to acknowledge the role of biological maturation when comparing physical capacities across different populations.

Comparing physical capacity among youth players from two countries with distinct soccer traditions is interesting, despite their small populations. Moreover, a comparison of physical capacities among youth soccer players from two different Nordic countries is lacking in the current literature. Based on current knowledge, the first aim of this study was to compare physical capacity between 14-year-old soccer players from Norway and Iceland. Considering the notably distinct structures and organization of youth soccer in Norway and Iceland, our hypothesis posits that the physical capacities of 14-year-old soccer players from these two Nordic countries would differ. Secondly, we aimed to assess the association between biological maturity and physical capacity in 14-year-old Icelandic soccer players. Our second hypothesis is to confirm the association between biological maturity and physical capacity in 14-year-old Icelandic soccer players as have been shown in the Norwegian players.

2 Materials and methods

The present study was a collaboration between researchers at the University of Iceland, Reykjavik, Iceland, and Western Norway University of Applied Sciences, Bergen, Norway. The data included in this study for the U14 players in Norway was collected in June 2018 as part of a longitudinal research project examining factors related to talent development in youth soccer. The results from the Norwegian sample have previously been published for other purposes (19, 20, 23). Data from Iceland was collected from February to May 2021. All tests were conducted indoors with experienced testing personnel. The same test protocol was used in both countries.

2.1 Participants

In total, 151 U14 male soccer players were included in this study. The Norwegian players ($n = 103$) were recruited from seven local U14 soccer teams. Among the Norwegian players, 80 were selected to local academy teams before the U14 season, whereas 23 played on lower-level teams, defining them as deselected players. The Icelandic players ($n = 48$) were recruited from two local U14 soccer clubs. Since there are no academies in Iceland, both teams included players at all levels.

Both the National Bioethics Committee of Iceland (VSN-19-206) and the Regional Committee for Medical and Health Research Ethics in Norway (2017/1731) approved the study, and the study was conducted in accordance with the Helsinki Declaration. Because players were under the legal age of consent, both the players and their parents gave written informed consent for participation. Results were treated anonymously for all participants.

2.2 Anthropometric data

Anthropometric measurements included height and weight. Height was measured with a stadiometer (Seca 206 and Seca 217, Hamburg, Germany). Measurements were performed barefoot using standard procedures. In Norway, body weight was assessed with an eight-polar bioimpedance method using multifrequency current (InBody^{TM} 720, Biospace Co.). In Iceland, body weight was assessed using a digital weight scale (FG-150KAL, A&D Company, limited).

2.3 Physical tests

In Norway, 40 m linear sprint, standing long jump (SLJ) and the Yo-Yo intermittent recovery test (IR1-test) were performed on the first test day, whereas countermovement jump (CMJ), and maximal oxygen uptake (VO_{2max}) were assessed on the second test day. The same order of tests was completed in Iceland, except for an additional test day for the IR1-test for practical reasons. The players were wearing t-shirts, along with shorts and indoor sports shoes during the tests.

2.4 40-m linear sprint

A 40 m linear sprint test was conducted to measure the player's speed. All players conducted a standardized 30-min warm-up protocol before the test, led by a physical trainer. The warm-up consisted of 10-min low-intensity running, followed by 5 min of dynamic stretching. In the final part of the warm-up, players performed 4 × 40–50 m linear runs with increasing intensity and speed, followed by two maximal linear accelerations of 20 m.

After the warm-up, all players performed three maximal sprints of 40 m separated by 2–3 min of rest. The players started from a standing position with split legs, with the toes of the front foot placed 60 cm behind the first photogates. The fastest sprint of three attempts was included in the analysis (24).

A wall-mounted photogate system (IC Control TrackTimer) was used in Norway, whereas a portable photogate system (Witty, Microgate, Italy) was used in Iceland. The height of the first photogate was 50 cm above the running surface, while the photogates at 10, 20, 30, and 40 m were positioned 120 cm above the running surface (24).

2.5 Jump performance

2.5.1 Standing long jump

Standing long jump (SLJ) was performed to measure the player's explosive strength in the horizontal plane. Players started with both feet placed behind a line marked on the ground and jumped as long as possible in a forward direction. Players were not allowed to move their feet before jumping. Players had magnesium under the soles of their shoes to identify the landing mark. The horizontal distance from the start line to the mark made by the heel closest to the start line was measured and used to determine the jumping length. The jump was not approved if the player touched the ground with one of their hands. The best of three attempts was used in the analyses.

2.5.2 Countermovement jump

Countermovement jump (CMJ) was performed to measure the players explosive strength in the vertical plane. Players started in a standing position with their arms on their hips, and with hips and legs extended. Players were instructed to jump as high as possible, after an initial knee flexion. They were also instructed to have straight legs in the air. Instructions on jump technique and trail jumps were given to ensure that players were familiar with the jumping technique. The best of three attempts was used in the analyses. The CMJ test was performed with the Kistler 9286B force plate (Kistler Instruments AG) in Norway and an optical measurement system with a sampling frequency of 1,000 Hz (Optojump RX 10, Microgate, Italy) in Iceland. Maximum jump height in centimetres (cm) was calculated from take-off velocity in Norway and from flight time in Iceland.

2.6 Aerobic capacity and intermittent endurance capacity

2.6.1 Maximal oxygen uptake

To determine VO_{2max}, players ran on the constant inclination of 5.3% on a motorized treadmill (Woodway PPS55, USA). The inclination of the treadmill was used to limit the effect of the running technique on test performance. The test protocol started with a speed between 7 and 10 km h^{-1}, with individual starting speeds decided for each player after the warm-up. After the start of the test, the speed was increased by 1 km h^{-1} every minute to voluntary exhaustion. The VO_{2max} was determined using the highest average of two consecutive 30-s measurements ($ml{\cdot}kg^{-1}{\cdot}min^{-1}$). Players' perceived exertion on the Borg scale was registered within 30 s after the test was finished.

Before the test, each player performed a 10-min warm-up on a treadmill, with a gradual increase in speed. Heart rate (HR) was measured with an HR monitor (Polar V800, Polar Electro OY). The volume of oxygen (VO_2) was measured using a computerized metabolic system with a mixing chamber (Oxycon Pro, Erich Jaeger GmbH). The flowmeter was calibrated with a 3-L volume syringe (Hans Rudolph, Inc.) before each test. The VO_2 and carbon dioxide (VCO_2) using high-precision gases were also calibrated (16.00 ± 0.04% O_2 and 5.00 ± 0.1% CO_2, Riessner-Gase GmbH & co, Lichtenfels, Germany).

2.6.2 The Yo-Yo intermittent recovery test

The Yo-Yo intermittent recovery test (IR1-test) was used to assess the players' intermittent endurance capacity. Standardized procedures were conducted, with a standard starting speed for all players (25). The total distance covered in metres was used for statistical analysis. In Norway, the test was performed on an indoor wooden sports floor, while in Iceland, players ran the test in an indoor soccer arena with artificial grass.

2.7 Questionnaire data

All players answered questions regarding the number of sessions and hours of weekly organised soccer training and the age at which they started to play organised soccer.

2.8 Bone age

Players underwent an x-ray of their left wrist to estimate skeletal and biological maturity based on their bone age (BA). The x-ray images were obtained using Siemens Yasi Max with the integrated imaging system FLUORPSPO Compacts (software version VE10; Siemens Healthineers). The field of view covered the hand, as well as 3 cm of the lower distal arm to include the epiphyseal plates in the radius and ulna. The parameters were as follows: tube-detector distance 1 m, x-ray energy 50-kilo volt (kV), and 1–1.5 milliampere seconds (mAs), with no processing or filtering of the images.

BoneXpert standalone version 2.5 (Visiana) was used to analyse the radiographs. The system automatically performs 8–13 independent BA measurements from 8 to 13 different bones in the left hand. The automated determination of BA rules out inter- and intra-observer variation. This BA determination was based on the Greulich Pyle methodology (26).

2.9 Statistical analyses

Descriptive data is shown as mean ± standard deviation (SD) and minimum (min) and maximum (max) values. The normality of data was assessed with the Shapiro-Wilkins test. One-way ANOVA analysis was performed to evaluate differences between the Icelandic and the Norwegian players regarding chronological age (CA), BA, height, weight, and number of weekly organised training sessions and hours. Because previous studies have shown a relationship between BA and physical capacity, and since we found a significant difference in BA between the Norwegian and Icelandic players one-way analysis of covariance (ANCOVA) was performed to compare the physical capacities between the Icelandic and Norwegian players, with BA as a covariate. The least significant difference (LSD) *post hoc* analyses were performed to compare the Icelandic players with the selected and deselected Norwegian players. Data presented in the Tables are unadjusted. The relationship between variables was assessed using Pearson's correlation coefficient *r*. An r -value between 0.01 and 0.29 was defined as a small correlation, between 0.30 and 0.49 as a medium correlation, and from 0.05 to 1.0 as a large correlation (27). The Statistical Products of Service Solution package (SPSS, version 29) was used for all statistical analyses, and *p*-values of ≤0.05 were considered statistically significant.

3 Results

3.1 Descriptive data

Mean CA of the players ($n = 151$) was 14.0 ± 0.3 years, whereas mean BA was 13.9 ± 1.0 years. When the Norwegian group was divided into the selected and deselected groups, no significant differences were observed between the groups regarding BA, date not shown. Mean body height and weight were 166.8 ± 8.6 cm and 53.8 ± 8.9 kg, respectively. For an overview of the characteristics of the players from Iceland and Norway separately, see Table 1.

The Icelandic and Norwegian players reported that they started with organised soccer training at an age of 5.5 ± 2.1 years and 5.8 ± 1.0 years, respectively. There was no significant difference between players from the two countries regarding when they started to play soccer.

TABLE 1 An overview of characteristics of the Icelandic and Norwegian U14 soccer players. Data are represented as mean ± SD.

	Norwegian players ($n = 103$)	Icelandic players ($n = 48$)	*p*-value
Chronological age (years)	14.1 ± 0.3	13.9 ± 0.3	<.001
Bone age (years)	14.0 ± 1.1	13.6 ± 0.7	.016
Height (cm)	167.3 ± 8.4	165.6 ± 8.8	.253
Weight (kg)	54.0 ± 7.2*	52.6 ± 7.2	.370

*n = 98.

3.2 Physical capacities between players from Iceland and Norway

Significant differences in speed and endurance capacity were seen between the Norwegian and Icelandic players (Table 2). Overall, the analysis showed that players from Norway ran faster, had higher VO_{2max} and ran longer in the IR1 recovery test. There was no significant difference between players from the two countries in SLJ and CMJ. ANCOVA analysis showed that the differences between players from Iceland and Norway were consistent also after adjusting for BA.

When splitting the Norwegian players into selected players and deselected players, the selected Norwegian players were significantly faster and had higher VO_{2max} than both the deselected Norwegian players and the Icelandic players, with no significant difference between the deselected Norwegian players and the Icelandic players. In the 40-meter test, IR1-test and $\dot{V}O_{2max}$ test, the selected Norwegian players performed significantly better than the deselected Norwegian players and the Icelandic players. In addition, the Icelandic players performed significantly better than the deselected Norwegian players in IR1-test and $\dot{V}O_{2max}$ test. In CMJ, both the selected Norwegian players and the Icelandic players were superior to the deselected Norwegian players, and there were no significant differences between the players in SLJ (Table 3).

3.3 Organised soccer training volume between players from Iceland and Norway

In general, there was no significant difference in the number of organised weekly training sessions between players from Iceland and Norway (Table 2). However, when splitting the Norwegian players

TABLE 2 An overview of the physical capacities and the weekly organised soccer training volume among the Icelandic and Norwegian U14 players. Data are represented as mean ± SD (min–max).

	Norwegian players	Icelandic players	*p*-value
Physical tests			
40 m linear sprint (sec)	5.90 ± 0.38 (5.11–7.41) ($n = 103$)	6.37 ± 0.44 (5.61–7.33) ($n = 48$)	<.001
SLJ (m)	1.88 ± 23 (1.25–2.58) ($n = 95$)	1.85 ± 22 (1.39–2.25) ($n = 48$)	.849
CMJ (cm)	29.1 ± 5.1 (14.9–39.4) ($n = 97$)	28.9 ± 4. (21.1–42.1) ($n = 48$)	.565
VO_{2max} (ml·kg^{-1}·min^{-1})	60.3 ± 6.5 (38.5–75.6) ($n = 95$)	54.8 ± 5.3 (45.1–66.9) ($n = 48$)	<.001
IR1-test (m)	1,235 ± 461 (200–2,280) ($n = 87$)	960 ± 423 (280–1,920) ($n = 48$)	<.002
Organised weekly soccer training			
Sessions (n)	4.33 ± 1.65 ($n = 96$)	4.63 ± 1.20 ($n = 48$)	.277
Hours (n)	6.80 ± 3.41 ($n = 97$)	5.78 ± 1.39 ($n = 48$)	.049

SLJ, standing long jump; CMJ, countermovement jump; VO_{2max}, maximal oxygen consumption; IR1-test, the Yo-Yo intermittent recovery test.

TABLE 3 An overview of the physical capacities and the weekly organised soccer training among the Norwegian and Icelandic players when splitting the Norwegian players in a selected and deselected group. Data are represented as mean ± SD. (min–max).

	Norwegian selected players (1)	Norwegian deselected players (2)	Icelandic players (3)	*p*-value	*Post hoc* (LSD)
Physical tests					
40 m (sec)	5.82 ± 0.33 (5.11–6.61) (n = 80)	6.17 ± 0.42 (5.50–7.41) (n = 23)	6.37 ± 0.44 (5.61–7.73) (n = 48)	<.001	1 > 2,3
SLJ (cm)	191 ± 22 (140–258) (n = 72)	179 ± 25 (125–227) (n = 23)	185 ± 22 (139–225) (n = 48)	.071	
CMJ (cm)	29.9 ± 4.8 (20.3–39.4) (n = 77)	25.9 ± 5.3 (14.9–36.1) (n = 20)	28.9 ± 4.3 (21.1–42.1) (n = 48)	.002	1 > 2 3 > 2
VO_{2max} (ml·kg^{-1}·min^{-1})	61.6 ± 5.7 (48.3–75.6) (n = 75)	55.6 ± 7.2 (38.5–67.9) (n = 20)	54.8 ± 5.3 (45.1–66.9) (n = 48)	<.001	1 > 2,3
IR1 (m)	1,329 ± 418 (520–2,280) (n = 75)	653 ± 235 (200–1,080) (n = 12)	960 ± 423 (280–1,920) (n = 48)	<.001	1 > 2,3 3 > 2
Organised weekly soccer training					
Sessions (n)	4.85 ± 1.44 (n = 75)	2.48 ± 0.75 (n = 21)	4.63 ± 1.20 (n = 48)	<.001	1 > 2 3 > 2
Hours (n)	7.83 ± 3.17 (n = 75)	3.27 ± 0.92 (n = 22)	5.78 ± 1.39 (n = 48)	<.001	1 > 2,3 3 > 2

SLJ, standing long jump; CMJ: countermovement jump; VO_{2max}, maximal oxygen consumption; IR1-test, the Yo-Yo intermittent recovery test. >: indicate significant better performance.

into selected and deselected players, both the selected Norwegian players and the Icelandic players reported significantly higher number of weekly organised soccer training sessions compared to the deselected Norwegian players (Table 3). Moreover, the Norwegian players reported a significantly higher number of organised weekly training hours than the Icelandic players (Table 2). Analyses also showed that the selected Norwegian players had a significantly higher number of organised weekly training hours than both the Icelandic players and the deselected Norwegian players. However, the Icelandic players reported a significantly higher number of organised weekly training hours compared to the deselected Norwegian players (Table 3).

3.4 Relationships between BA and physical capacities among Icelandic players

Among the Icelandic players, there was a strong correlation between BA and performance on the 40 m linear sprint test (r = −0.566, $p < 0.001$), and medium correlations between BA and jumping performance (SLJ: r = 0.380, $p = 0.008$, CMJ: r = 0.354, $p = 0.014$). On the other hand, no significant correlations were observed between BA and performance on the IR1-test (r = 0.206, $p = 0.161$) nor the $\dot{V}O_{2max}$ test (r = 0.125, $p = 0.369$).

4 Discussion

In the present study, associations between BA and physical capacities in Icelandic U14 soccer players were investigated, and the physical capacity level and the volume of weekly organised soccer training between Icelandic and Norwegian youth soccer players were compared. The results showed that the Norwegian players were faster, had higher intermittent endurance capacity and higher $\dot{V}O_{2max}$ than the Icelandic players. Moreover, the Norwegian players reported a significantly higher number of weekly training hours than the Icelandic players, on average. In addition, BA of the Icelandic players was associated with speed and maximal jump performance, but not with intermittent endurance capacity or $\dot{V}O_{2max}$.

When comparing the U14 players from Iceland and Norway, our findings showed, after adjusting for biological maturity level, that the Norwegian players ran significantly faster than the Icelandic players on the 40 m linear sprint test. Overall, the Norwegian players also had significantly higher VO_{2max} and performed significantly better on the intermittent endurance capacity test compared to the Icelandic players. However, when splitting the Norwegian players into selected and deselected players, only the selected Norwegian players were superior to the Icelandic players when it comes to speed, intermittent endurance capacity and $\dot{V}O_{2max}$.

Differences in running capacity between the Norwegian selected players and Icelandic players may be caused by different reasons. One possible explanation refers to the different organisation of youth soccer in the two countries. Norwegian soccer academies may provide a more conducive training environment with high-level coaches, skilled teammates, and better training facilities, which can result in increased motivation and improved physical capacities (28). The organisation of youth soccer and talent identification in Norway correspond to general recommendations by FIFA, such as investment in the professionalisation of academies, when it comes to the selection of players (16).

Faster running speed and better physical capacity among the selected Norwegian players may be related to the selection of players *per se*, i.e., players with outstanding physical capacity are more likely to be selected to academies (19, 29), although previous studies have shown inconsistent and conflicting findings regarding physical fitness and selection to academies. The higher number of organised weekly training hours seen among the selected Norwegian players could also be an explanation. As mentioned before, the selected Norwegian players may also have higher training intensity due to higher competition among players and superior training motivation. Further research and assessments are needed. On the other hand, there was no significant difference between the deselected Norwegian players and the Icelandic players in 40 m linear sprint time and maximal oxygen consumption, despite the significantly higher number of organised training hours among the Icelandic players.

Our results showed a relationship between BA and running speed and jumping performance among the Icelandic players. This is in accordance with previous findings among Norwegian players at the same age (19, 20) and confirms previous findings regarding the effect of biological maturation on speed and explosive leg strength (17, 18, 21, 22). Our findings indicate that biological maturity level affects physical capacity among Icelandic youth soccer players, as has been demonstrated in other countries. Furthermore, there was no relationship between BA and endurance capacity among the Icelandic players. This is also in line with previous findings among Norwegian U14 soccer players (19, 20), and indicates that endurance capacity is not influenced by biological maturity status in highly trained youth soccer players. However, a recent investigation suggests that the positive change in VO_{2max} was paralleled by the increase in fat-free mass. Therefore, an increase in endurance capacity may be more related to body composition development, growth and maturation rather than different intensity or volume of the training (30). This finding indicates that physical training for youth soccer players needs to be investigated further in more detail in the future.

The present study has some limitations that are worth mentioning. The Icelandic measurements were conducted during the end of the COVID-19 pandemic, which presented unexpected obstacles, such as training bans, quarantine and additional limitations when measuring the youth soccer players. During the late COVID-19 period very limited training restrictions occur amount youth soccer players in Iceland. However, this may have affected the players' results in the various measurements and might skew results. It is also worth mentioning that different equipment was used for the 40 m sprint test and the CMJ test in the two countries. In the CMJ test, maximum jump height was calculated based on take-off velocity in Norway, while in Iceland it was derived from flight time. To ensure reliable results, only jumps with correct technique were considered valid (i.e., players were instructed to maintain straight legs in the air for accurate flight time). The portable photogates employed for the 40 m sprint test in Iceland were set up by experienced personnel, and there is no reason to suspect that the variance in running speed was influenced using a portable system in Iceland vs. the wall-mounted system in Norway. A strength of the study was that experienced personnel administered all tests. However, a limitation was the use of different photogate systems for the 40 m sprint test. Moreover, the IR1-test was done on different surfaces in the two countries. In Norway, the test IR1 test was conducted indoors on a wooden sports floor, while the test was conducted indoors on artificial grass in Iceland. It cannot be ruled out that different running surfaces may have had an impact on the test results. However, it is unlikely that the COVID-19 pandemic, the use of different equipment and different running surface alone can explain the difference between the Norwegian and the Icelandic players.

5 Perspective

In this study we compare physical capacity between U14 soccer players from Iceland and Norway. The main results showed that the Norwegian players had exhibited superior endurances capacity and ran faster than the Icelandic players. Furthermore, the Norwegian players reported a higher number of weekly organised soccer training hours than the Icelandic. These results are interesting, because the Fédération Internationale de Football Association (FIFA) highly recommended the soccer clubs to utilise the professional soccer academic during the process of the identification and talent development of the youth soccer players. In Norway, many of the promising young soccer players are selected to the academies at an age of 13, on the other hand, the traditional academies are not established or utilised in Iceland. However, the success of the Iceland men senior soccer team has been remarkable during the last decades, which indicate great potency of the Icelandic system. Furthermore, both Iceland and Norway were qualified for the male European U20 championship in 2023, showing that both nations can reach high international junior levels. Further research is needed to investigate the relationship between development of physical capacity, training load and different organisational structures of both youth and senior soccer players in Scandinavian.

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 Both the National Bioethics Committee of Iceland (VSN-19-206) and the Regional Committee for Medical and Health Research Ethics in Norway (2017/1731) approved the study, and the study was conducted in accordance with the Helsinki Declaration. 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

SB: Data curation, Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing, Project administration, Software. EJ: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. CR: Investigation, Methodology, Validation, Writing – original draft, Writing – review & editing. HG: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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Impact of implicit vs. explicit Instructions on tactical performance in under-20 soccer players

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Introduction: This study aimed to verify whether implicit and explicit informational constraints generate differences in tactical performance and behavior in U-20 national-level soccer players.
Methods: Thirty-two under-20 male athletes from two clubs participated. Four 4-a-side small-sided games (SSG) protocols were used: R1 - explicit rule for high-press marking, R2 - implicit rule for high-press marking, R3 - game with both previous rules simultaneous and FR - free game, without additional rules. SSGs comprised 4 vs. 4+ goalkeepers games on a 42 m × 29 m field. Position data from 10 Hz Global Positioning System (GPS) devices were used to evaluate individual and collective tactical behavior (spatial occupation metrics) and performance (interpersonal coordination). MANOVA was used for normally distributed variables, and Friedman's with Dunn or Bonferroni *post hoc* was used for variables without normal distribution. For SEI, an ANOVA was used with Bonferroni *post hoc*.
Results: The R1 protocol showed higher SEI, length, width, and LpWratio than the FR protocol ($p = 0.009$). There was an effect of the different protocols in SEI values ($p < 0.001$). Under the explicit rule, players also showed the highest in-phase interpersonal coordination values ($p < 0.001$).
Discussion: Providing players with explicit tactical instructions improves tactical performance acutely for high-pressing defensive actions.

KEYWORDS

small-sided games, informational constraints, ecological dynamics, tactical training, position data

1 Introduction

Small-sided games (SSGs) are adopted in football training to simultaneously develop physical, physiological, technical, and tactical skills (1). Moreover, SSGs allow for keeping the internal logic of the sport (increasing the specificity of the training) while providing coaches with the possibility to manipulate constraints to adapt the task difficulty to players' levels and sessions' aims (2). When manipulating constraints, the players' exploratory behavior can be shaped intentionally by the coach to focus on specific affordances within the available landscape (3, 4). Within the constraints' manipulation landscape, informational constraints refer to the information available—or made available—for action (5). Coaches usually change informational constraints by providing players with additional information about the task. This information can be provided explicitly—with specific and clear goals—or implicitly—favoring exploration throughout the task. The literature has extensively explored task constraints, such as pitch size (6, 7) and the number of players (8, 9). However, the impact of informational constraints remains under-researched, especially in team sports such as soccer.

Although scarcely investigated, informational constraints have previously been shown to shape players' behaviors in game-based tasks, such as SSGs. For example, a study showed that when players were informed about a shorter bout duration, they increased their pace despite the total game time being similar across the conditions (10). Another study showed that a strong feedback strategy decreased players' tactical performance compared to an unobtrusive feedback strategy (11). Therefore, it is arguable that providing players with instructions can direct their attention towards specific affordances. However, the available literature on informational constraints and small-sided games focused on general information, including match status (12), bout duration (10), and feedback (11). Little is known about the impact of explicit tactical instructions on players' behaviors during SSGs.

Raab (13) suggests that adopting implicit or explicit learning strategies should rely on task complexity. At this point, Lola et al. (14) observed that in highly complex situations, the explicit learning group outperformed the implicit group in a badminton task. The authors suggested that the verbal instructions guided explicit learning and helped novices focus on the most relevant environmental cues, improving their learning (13). Raab (13) points out that decisions under high-complexity contexts require some explicit learning to quickly improve. According to the author, "if-then" explicit rules (e.g., "*you will score a point if you regain ball possession in the offensive midfield*") can facilitate decision-making during the task. However, the complexity of this task can increase when the defending team coordinately advances on the pitch to constrain the space and time of the attacking team (known as high-press defending). This complexity increase could be explained by the increased information available in the task (13) and a restricted time to accept one of the affordances within the available landscape. At this point, it could be assumed that explicit learning might be necessary when perceptual-cognitive demands are high (13), which seems to be the case when dealing with elite team sports, such as soccer. However, to our knowledge, no studies are available investigating the possible effect of implicit and explicit informational constraints on tactical performance during ecologically-representative complex tasks in soccer (such as SSGs).

The literature suggests that some tactical contents are more complex for players to learn and execute (15, 16). For example, it has been shown that the performance in defensive coverage actions is higher than in defensive concentration actions (17). Interestingly, while effective defensive coverages require coordinating efforts among two teammates, effectively concentrating (protecting the central area of the pitch) might require the whole team to coordinate, which might explain the higher complexity of this principle. Reinforcing this rationale, the number of players seems to affect the players' decisions (18, 19). Caso and Kamp (18) showed that games with fewer players generated more creative decisions than larger formats. Also, Silva et al. (16) demonstrated that the space management of the players was better in the smaller format (3 vs. 3) than in the larger one (6 vs. 6). Therefore, the more players involved in an action, the more complex it is expected to be.

Based on the abovementioned rationale, the high-press defensive strategy can be assumed to be a highly complex tactical content due to the need for coordination among teammates for better execution (20). The high press is characterized by trying to regain the ball as close to the opposing goal as possible. This defensive strategy has been linked with success in elite soccer as more advanced defensive pressure allows ball recoveries in more advantageous pitch positions (21, 22). González-Rodenas, Calabuig, and Aranda (23) suggested that the closer to the opponent's goal the ball is recovered, the higher the possibility of scoring a goal and creating goal-scoring opportunities. Hughes and Lovell (24) showed that 49.45% of the balls recovered in the opponent's defensive midfield led to shots on goal, and 7.69% of the actions generated goals. Therefore, stimulating the players to high-press the opposing team is relevant for defensive success in soccer. When practicing this content, implicit or explicit informational constraints can be manipulated. Therefore, training this content seems a promising context for testing whether implicit or explicit informational constraints influence players' tactical performance in soccer. For example, scoring rules could be explicitly (i.e., giving a point score to the defending team every time they recover the ball in their offensive midfield) or implicitly (giving a point score to the offensive team every time they can shoot on goal from their offensive midfield) manipulated. These task constraints will shed light on how informational constraints affect players' actions during SSGs.

Studies have used different Electronic Performance and Tracking Systems (ETPS), such as Global Positioning Systems (GPS) position data, to evaluate players' positioning in game-based tasks, including SSGs (25–27). Conventional game analysis approaches rely on discrete event-based data, while innovative methods suggest integrating position-based data to comprehensively understand the game's inherent dynamics, often beyond traditional analysis's scope (28, 29). Position-based data enable the analysis of the actions executed by players as they adapt to dynamically changing environments (30), considering both individual and collective perspectives (31). Studies have adopted measures of movement coordination to quantify performance through space-time interactions among players (32). Classical studies relied on players' and teams' spatial occupation metrics, such as length, width, and spatial exploration, to describe space management during game-based tasks and official matches (33–35). Regarding movements on the field in length and width (i.e., in the longitudinal and lateral axes, respectively), it was shown a reduction in the percentage of time that dyads (i.e., all possible pairs of players from the same team) maintained coordination in the in-phase pattern in SSGs that involved modifications to the spatial references of the playing field when compared to SSGs that did not undergo these modifications (36, 37). Also, another study observed that in situations of defeat, the team showed lower coordination percentages, indicating it to be a characteristic that distinguishes winning from losing teams (38). As the high-press defensive strategy is linked to the pitch's occupation, evaluating game-based tasks oriented to this pedagogical purpose using position-based data is theoretically founded.

Although the literature on the Constraints-led Approach (CLA) using SSGs has advanced remarkably over recent years, the influence of explicit and implicit informational constraints on players' actions remains unknown. Investigating this would improve the understanding of players' adaptive actions throughout game-based tasks, as coaches regularly provide information during training. Therefore, this study aimed to compare the tactical behaviour and performance during SSGs with explicit and implicit informational constraints. The literature suggests that the benefits of explicit learning are higher under high-complexity contexts (13). Therefore, the explicit rule condition is expected to lead to a higher tactical performance, demonstrated by a higher percentage of in-phase coordination tendency (39).

2 Methods

2.1 Sample size estimation

The sample was statistically determined after a pilot study conducted over four training sessions of a U-17 male soccer team. The pilot study comprised a specific data collection session in which players engaged in small-sided games similar to those adopted in the main data collection. For this pilot study, the technical staff classified the participants as defenders, midfielders, and forwards. All the players were divided into three 4-a-side teams composed of one defender, two midfielders, and one forward. Players performed small-sided games with the same rules adopted in the main study (see the section "procedures") for four minutes, engaging in all four experimental conditions during the four data collection sessions. Finally, the tactical performance obtained through the System of Tactical Assessment in Soccer (FUT-SAT (40); was used as a criterion for sample size estimation. The sample size calculation was performed using the software G*Power (Version 3.1.9, Universitat Kiel, Germany) considering the following parameters: f tests family, ANOVA: repeated measures within factors, effect size $f = 0.219$, partial $\eta^2 = 0.046$, number of groups = 1, number of measurements = 4, alfa = 0.05, beta = 0.80, following the literature recommendation (41). The effect size adopted in the sample size estimation was obtained from the previous pilot study. The sample size estimation indicated a minimum of twenty observations to ensure the expected effect size.

2.2 Participants

The final sample comprised 32 U-20 male soccer athletes (18.2 ± 1.2 years; 9.2 ± 1.6 years of practice in the sport and 5.1 ± 0.9 years of experience in official competitions) from two national-level soccer academies. The final sample was higher than originally determined to account for sample dropouts and injuries and included players from different clubs, increasing the sample's representativeness. Inclusion criteria comprised belonging to officially registered clubs, competing in U-20 regional-to-national level competitions, and engaging in at least five weekly training sessions. Participants were excluded if they presented any injuries at the beginning of the data collection or could not participate in all data collection sessions. Participants are classified as tier 3 according to the literature (42). The players' level was chosen due to the complexity level of the tactical content analyzed in the current study, which is expectedly highly complex. Also, only male players were included, as the availability of competitive youth academies in the region was limited at the time of the data collection. The local ethics committee approved the study (Approval No. 46940821.7.0000.5149), and the principles of the Declaration of Helsinki were followed. Written informed consent was obtained from all participants and their legal guardians, ensuring their understanding and voluntary participation in the research.

2.3 Procedures

2.3.1 Team composition

Previous studies showed the influence of playing position and tactical knowledge on players' behaviors (43). Therefore, both criteria were adopted to ensure that balanced teams would be composed, similar to previous studies on this topic (44, 45). The processes for organizing balanced teams, described below, lasted two days in each club.

To conduct the team composition procedures, the technical staff classified the participants within each club as defenders, midfielders, and forwards. These groups performed the field test of the System of Tactical Assessment in Soccer (40) adopted to rank the players within each playing position. This classification was based on the percentage of successful tactical actions, as previously suggested in the literature (46). The two best defenders and forwards and the four best midfielders were used to compose teams A and B, which played only against each other, while the remaining participants composed teams C and D (see Figure 1), which also played only against each other. Keeping teams and matches stable during the data collection was required as previous studies showed the players' tactical level (47) and the level of the opposition (48) could influence the players' behavior. The same experimental design was repeated in the second team that participated in the study ($n = 32$).

2.3.2 Data collection procedures

This study was a randomized, within-subject trial where the participants engaged in four experimental conditions on different days. Participants could not be blinded as the informational constraint manipulated involved providing them with specific action rules. The randomization was conducted to allow all experimental conditions to be played in all possible orders within

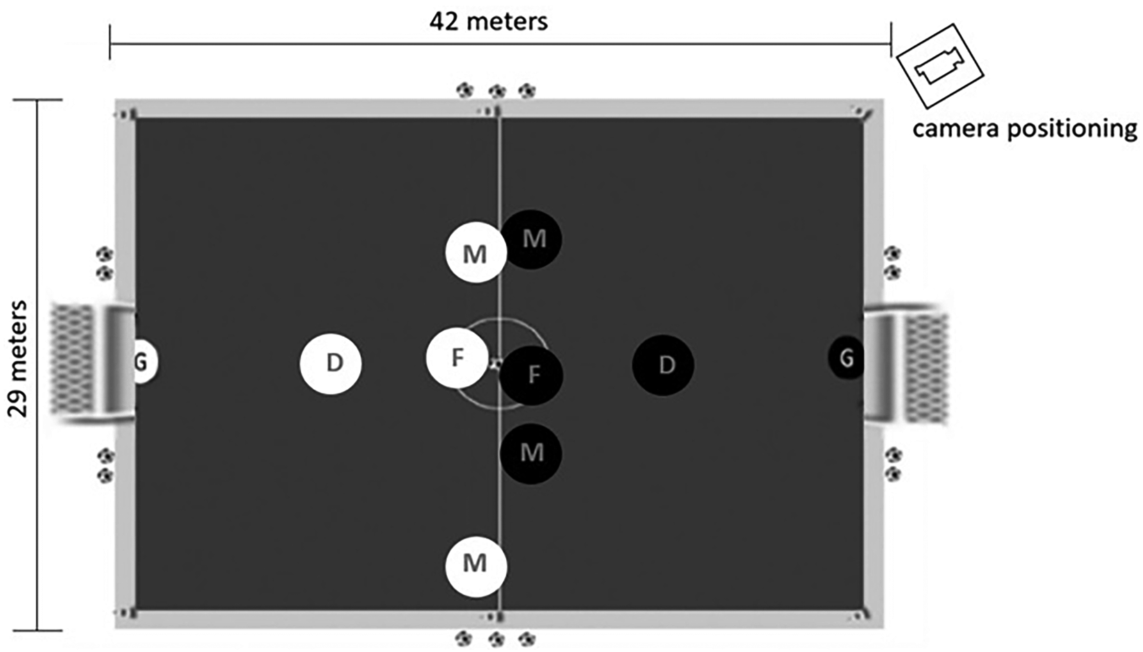

FIGURE 1
Representation of the procedures of data collection on each club.

a session (from bout one to bout four), reducing the influence of the learning effect on the observed responses (49).

After the teams were formed, a familiarization session was held in which players participated in each experimental condition for four minutes. In this session, players engaged in all the formats they would play during the main collection. Also, they were allowed to ask questions regarding the rules and scoring systems, ensuring comprehension of the study's design. Players were considered familiar with the experimental conditions' when no remaining questions were raised.

In sequence, the main data collection started. Each data collection session started with a 10-min standardized warm-up composed of on and off-the-ball displacements with changes in direction and speed. After the warm-up, in each session, participants played three SSGs from the same experimental condition for four minutes, with four minutes of passive recovery (1:1 work-to-rest ratio). This procedure was adopted to reduce the influence of fatigue on players' performance during the SSGs and was repeated for five data collection sessions in each club for two weeks. The experimental conditions' presentation order was randomized and balanced to control for learning effects. The data collection sessions started at the same time every day to control for the influence of the circadian rhythm on players' responses (50). Four experimental conditions were investigated: FR (free-rule), R1 (rule 1 - explicit rule), R2 (rule 2 - implicit rule), and R3 (combination of rules 1 and 2). The FR contidion is a free-play game without any additional restrictions. In the R1 condition, an explicit rule for high-defensive pressure was applied. In this, both teams were told they would score two additional points every time they regained the ball in their offensive midfield, stimulating them to move forward during the defensive phase. Recovering the ball in the offensive midfield will likely increase the possibility of shooting on goal and scoring goals (23). The R2 condition involved an implicit rule for high-defensive pressure that incentivized players to retrieve the ball from the opposing team's pitch without being explicitly told to do so. Specifically, teams would receive two additional points each time they could shoot on goal from their offensive midfield. While the defending team was not given any specific instructions, they may have implicitly learned that implementing a high-press defending strategy would be the most effective way to prevent the other team from scoring. Finally, in the R3 conditions, players were given the instructions mentioned above. Providing encouragement or verbal instructions during SSGs was not permitted.

2.3.3 Small-sided games

After teams were composed, players engaged in the 4-a-side SSGs (Figure 2) in a 42×29 m pitch. This pitch has an area per player equal to 121.8 m^2, similar to the 121.5 m^2 observed in the 36×27 m pitch in the 3-a-side SSG extensively adopted in the literature (40, 47). The 4-a-side SSG was adopted as previous studies investigated similar dependent variables in this format (16, 19, 51), which facilitates the interpretation and discussion of the results. The SSGs were played on a natural surface grass pitch, and all official rules, including the offside, were applied. The adoption of the offside rule, which differs from other previous studies, intended to increase the representativeness of the task, as it has been shown that removing this rule increases in-depth players' spatial exploration (52). White elastic bands marked the sidelines, the midfield, and the goal lines to facilitate players' identification of the available space. The literature showed that this

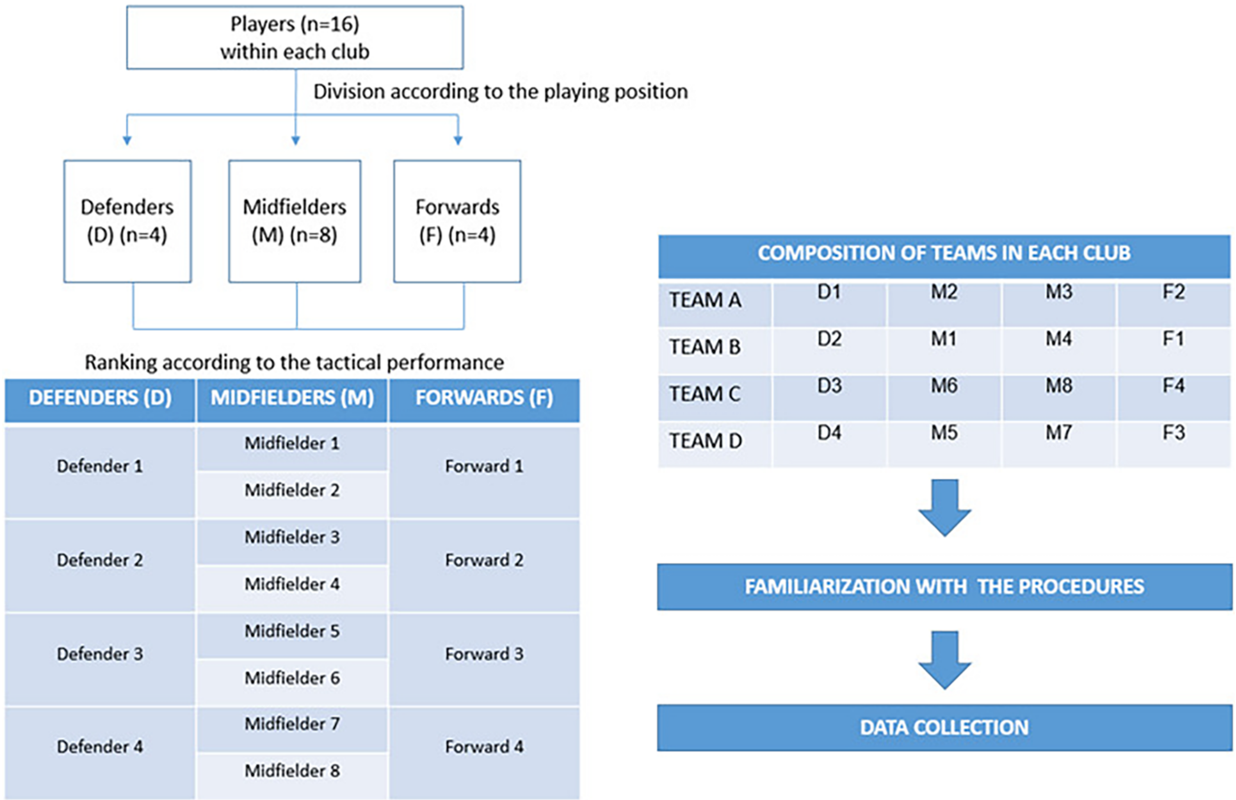

FIGURE 2
The standard format of the small-sided game adopted in the study.

strategy to mark the pitch facilitates players' synchronization during SSGs (53). Extra balls were positioned at the sidelines to facilitate the restart of the game when the ball was kicked out of the field. Goalkeepers were part of the study but were removed from the statistical and positional analyses to avoid misinterpretations.

2.4 Instruments

2.4.1 System of tactical assessment in soccer—FUT-SAT

The tactical performance of the players, used as a criterion for team composition, was evaluated using the System of Tactical Assessment in Soccer—FUT-SAT (40). The assessment considers ten core tactical principles: five related to the offensive phase (penetration, offensive coverage, depth and width, mobility, and offensive unity) and five related to the defensive phase (delay, defensive coverage, balance, concentration, and defensive unity). The analysis was performed by an expert in the system who evaluated players' actions from the video footage. The camera was positioned high to allow all players to be captured over the whole bout. In addition, the software *Soccer Analyser*®, allowed the pitch to be split into twelve game zones, facilitating the interpretation of the tactical principles. Considering the observational characteristics of the data provided by the FUT-SAT, a within- and between-observers agreement analysis was required to ensure the consistency and external validity of the observations. For this purpose, 10% of the videos were reassessed by the original expert and second expert analyst, following the literature guidelines (54). The Intraclass Correlation Coefficient ($CCI_{3,1}$) was used to calculate the agreement. The values ranged within-observer 1 ICC = 0.936 [IC 95% = 0.718–0.987; $F_{(7,7)} = 30.48$; $p < 0.01$] and observer 2 ICC = 0.917 [IC 95% = 0.644–0.983; $F_{(7,7)} = 23.04$; $p < 0.01$]. The values for between-observer agreement ICC = 0.948 [IC 95% = 0.883–0.977; $F_{(23,23)} = 37.26$; $p < 0.01$]. The literature shows that these values are considered satisfactory (55). Every small-sided game was recorded (JVC® HD Everio model GZ-HD520 Camcorder, Brazil) for this assessment.

2.4.2 Electronic performance and tracking systems (EPTS)

Electronic performance and tracking systems (EPTS) were adopted in the current study to track players' positions and displacements in the game-based tasks. The adopted EPTS was a 10 Hz GPS device with Bluetooth or Adaptative Network Topology (ANT+), adopting a GPS constellation system (EE. UU.) embedded with a triaxial accelerometer, gyroscope, and digital compass (Polar®, Team Pro, Kempele, Finland) and processed in MATLAB 2010a (The MathWorks Inc., Natick, MA, USA). The manufacturer does not provide information regarding satellite availability in each data collection. The equipment used in the current study has been previously tested in the literature for the accuracy and reliability of movement detection (56). Each player wore a chest strap with the device attached to it. Latitude and longitude data were downloaded using the manufacturer software (Polar Team Pro Web Service, Polar®, Team Pro, Kempele, Finland), synchronized, and converted into meters using the Universal Transverse Mercator (UTM) coordinate system and a MATLAB routine (57). The data were smoothed using a second-order 0.5 Hz Butterworth low pass filter. After converting the positional data into meters, a rotation matrix was calculated for each SSG with the field vertices positions, aligning the length of the playing field with the x-axis and the width with the y-axis. Then, the rotation matrix was applied to the athletes' positional data for alignment with the playing field referential (20).

The following variables were calculated: (a) width, determined by the distance between the players most to the right and left of the team; (b) length, determined by the distance between players who are most vertically apart (26); (c) length by width ratio (LPWratio), which indicates the team's preferred positional axis, with higher values indicating a deeper positioning (48); (d) the centroid of each team, calculated as the average position of each player on each instant (58) and used to calculate the distance between the centroids, understood as the Euclidian distance between these points every instant; (e) spatial exploration index (SEI), defined as the average difference between a player's average position and his actual position at each moment of the game (26). The SEI indicates how a player explores the pitch, irrespective of the preferential axis, with higher values indicating a more exploratory behaviour (52). The width, length, LPW ratio, and stretch index were collectively measured, while the SEI was individually analyzed. Position data from this device was previously tested for inter and intra-session reliability and showed acceptable values (59).

Besides the linear measures, players' interpersonal coordination tendencies were evaluated for both longitudinal and lateral transformed coordinates using the vector coding technique (32). The coupling angle between two-time series represents an instantaneous spatial relationship that may be characterized by different coordination patterns, including anti-phase and in-phase coordination patterns (32). An in-phase pattern is considered when coupling angles are around 45° (from 22.5 to 67.5°) and around 225° (from 202.5 to 247.5°) (i.e., the positive diagonal). This happens, for example, when two players are moving forward to press the opposing player. On the other hand, an anti-phase pattern is considered when coupling angles are around 135° (from 112.5 to 157.5°) and around 315° (from 292.5 to 337.5°) (i.e., the negative diagonal). This happens, for example, when fullbacks move in opposite directions to increase the team's width.

2.5 Data analysis

Initially, data were screened using descriptive statistics. Next, the assumption of normality of the data was tested using Shapiro-Wilk's test. Then, a MANOVA with Bonferroni's *post hoc* was adopted to test the influence of the experimental condition on the tactical responses. This technique of including all dependent variables in the model was chosen to reduce the inflation of the type I error (60). When deviations from a normal distribution (distance between centroids, mobility, and depth and width) were found, Friedman's test with Dunn's *post hoc* was adopted. For the SEI, an ANOVA with Bonferroni's *post hoc* was adopted. The effect size (η^2p) was classified into no effect ($\eta^2p < 0.04$), minimum effect ($0.04 \le \eta^2p < 0.25$), moderate effect ($0.25 \le \eta^2p < 0.64$), and strong effect ($\eta^2p \ge 0.64$) (61). The level of significance was set at 5%. All analyses were conducted using the statistical software IBM SPSS Statistics (IBM Corp. Released 2010. IBM SPSS Statistics for Windows, Version 19.0. Armonk, NY: IBM Corp.).

Considering the observational characteristics of the data provided by the FUT-SAT, a within- and between-observers agreement analysis was required to ensure the consistency and external validity of the observations. For this purpose, 10% of the videos were reassessed by the original expert and second expert analyst, following the literature guidelines (54). The Intraclass Correlation Coefficient ($CCI_{3,1}$) was used to calculate the agreement. The values ranged within-observer 1 ICC = 0.936 [IC 95% = 0.718–0.987; $F_{(7,7)} = 30.48$; $p < 0.01$] and observer 2 ICC = 0.917 [IC 95% = 0.644–0.983; $F_{(7,7)} = 23.04$; $p < 0.01$]. The values for between-observer agreement ICC = 0.948 [IC 95% = 0.883–0.977; $F_{(23,23)} = 37.26$; $p < 0.01$]. According to the literature, these values are considered satisfactory (55).

3 Results

The MANOVA showed an effect of altering the rules of the SSG on the dependent variables [Pillai's Trace = 0.26; $F_{(9,240)} = 2{,}53$; $p = 0.009$; $\eta^2p = 0.087$, moderate effect]. There were significant differences in the length ($F = 5.91$; $p = 0.001$; $\eta^2p = 0.180$, moderate effect), width ($F = 3.37$; $p = 0.022$; $\eta^2p = 0.112$, moderate effect), and LpWratio ($F = 2.81$; $p = 0.045$; $\eta^2p = 0.09$, moderate effect) when comparing the R1 (higher) and FR (lower) protocols. For the distance between the centroids, Friedman's test did not report significant differences ($F = 1.92$; $p = 0.145$; $\eta^2p = 0.149$, moderate effect). In summary, players tended to stretch the pitch occupation when playing under the influence of the explicit rule. Figure 3 shows the results.

When analyzing the SEI, the ANOVA indicated a main effect of the experimental condition on the observed values [$F_{(3,81)} = 12.92$; $p < 0.001$; $\eta^2p = 0.135$, moderate effect]. The highest SEI was observed in the R1 condition (8.6 ± 1.1), significantly higher than all the other experimental conditions [R2 = 7.8 (1.1); R3 = 8.1 (1.1); FR = 7.7 (1.0)]. This means that players moved to different regions of the pitch more constantly in the explicit rule condition. Figure 4 shows the results regarding the SEI.

Finally, the MANOVA showed a significant effect of changing the rule on the interpersonal coordination tendencies in both in-phase and anti-phase [Pillai's Trace = 0.09; $F_{(12,1626)} = 4.51$; $p < 0.001$; $\eta^2p = 0.03$; no effect]. For longitudinal displacements, the ANOVA showed an effect of protocol on anti-phase interpersonal coordination ($F = 4.34$; $p = 0.005$; $\eta^2p = 0.02$, no effect), lower in the R1 condition than in the R2 and FR conditions, and for in-phase interpersonal coordination $F = 13.05$; $p < 0.001$; $\eta^2p = 0.07$, moderate effect), higher in the protocols R1

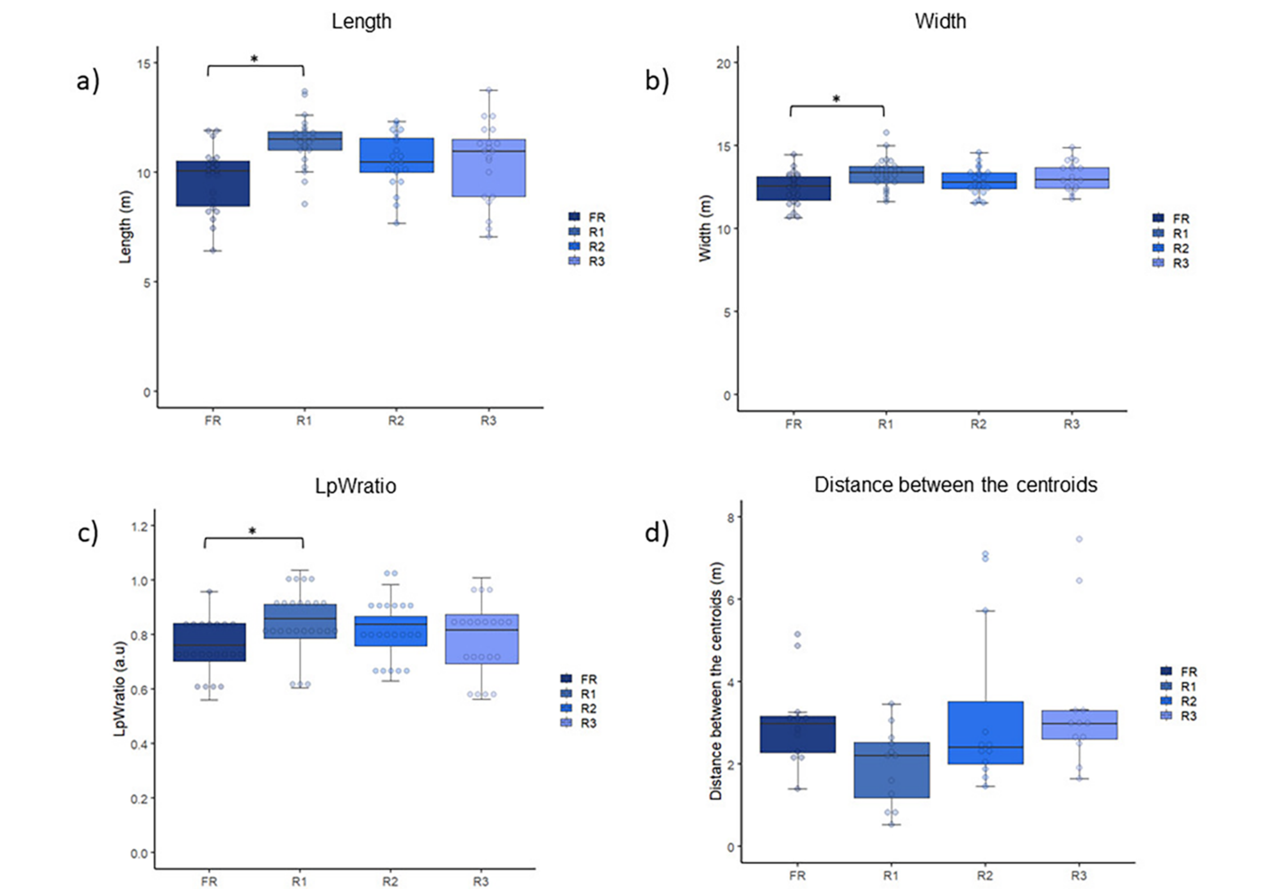

FIGURE 3
Comparison of the (A) length, (B) width, (C) lpWratio, and (D) distance between centroids between the four experimental conditions. *significant differences.

and R2 than in the protocols R3 and FP. No differences were observed in the in-width displacements. Figure 5 shows the data regarding this analysis. These results indicate that the presence of rules allowed players to better coordinate their movements during the game.

4 Discussion

This study aimed to compare the tactical behavior and performance of U-20 soccer players during small-sided games (SSG) with implicit and explicit informational constraints. Four distinct experimental conditions were examined, namely, a free rule (FR), an explicit rule (R1), an implicit rule (R2), and a combined rule (R3). The main results indicate that players achieved a higher percentage of in-phase coordination tendency in the explicit rule condition, which confirms the hypothesis. Also, it has been shown that summing up implicit and explicit rules can hinder players' performance. Finally, the explicit condition leads players to occupy the pitch in a stretched way, indicated by higher length and width values. The study's innovation lies in exploring how implicit and explicit informational constraints affect players' performance in high-complexity tactical scenarios. The anticipated outcome was a superior tactical performance under explicit conditions, substantiated by the findings, although the effect sizes are small.

In the current study, players showed higher in-phase synchronization (in-length) values in the explicit instruction condition than in the FR. According to Raab (13), explicit learning is more advantageous than implicit when complex tasks are learned. For example, in soccer, the high-press defensive action should be considered a highly complex task as it requires players to effectively and timely coordinate their actions to achieve the collective goal (20), which explains why players showed higher in-phase coordination in the explicit rule condition. Lola et al. (14) in a task involving novices in a badminton decision-making task. Besides, Batista et al. (62) observed that explicit defensive technical instruction increased the ball recovery in inner zones compared to a non-instruction condition in semi-professional soccer players. Raab (13) argues that some explicit learning, guided by "if-then" rules (such as "if you regain the ball further on the pitch, you will score an additional point"), is required for players to learn how to map appropriate decisions during the tasks. Therefore, as explicit learning is required during specific decision-making in sports when perceptual-cognitive requirements are high, the tactical performance during the defensive high-press benefits from

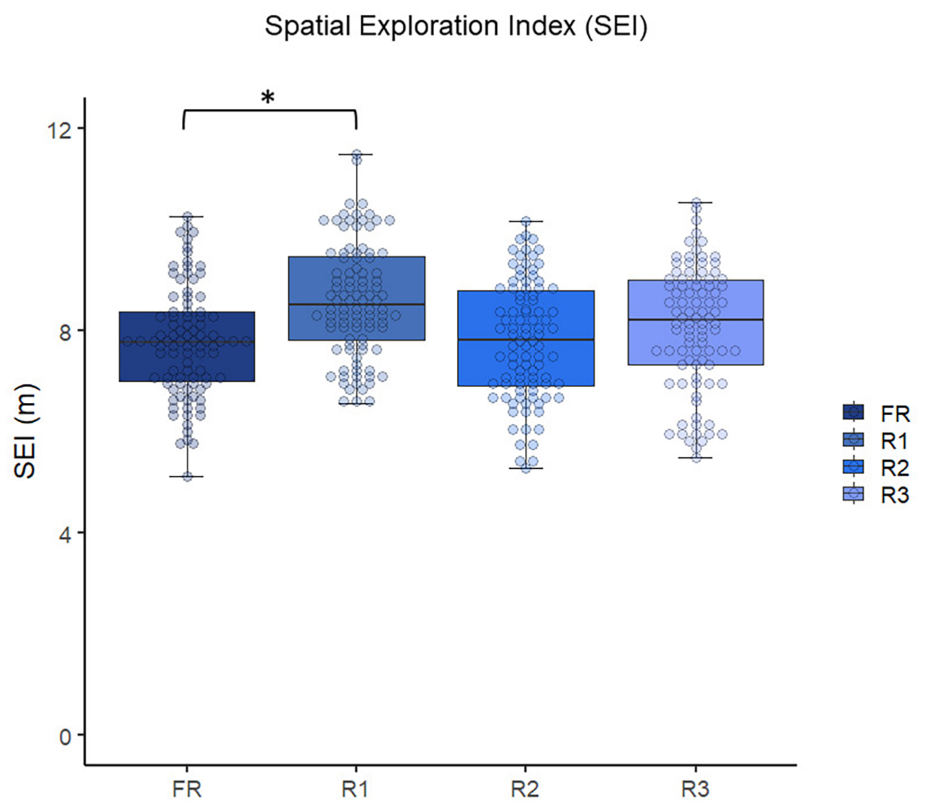

FIGURE 4
Comparison of the SEI between the four experimental conditions. *significant differences.

providing players with explicit instructions—experimental condition R1 - which explains the current results.

Interestingly, the protocol combining the two rules did not induce similar differences as observed in the explicit instruction condition. Although players received the same information, they adopted a game pattern close to the control situation (without additional rules). Even if informational constraints can modify players' actions (63), these constraints can emphasize some specific affordance landscapes (64), and exaggerating the information provided might lead players to neglect them and adopt a free-play pattern. In line with this, Machado et al. (65) observed a low attacking pattern variability when more rules were added to the game. Therefore, from a pedagogical point of view, coaches should cautiously increase the number of rules in a given game, as providing players with excessive information can reduce their ability to explore affordances and promote few self-organization and adaptation actions. This is particularly important considering the current study sample comprised high-level U-20 players from elite youth academies. Notwithstanding, the experience and accumulated training hours did not reduce the impairment caused by the excessive number of rules provided in the R3 condition, which could indicate a more deleterious effect in younger groups.

Besides the abovementioned rationale, it is worth pointing out the role of the players' synchronization measurement as a performance indicator in soccer (38). Sampaio and Maçãs (66) argued that interpersonal coordinated movements are fundamental in improving players' skills. This coordination seems to be also related to players' experience, as Figueira et al. (67) showed that older players present better intra-team synchronization. However, it seems essential to consider the coordination regarding the pitch's axes (longitudinal and lateral). At this point, Duarte et al. (68) verified that professional soccer players are keener to coordinate their behavior in-depth than in width due to the attraction caused by the goals. A similar result was also observed in the current study. Therefore, future studies are encouraged to expand the link between coordination and performance, looking primarily at the in-depth coordination patterns.

In the current study, players' spatial occupation was also measured. At this point, higher SEI, width, length, and LpWratio were observed in the R1 condition compared to the FR. Therefore, it can be assumed that the explicit rule led to a more spread and variable tactical positioning on the pitch. Previous studies showed a higher SEI when the players were less familiar with the task (69–71). For example, higher values of SEI were observed in the progression-to-the-target SSG than in the regular format (71). Also, Clemente (69) showed higher SEI values in the half-size condition compared to the full-size. Therefore, it could be assumed that the high-press defensive strategy, which was more prominently emphasized in the explicit-rule condition, generated a less familiar tactical scenario, which required a higher tactical exploration of the players, which explains the current findings. Another possible explanation is related to the area to cover during the game. Gonçalves et al. (72) showed that higher SEI values are

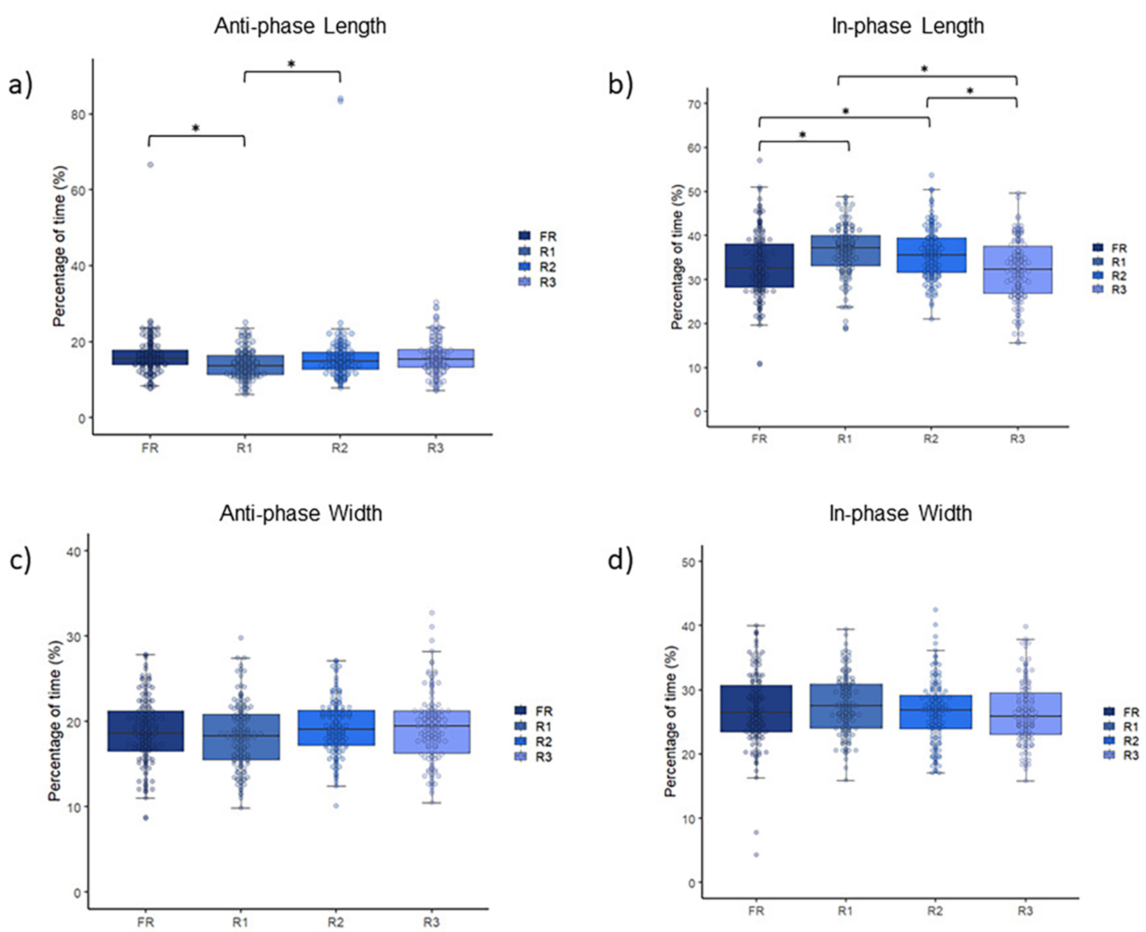

FIGURE 5
Comparison of the (A) in-phase length, (B) anti-phase length, (C) in-phase width, and (D) anti-phase width between the four experimental conditions. *significant differences.

associated with larger covered areas during the games. Therefore, pressing the opponent high, emphasizing more clearly the explicit rule condition, enlarged the areas to cover, and increased the SEI values. Therefore, the main explanation for the higher SEI values found in the current study in the R1 condition might rely not on the nature of the rule (explicit vs. implicit) but on the intended behavior (defensive high-press).

Besides, the R1 condition elicited higher values of length, width, and LpWratio, which indicates players' tendencies to enlarge the team's shape during this condition. The previously discussed higher SEI might explain the larger collective spatial occupation of the players. At this point, Barnabé et al. (73) showed that older and more experienced players exhibited a higher dispersion and expanded positioning during the attack. As the current study analyzed the tactical behavior of highly trained U-20 athletes, it is assumed they are keener to enlarge the team shape when required (e.g., during a defensive high-press action from the opposing team), which aligns with the current findings. Also, Praça et al. (71) suggested that off-the-ball players should move to create passing opportunities far from the ball to allow the team to progress toward the opposing goal, which could increase the spatial occupation. In the present study, due to the tougher defensive press observed in the R1 condition, offensive players might similarly enhance their off-the-ball movements by exploring more spaces (higher SEI) and enlarging the team shape (higher length and width), which explains the current findings. Although high-press might rely on the compactness of the defending team (74), the length might be higher due to the impossibility of keeping compactness in the offensive midfield (due to the offside rule). Together, the higher length during high-press, the need to increase the team shape from the offensive team, and the players' ability to adjust their behavior to these new contextual features explain the current findings.

For the distance between the teams' centroids, there were no significant differences between the experimental conditions. This result is in line with a previous one (75) that showed no differences between the teams' centroids' distances in different game moments, which suggests a low sensibility of this variable to detect changes concerning game strategies (such as the high-pressing). On the other hand, Folgado et al. (20) found a higher team's centroids distance in the 3 vs. 3 game than in the 4 vs. 4 in U-13 soccer players. However, the authors did not report using the offside rule, which might explain this divergence. Specifically, players are encouraged to move deep on the field without the offside rule, increasing the length (52). Consequently, players from the defending team are encouraged to protect their own goal instead of pressing high (76), which might have caused the higher centroid distance observed. Also, Frencken et al. (77) compared the teams' centroid positions and verified a strong association between the two teams in the longitudinal axis (length of the pitch) and that smaller pitches resulted in lower teams' centroid distances. Therefore, the tendency of coupling in-length displacements and the reduced available pitch in the current study might have reduced the possibility of the teams adapting their position—concerning the position of the team's centroid—under different experimental conditions. Notwithstanding, future studies in larger pitches are encouraged to test such an assumption.

The present study has some limitations that should be considered carefully. One is that game phases were not analyzed separately, as suggested in the literature (31, 78). This may have affected the results on positional data during game phases as the differences between defense and offense positioning strategies (e.g., high-press vs. low-block) were not captured. This also is likely to increase the variability of the data, which might explain the current small effect size values for some variables. Therefore, it is suggested that future studies develop methods to split position data into game phases. For this reason, future studies should test the link between instructional constraints and defensive high-press in larger pitches. Also, it has been shown that machine learning and artificial intelligence techniques might be useful in identifying key performance indicators in soccer (79–81). Therefore, it would be useful to integrate the current research problem into a multidimensional performance analysis to identify which performance components are strongly influenced by explicit/implicit instructions. Finally, the findings may not reflect the chronic effects of positional play; thus, longitudinal studies are encouraged.

From a practical standpoint, coaches should consider that the way information is provided to the players acutely impacts their performance in game-based tasks. When training complex tactical content, providing explicit information can enhance tactical performance, even if only in the short term. This approach is particularly useful in pre-match training sessions, where acute strategic adjustments are often emphasized. However, overloading players with additional information and combining implicit and explicit instructions may diminish performance and impede tactical learning. For this reason, choosing the right information seems more important than providing extensive, cumulative instructions.

5 Conclusion

Providing the players with explicit instructions on complex tactical concepts significantly increased their performance. From a practical point of view, this means that coaches should consider incorporating explicit tactical instructions in their training regimens to enhance player adaptability and tactical execution. On the other hand, summing up instructional constraints can impair players' self-adaptation processes during the game. Therefore, coaches should carefully select information to be given to the athletes, as the "more-is-better" approach has been denied by the current study. Furthermore, the explicit instruction condition was the only one showing regular differences from the control (no instructions) condition. Finally, the tactical performance was higher under the explicit instruction condition and characterized by a game with larger pitch occupation (higher length and width) and spatial exploration (SEI).

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 Universidade Federal de Minas Gerais. 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

CA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. LA: Funding acquisition, Project administration, Resources, Writing – original draft, Writing – review & editing. IL: Writing – original draft, Writing – review & editing. FM: Formal Analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. BB: Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. SR: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing – original draft, Writing – review & editing. GP: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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Talent selection in 3 × 3 basketball: role of anthropometrics, maturation, and motor performance

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Introduction: 3 × 3 basketball is becoming more and more professionalized, which is leading to a growing interest in talent development and talent selection. Different studies have demonstrated relevant factors in the talent selection process of 5v5 basketball but not in 3 × 3 basketball. Therefore, this study investigated the main predictors in the talent selection process in 3 × 3 basketball athletes.

Methods: A total of 192 athletes (M_{age} = 16.11 ± 0.45 years; n = 85 were female) 3 × 3 basketball athletes were assessed for various anthropometric and motor performance variables as well as maturity status. All assessments were carried out during selection camps for the German "under 17" youth national team. Binomial logistic regression was conducted to determine which variables predicted selection (either 'selected', n = 30 female and n = 34 male, or 'non-selected', n = 55 female and n = 73 male).

Results: The regression model was statistically significant in female athletes (χ^2 (3) = 26.86, p < .001). It explains 37.9% (Nagelkerke's R^2) of the variance in selection status and suggests that the general motor-performance component (p < .001) and the anthropometric- and maturation-related component (p = .004) seem to be relevant for being selected. In male athletes, the binomial logistic regression model was also statistically significant (χ^2 (3) = 11.38, p = .010) with explaining 14.2% (Nagelkerke's R^2) of the variance in selection status but only the anthropometric- and maturation-related component (p = .004) predict selection.

Discussion: Anthropometric conditions (such as body height, body weight, and wingspan) and the maturity status are particularly important in talent selection in 3 × 3 basketball for both sexes. Regarding motor-performance variables, we found a predictive value for talent selection only in females (without sprinting), but not in males which means that more 'athletic' female athletes seem to be favoured in talent selection. The results suggest that the talent selection process might be biased by maturation status even in middle adolescence. Therefore, coaches who decide on athletes' selection should be aware of the temporal advantages induced by earlier maturation when evaluating talented athletes and should consider strategies such as bio-banding to evaluate the real and potential value of talented athletes.

KEYWORDS
APHV, maturity status, talent development, team sports, talent predictors

1 Introduction

In many team sports such as volleyball, handball, or basketball, there is an increasing interest in new ways of implementation apart from the classic ones. For example, in basketball, there is a variation called streetball that is played three vs. three on a half court with only one basket. It is characterized by an intermittent profile with a 1:1 work: rest ratio, with games lasting approximately 15 min and short ball possessions (6–8 s). Better shooting and defensive efficiency or low number of turnovers are some of the key technical-tactical indicators of the performance profile in a physically demanding game with quick actions such as accelerations, decelerations, changes of direction and explosive jumps [for an overview (1)]. In the late 2000s, the International Basketball Federation (FIBA) started its first attempt to institutionalize streetball or so-called "3 × 3 basketball" with standardized rules. Subsequently, the game experienced a considerable increase in popularity and global participation with 182 national federations becoming involved, finally leading to its inclusion in the Tokyo Olympic games in 2021 (2).

Hence, it is not surprising that 3 × 3 basketball is becoming more and more professionalized with increasing interest in talent development aiming to compete and win at the highest (international) level. Typically, one of the first steps in this talent development process is to select the most talented athletes in terms of sport-specific requirements such as motor performance or anthropometric conditions (3, 4). Talent selection refers to the on-going process of choosing athletes within the development program who meet relevant sport-specific requirements to progress into a future team (3). Whereas there are currently no studies in 3 × 3 basketball that have investigated relevant factors in the talent selection process, there are already many analyses in "classic" basketball (5v5) that have identified different factors with a relevance for the selection of young basketball athletes (5–8). One of these factors are anthropometric conditions such as body height, body weight, or wingspan (8, 9). For example, Soares et al. (10) showed that among young female basketball athletes (between 10.5 and 15.5 years), taller athletes are selected more often for higher competitive levels. Also, Torres-Unda et al. (8) investigated 13- to 14-year-old male basketball athletes and found that elite athletes were taller compared to nonelite athletes. In general, the importance of height and other body dimensions (body weight, wingspan) are well documented in basketball (11, 12). Looking at senior basketball, some studies have shown that body height is one of the main predictors of performance (11), and teams with taller athletes are ranked higher in the FIBA World Cup compared to teams with shorter athletes (13). Such performance predictors are closely linked to coaches' decisions to pick players for the highest level. For example, Cui et al. (14) show that body height is an essential prerequisite for being picked in the National Basketball Association (NBA) draft.

Besides anthropometric factors, other important aspects in talent selection are the physical and physiological capacities (15). Basketball is characterized by different strength- and power-related actions such as jumping, sprinting, or shuffling (16, 17). Therefore, motor performance seems to be essential for elite (youth) athletes. Torres-Unda et al. (8) underlined the importance of physical fitness and found that selected athletes outperform non-selected athletes in physical tests such as sprints, jumps, and endurance tests. Joseph et al. (18) postulated the relevance of power-related motor-performance variables and demonstrated that selected female athletes in certain age cohorts show better performance in 20 m sprint time or countermovement jump (CMJ) height than non-selected athletes. Also, Ramos et al. (7) showed that athletes in higher-ranked teams perform better in agility performance tests than those in lower-ranked teams. 3 × 3 basketball is also characterized by a fast pace with numerous quick and high-intensity actions. However, medium- to high-intensity actions during live time are greater in 3 × 3 basketball than in 5v5 basketball [for an overview (1)]. More specifically, 3 × 3 athletes perform more change of directions, accelerations, and decelerations per minute (19). Furthermore, competitions are organized in tournaments with several games per day on consecutive days (20), and this imposes a high physical load. Therefore, the importance of motor performance could be even greater in 3 × 3 basketball than in 5v5 basketball.

In addition to these two factors, Malina et al. (21) postulated that the talent selection process is biased by biological maturation–that is, the progress toward the adult or mature state. The biological maturity status of individuals with the same chronological age can vary widely, especially during different stages of adolescence (between 10 and 16 years). These differences depend on various factors such as the time of fastest upward growth defined as the age of peak height velocity (APHV). Whereas females reach their APHV at approximately 12 years, males reach it at around 14 years (22). Nevertheless, this can vary from individual to individual, with some reaching this growth spurt several years later or earlier than others (23). APHV is related to major changes in different systems. For example, previous studies have shown that growth and sex hormones strongly increase in concentration at this stage (24, 25), and that they influence anthropometric conditions (e.g., body height, body weight, body segments) and/or motor-performance variables [e.g., strength (26)]. This can result in large differences between children and young adolescents of the same chronological age in terms of anthropometric conditions and motor-performance variables (27). For the process of talent selection, these interindividual differences between adolescents can lead to temporary advantages or disadvantages in their age cohorts (28, 29). Early-matured athletes (meaning APHV is low) could be taller and stronger and therefore will be selected more often than late-matured athletes (meaning APHV is high) (5, 30).

In recent years, more and more studies have investigated the influence of maturity status on different anthropometric and motor-performance-related variables as well as on talent selection in team sports (5, 31–34). Most studies found that—expectedly—early-matured athletes performed better in motor-performance tests, were taller, and were selected more often for squads [for an overview (27)]. In basketball, some studies investigated the influence of maturity status and found advantages for early-matured adolescents on anthropometric and motor-performance variables, as well as in career progression. For example, Arede et al. (31) demonstrated that basketball athletes with a lower APHV (early-matured) are taller and heavier than athletes with a higher APHV (late-matured). Guimarães et al. (35) showed advantages in sprint or change-of-direction (COD) test as well as in anthropometric conditions (e.g., body height, body weight) for early maturation groups. Also, according to Ribeiro Junior et al. (9), early-matured athletes had a greater chance of reaching the highest national league. However, these maturation-related benefits are temporary and diminish as the athletes mature. For example, early-matured females and males do not exhibit a higher final body height than their on-time or late-matured peers (36, 37). In addition, Lefevre et al. (38) found that the late-matured males not only caught up with the early-matured males in adulthood, but also performed better in explosive strength tests.

Most of these studies examined the maturity status in male athletes in early stages of adolescence (between 12 and 14 years)– that is, at the time when the growth spurt often sets in. But there are also some studies on the influence of maturation after the growth spurt in middle or late adolescence (15–16 years). These could still find advantages for groups with a low APHV. For example, Luna-Villouta et al. (39) and Vandendriessche et al. (40) found that interindividual differences related to biological maturation are still present at the ages of 15–16 years. In this context, Arede et al. (5) reported on the influence of maturity status in 5v5 basketball at an age of around 15 years and concluded that maturity is a decisive factor in the selection of the "under 16" national team. Consequently, maturity status could influence talent selection processes at all stages of adolescence and needs to be considered to ensure a fair system where talented athletes are prevented from not being selected due to later maturation (41). This is particularly important when considering effects such as those described in the "underdog hypothesis", which proposes that later maturing athletes need to be more advanced in technical-tactical skills to remain competitive in talent selection processes (42). However, earlier maturation could result in the selection of less skilled athletes to the detriment of more skilled but later maturing athletes. Kelly et al. (43) also found support for such effects in 5v5 basketball. Nevertheless, in recent years, the FIBA has organized international 3 × 3 basketball youth tournaments for certain age groups. Therefore, in Germany, talent development and selection in 3 × 3 basketball are still organized in annual age groups with specific cut-off dates based on an athlete's chronological age. Although the approach of classifying teams into certain age groups (e.g., "under 17" meaning the athletes are at the age of 16 years or younger) is intended to provide a fair system of practice and competition (44), it does not take biological maturation into account and therefore does not ensure fair conditions for all.

To sum up, talent selection is based on a wide range of factors, but anthropometric conditions, motor-performance variables, and maturity status seem to be the relevant factors in "classic" basketball. In 3 × 3 basketball, to the best of our knowledge, there is still no research investigating which factors in the talent selection process are mainly used to distinguish between selected and non-selected athletes (for females and males). Therefore, the aim of this study was to investigate the main predictors of selection and non-selection in male and female athletes. Based on current literature in 3 × 3 (19, 20) as well as on studies in classic 5v5 basketball (5, 7, 8), we hypothesized that anthropometric conditions and motor-performance variables would play a crucial role in the talent selection process and explain the variance in selected and non-selected athletes. Furthermore, even though talent selection in 3 × 3 basketball starts very late (beginning at "under 17" national team) compared to other team sports, we hypothesized that maturation status would have a major influence on selection.

2 Material and methods

Data were collected in September 2021 and September 2022 in two separate cohorts of athletes. All measurements were carried out as a part of the 3 × 3 basketball "under 17" national selection tournament of the German Basketball Federation (Deutscher Basketball Bund, DBB). This annual tournament is one part of a multi-stage selection process with the aim to form the 3 × 3 basketball "under" 17 youth national team. It is the very first stage of talent selection at the national level. In order to be invited to this event, all athletes must be part of their respective 3 × 3 basketball state teams (e.g., Bavaria, Lower Saxony), for which they are selected by qualified regional coaches mainly on the basis of their performance in competitions in 5v5 basketball as well as in 3 × 3 basketball. This means this population is pre-selected at regional level and sent to national selection tournament by the state federations. Approximately one third of the athletes participating in the annual national tournament are selected based on coaches' evaluations of the athletes' performance at the national selection tournament. These athletes will then be invited to the so-called "selection training program", where the final 3 × 3 basketball "under 17" youth national team is formed.

Each nation can send one national team to the international championships, usually consisting of four players in 3 × 3.

2.1 Participants

A total of 192 German young female and male athletes ($M_{age} = 16.11 \pm 0.45$ years; $n = 85$ were female) were included in this study. All athletes were in reportedly good physical condition. Three participants were partly excluded (two female athletes and one male athlete) because they could then not perform the whole test battery due to an existing injury. One female did only perform the chest-pass test and the other female did not perform the change-of-direction (COD) test. The male athlete could not perform the drop-jump (DJ) test. These athletes were included in the analysis for the tests in which they participated. All athletes were part of 3 × 3 basketball "under 17" youth state teams and participated in a developmental program of their respective state team. However, all athletes started to compete in 5v5 basketball and still compete in it, but the developmental programs and youth teams (state and national) are separate. Athletes and their parents or legal representative(s) were informed based on the declaration of Helsinki about the testing protocols and gave written consent. The procedures were approved by Goethe University Frankfurt am Main, Department of Psychology and Sports Science, Ethics Committee (2021-30, June 28, 2021).

2.2 Procedure

Upon arriving and after being informed about the schedule, athletes' birth dates were collected. Subsequently, athletes were assessed in anthropometry following a standardized physical warm-up and motor-performance tests. All tests were performed in an indoor sports facility.

2.3 Measures

2.3.1 Anthropometry

Similar to previous investigations in 5v5 basketball (6, 32, 45), anthropometric assessments consisted of measurements of body height in cm, sitting height in cm, leg length in cm, wingspan in cm, and body weight in kg. Body height was measured using a laser rangefinder (±0.1 cm; Bosch, Gerlingen, Germany); sitting height and leg length, using a measuring tape (±0.1 cm; Busduga, Leutkirchen, Germany); and wingspan, using a measuring tape (±0.1 cm; Stanley, Idstein, Germany). Body weight was measured in sports clothing without shoes and was assessed using a digital scale (±0.1 kg; Bohmann, Hamburg, Germany). Following Mirwald et al.'s (46) procedure, maturity status (APHV) was calculated with the BioFinal 3.4 software (47) that uses sex-specific formulae. APHV was used for further analyses.

2.3.2 Sprint test

Athletes performed two maximal sprints of 20 m to assess sprint performance (48). Split time at 5 m and 10 m as well as at 20 m were measured with a photocell system (Microgate, Bolzano, Italy). Athletes were instructed to carry out a self-initiated start from a standardized standing position one meter behind the starting line. They performed two trials of sprints. If the two trials were too far apart from each other (>10%), they performed a third trial. Between trials, athletes had a short break (1.5 min). The fastest time trial at 5 m split time was used for further analyses. Analyses were based on the time for 5 m, the time between 5 m and 10 m, and the time between 10 m and 20 m.

2.3.3 Vertical jump-and-reach test

Maximal vertical jump-and-reach height was assessed with a self-constructed device similar to the device used by Muehlbauer et al. (49). The height of the lowest plastic swivel vane was measured with a laser rangefinder (Bosch, Gerlingen, Germany). The plastic swivel vanes had a thickness of 1.0 cm. Athletes were instructed to jump from the side of their dominant hand (lefthanders start from the left side; righthanders start from the right side). Jumps were performed inside a 3 m area without any other instructions except for jumping as high as they could and reaching the highest plastic swivel possible. The athletes performed two jumps. A third jump was performed when the first two were more than 10% apart from each other. The highest jump was used for further analyses.

2.3.4 Countermovement jump (CMJ)

Maximal CMJ height was assessed using a photocell system [(50); OptoGait, Micogate, Bolzano, Italy]. Athletes performed two maximal CMJs. Jumps were standardized with hands on the hips, a knee flexion angle of about 90°, and the instruction to jump as high and explosively as possible. The highest jump was used for further analyses.

2.3.5 Drop jump (DJ)

Maximal DJ height and contact time were assessed to calculate the reactive-strength index (RSI) according to the protocol of Markwick et al. (51) and using a photocell system (OptoGait, Micogate, Bolzano, Italy). Athletes performed two bilateral DJs from a 24 cm high box. All jumps were performed in a standardized fashion with the hands on the hips. Athletes were instructed to lean forward with one leg (leg could be chosen by athletes) and let themselves drop to the ground. As soon as they hit the ground, they should jump as quickly as possible and as high as possible. The jump with the highest RSI was used for further analyses.

2.3.6 Change-of-direction (COD) test

To test the ability to change directions, athletes performed a COD test by using a photocell system (±0.1 s; WK, Ditzingen, Germany). Setting and test protocol was based on Willberg et al. (52). Athletes performed the COD test twice. If the deviation between both test trials was too high (>10%), a third test trial was carried out. The fastest run was used for further analyses.

2.3.7 Chest-pass test

Chest-pass test was used in similar studies to measure the explosive upper-body strength (7, 53). The chest-pass test was carried out on a basketball court with an official 3×3 basketball (Wilson Sporting Goods, Chicago, United States of America). Athletes stood in a standardized position behind the line. The instruction was to hold the ball at chest level and throw it as far as possible with both hands in a linear way. The length was recorded with a measuring tape (±0.1 m; Stanley, Idstein, Germany). The best result was used for further analysis.

2.4 Statistical analysis

Data were analyzed with IBM SPSS statistics Version 29.0.0.0 for Macintosh (IBM, New York, USA). All analyses were computed for each sex separately.

To avoid overestimation of the binomial logistic regression model, data were reduced by using principal component analysis (PCA) with varimax rotation. We used varimax rotation to simplify the factors by maximizing the variance of loadings within factors, across variables, for easier interpretation of the components. Afterwards, the resulting components of the PCA were analyzed in a binomial logistic regression to determine which components predicted talent selection (54). The selection status of an athlete was coded in binary form and used as the dependent variable. The descriptive data are presented as means and standard deviations. The significance level was set *a priori* at $p < .05$.

3 Results

Descriptive data from all tests for female ($n = 85$) and male athletes ($n = 107$) are shown in Table 1.

3.1 Predictors of talent selection

3.1.1 Principal component analysis (PCA)

A PCA (varimax rotation) was calculated to reduce the number of variables for the following binomial logistic regression in order not to overload the model. The Kaiser-Meyer-Olkin test of sampling adequacy (KMO) and the Bartlett test of sphericity were calculated for each sex to check whether the data were suitable for PCA. According to Hair et al. (55), practical significance is given when the component loading is $\geq \pm .500$. Therefore, only component loadings $\geq \pm .500$ were linked to a component.

For female athletes, KMO was.75 and the Bartlett test of sphericity was $p < .001$, χ^2 (66) = 565.341. Concerning the Kaiser rule, PCA revealed three components with an eigenvalue greater than 1.0 (55). Additionally, a scree plot (56) favoured a three-component solution. This three-component solution explained a cumulative variance of 69.43% (1st component: 35.97%; 2nd component: 23.52%; 3rd component: 9.93%). Chest pass, vertical jump and reach, CMJ, sprint 5–10 m, sprint 10–20 m, DJ RSI, and the COD test loaded on the first component (general motor-performance component); age of peak height velocity (APHV), body height, body weight, and wingspan, on the second component (anthropometric- and maturation-related component); and sprint 0–5 m, sprint 5–10 m, and sprint 10–20 m, on the third component (sprint component). Component loadings for female athletes are shown in Table 2.

For male athletes, KMO was.71 and the Bartelett test of sphericity was $p < .001$, χ^2 (66) = 688.92. Similar to the PCA of female athletes' data, three components with an eigenvalue greater than 1.0 were found and the scree plot also favoured a three-component solution. This three-component solution explained a cumulative variance of 68.18% (1st component: 32.44%; 2nd component: 26.47%; 3rd component: 9.28%). APHV, body weight, body height, and wingspan loaded on the

TABLE 2 Principal component loadings for female athletes.

Item	Component 1	2	3
APHV		−.842	
Body height		.906	
Body weight		.768	
Wingspan		.905	
Chest pass	.519		
Jump and reach	.810		
CMJ	.817		
Sprint 0–5 m			.846
Sprint 5–10 m	−.455		.660
Sprint 10–20 m	−.554		.678
DJ RSI	.773		
COD test	−.731		

Rotation method: varimax with Kaiser normalization. Loadings smaller than 400 are not represented. APHV, age of peak height velocity; CMJ, countermovement jump; DJ RSI, drop jump reactive strength index; COD, change of direction.

TABLE 1 Descriptive data from all sociodemographic, anthropometric, and motor-performance variables for both sexes.

	Female				Male			
	Selected		Non-selected		Selected		Non-selected	
Variable	*n*	M ± SD	*n*	M ± SD	*n*	M ± SD	*n*	M ± SD
Chronological age	30	15.99 ± 0.52	55	16.07 ± 0.43	34	16.12 ± 0.47	73	16.19 ± 0.41
Age of peak height velocity	30	12.26 ± 0.49	55	12.48 ± 0.44	34	13.18 ± 0.76	73	13.50 ± 0.64
Birth quartile (1st/2nd/3rd/4th)	30	23%/13%/43%/20%	55	27%/27%/29%/16%	34	35%/26%/15%/24%	73	42%/19%/22%/16%
Body height (cm)	30	176.83 ± 7.60	55	173.85 ± 6.69	34	190.43 ± 7.84	73	185.87 ± 7.79
Body weight (kg)	30	70.51 ± 9.34	55	67.40 ± 9.78	34	81.39 ± 10.83	73	76.36 ± 10.89
Wingspan (cm)	30	181.01 ± 8.93	55	176.79 ± 8.12	34	197.34 ± 7.65	73	191.97 ± 9.30
Chest pass (cm)	30	11.21 ± 1.22	55	10.53 ± 0.90	34	14.73 ± 1.61	73	14.21 ± 1.61
Jump and reach (cm)	30	53.92 ± 5.56	54	49.75 ± 5.38	34	73.70 ± 8.41	73	70.37 ± 6.44
CMJ (cm)	30	31.40 ± 4.85	54	27.81 ± 4.12	34	37.69 ± 5.73	73	37.22 ± 5.14
DJ RSI	30	1.39 ± 0.32	54	1.21 ± 0.29	34	1.55 ± 0.37	72	1.51 ± 0.34
Sprint 0–5 m (s)	30	1.06 ± 0.11	54	1.06 ± 0.08	34	0.98 ± 0.08	73	0.99 ± 0.08
Sprint 5–10 m (s)	30	0.80 ± 0.03	54	0.82 ± 0.04	34	0.74 ± 0.03	73	0.75 ± 0.04
Sprint 10–20 m (s)	30	1.43 ± 0.07	54	1.48 ± 0.06	34	1.31 ± 0.06	73	1.32 ± 0.06
COD test (s)	30	7.90 ± 0.53	53	8.10 ± 0.47	34	7.28 ± 0.39	73	7.31 ± 0.44

CMJ, countermovement jump; DJ RSI, drop jump reactive strength index; COD, change of direction.

TABLE 3 Principal component loadings for male athletes.

Item	Component 1	2	3
APHV	−.858		
Body height	.899		
Body weight	.843		
Wingspan	.891		
Chest pass			−.776
Jump and reach		.855	
CMJ		.881	
Sprint 0–5 m			.706
Sprint 5–10 m		−.701	
Sprint 10–20 m		−.743	
DJ RSI		.623	
COD test		−.402	.561

Rotation method: varimax with Kaiser normalization. Loadings smaller than 400 are not represented. APHV, age of peak height velocity; CMJ, countermovement jump; DJ RSI, drop jump reactive strength index; COD, change of direction.

TABLE 4 Binomial logistic regression for female and male athletes.

Sex	Variable	B (*SE*)	Wald	*df*	*p*
Female	Constant	0.825 (.290)	8.079	1	.004
	General motor-performance component	−1.189 (.341)	12.168	1	<.001
	Anthropometric- and maturation-related component	−0.903 (.317)	8.108	1	.004
	Sprint component	0.491 (.280)	3.081	1	.079
Male	Constant	0.861 (.230)	14.044	1	<.001
	Anthropometric- and maturation-related component	−0.737 (.253)	8.477	1	.004
	General motor-performance component	−0.266 (.220)	1.458	1	.227
	Muscular-coordination component	0.163 (.218)	0.559	1	.455

first component (anthropometric- and maturation-related component); vertical jump and reach, CMJ, sprint 5–10 m, sprint 10–20 m, DJ RSI, and the COD test, on the second component (general motor-performance component); and chest pass, sprint 0–5 m, and the COD test, on the third component (muscular-coordination component). Component loadings for male athletes are shown in Table 3.

3.1.2 Binominal logistic regression

The results of the binomial logistic regression are summarized in Table 4 for both sexes. Multicollinearity was checked according to Tabachnick and Fidell (54) but was not present ($r > .90$) for either sex. For female athletes, the overall model was statistically significant, χ^2 (3) = 26.86, $p < .001$, and included the general motor-performance component ($p < .001$) and the anthropometric- and maturation-related component ($p = .004$). The model explained 37.9% (Nagelkerke's R^2) of the variance in selection status. It correctly classified 73.5% of the female athletes and the success rate of predicting non-selected athletes was 83.0% while it was 56.7% for selected athletes. For male athletes, the overall model was also statistically significant, χ^2 (3) = 11.38, $p = .010$, but included only the anthropometric- and maturation-related component ($p = .004$). The model explained 14.2% of the variance (Nagelkerke's R^2) in selection status, and it correctly classified 69.8% of the male athletes. The success rate for predicting non-selected athletes was 90.3% and for selected athletes 26.5%.

4 Discussion

The aim of the present study was to identify the main predictors in the talent selection process for 3 × 3 basketball that distinguish between selected and non-selected athletes. We hypothesized that anthropometrics, motor-performance variables, and maturity status would explain the variance in the talent selection process. As expected, our results show that anthropometric conditions (such as body height, body weight, and wingspan) and the maturity status seem to be relevant factors for selection in both sexes. This means that selected female and male athletes were taller, heavier, had a greater wingspan, and an advanced maturity status compared to non-selected athletes. Regarding the motor-performance variables, we found a predictive value for talent selection only in female athletes (without sprinting), but not in male athletes.

Results on anthropometric conditions are in line with the current literature on classic basketball that also shows advantages for selected athletes in different anthropometric conditions. For example, selected athletes are taller (6), heavier (57), and have a greater wingspan (12) than non-selected or lower-ranked athletes. Many studies (6, 9, 35, 58) have investigated classic youth basketball athletes in different age groups and indicated the importance of being tall in the talent selection process in all age groups (ranging from 10 years to 16 years). Ribeiro Junior et al. (9) examined the career progression of youth athletes and found that being tall is one of the main reasons for reaching the highest league. Also, Cui et al. (14) examined the draft of the NBA and postulated that even in the transition to senior basketball, being tall is a key determinant for being drafted. Consequently, anthropometric conditions seem to be very relevant in basketball and are also related to game performance and success. In this context, some studies have examined the relationship between technical actions and found that taller athletes have advantages in different technical skills such as rebounding, passing, or shooting compared to their shorter peers (8, 11, 59). For example, Garcia-Gil et al. (11) found that technical actions such as shooting or passing correlate significantly with greater wingspan. These anthropometric characteristics are important in basketball for both defensive actions (e.g., covering wider and higher space or blocking shots from shorter athletes) as well as offensive actions (e.g., shooting or dunking). Comparing 3 × 3 with 5v5 basketball, the number of passes, shots, and rebounds in 3 × 3 basketball is higher compared to the classic variation (60). Due to an increased frequency of technical actions as well as a reduced number of players, the importance of anthropometrics could be even greater in 3 × 3 compared to 5v5 basketball.

Based on this, it is not surprising on the one side that coaches focus on height and other anthropometric conditions in the talent selection process. But, on the other side, the results of this study and of previous research (5, 7, 8) show that anthropometric conditions correlate with maturity status. This means that early-matured athletes are taller, heavier, and have a greater wingspan than late-matured athletes. This is shown especially for early adolescence (around growth spurt), but our results demonstrate an influence even in middle adolescence. The talent selection process in 3 × 3 basketball is very late compared to, for example, football (starting around two to three years earlier). The chronological age of the athletes in this study was 16.04 (females) and 16.16 (males), which means that they were in middle adolescence and past their APHV, which was at age 12.40 in females and at age 13.40 in males. Consequently, the talent selection process could be biased by maturation status in all stages of adolescence. In 5v5 basketball, different studies have already shown that early-matured athletes tend to be selected in preference to late-matured athletes (5, 8, 57). In this context, Leyhr et al. (6) examined the influence of different factors of the talent selection process in 5v5 basketball in Germany and found significant differences in selection status with advantages for those athletes who had a lower APHV. This was also shown in a study by Arede et al. (5), who examined the discriminating variables in the Portuguese "under 16" national team. They postulated that maturity status seems to be a key variable in 5v5 basketball, and that it increases the probability of selection. Torres-Unda et al. (59) demonstrated that early-matured athletes dominate in higher-performing 5v5 basketball teams (finalists and semifinalists) compared to lower-performing teams (quarter finalists). Overall, our results are in line with previous studies suggesting a bias even in middle or late adolescence. In addition, it should be noted that the equation formula of Mirwald et al. (46) for estimating the APHV tends to become more inaccurate with increasing chronological age (61). For instance, Kozieł and Malina (62) showed that predicted APHV is systematically later than observed APHV in early-matured athletes and systematically earlier than observed APHV in late-matured athletes. This may also explain why our estimates of APHV for male athletes were slightly higher and our estimates for female athletes were considerably higher than the average APHV in the population of athletes of different sports [for an overview, see (63, 64)]. Therefore, the maturity bias could be even greater. However, knowing the limitations of Mirwald's (46) formula, it is still a time, cost-effective and non-invasive method that does not require any measurements from people other than the athlete (e.g., parental height), as it is the case with Khamis and Roche's equation (65), and does not require any special or costly equipment, as it would be needed to determine skeletal age (23).

Even though maturity status positively influences anthropometric conditions temporarily, different studies show no advantages in terms of anthropometric conditions for early-matured female or male athletes when they are fully mature. Vizmanos et al. (36) postulated that maturity status does not affect final height in females or males. In comparison, Chen et al. (37) even found that late-matured females and males tend to have higher body height at 18 years than early-matured females and males. Nonetheless, results of both studies highlight the importance for coaches and scouts to be aware of the effects of biological maturation and refrain from overestimating (temporally) height differences. Considering that in senior 5v5 basketball, taller athletes still perform superiorly regardless of position (13), it is crucial to avoid deselection of young athletes because of temporary height differences. Furthermore, considering that Kelly et al. (43) found "underdog" effects in 5v5 basketball, late-matured athletes may reveal their more competitive technical-tactical skills as temporary height differences fade. Considering that our results show that the more mature, and therefore taller, athletes are favoured in the selection process, it is particularly important to make coaches aware of temporal height differences as well as "underdog" effects. Otherwise, coaches might deselect late-matured athletes without recognizing their true potential. In this context, Malina et al. (66) showed that when athletes were grouped by their maturity status (bio-banding) and temporal advantages disappeared, coaches noted aspects of play not ordinarily seen due to their dependence on size.

Contrary to our expectations, we found inconsistent results for the motor-performance-related component. Whereas the general motor-performance component is also included in the model (37.9% of variance; without sprints) for female athletes, it is surprising that no motor-performance-related component was included in the male model. Most studies on associations between motor performance and success in talent selection processes found a positive influence of motor-performance variables. In this context, Torres-Unda et al. (8) examined male youth athletes and highlighted the relevance of speed-related outcomes for predicting future success in 5v5 basketball. Also, Ramos et al. (7) found that male and female athletes from higher-performing teams performed better in different motor-performance tests (e.g., sprint, COD test, upper-body power test) than athletes from lower-performing teams. This underlines the relevance of power-related performance. Especially in 3 × 3 basketball, we would expect these variables to be relevant, because 3 × 3 athletes perform even more CODs, accelerations, and decelerations per minute compared to 5v5 athletes (1, 19). But in contrast to this literature and our expectations, our findings in male athletes reveal no predictive value of the motor-performance variables for talent selection. One possible explanation could be linked to the system of talent selection process in Germany, which is organized in a two-step selection procedure. In the first step, all associations of the respective states select talents from their regional team. Then, the second step consists of a final selection for the national team. Most studies that found an influence of motor-performance variables investigated the first-step selection. In this study, only the second step of the selection process was examined, meaning all invited athletes had been preselected. We speculate that there are motor-performance benchmarks that an athlete must reach to successfully pass the first-step selection. This is why this group of athletes becomes more homogeneous in the second-step selection, indicating that the importance of the motor-performance components may become more and more negligible. In this context, Leyhr et al. (6) examined 5v5 preselected basketball athletes who played in a selection tournament for the "under 15" German national team and also found similar results. In addition, they elucidated no differences in sprinting or COD performance between selected and non-selected male athletes, but differences in jumping performance.

However, results for female athletes are in line with the current literature, and motor-performance tests differentiate between selected and non-selected athletes even in the second-step selection. One possible explanation could be the number of active participants or the depth of the competition (e.g., the more players competing for finite number of starter places in a single team, the more likely that at earlier stages of talent selection motor-performance benchmarks are reached). The number of male athletes is considerably greater than that of female athletes ($n_{\text{males}} = 107$, $n_{\text{females}} = 85$), meaning that the motor-performance benchmarks for female athletes are reached in different steps of selection. Similar tendencies can be seen in other domains such as the relative age effect. In a systematic review, de la Rubia et al. (67) postulated that in women's sports, even with an overrepresentation of relatively older athletes, relative age did not have an influence on competition performance due to factors such as the number of active participants or the depth of the competition (e.g., reduced number of female athletes competing for a limited number of places on a team compared to male athletes).

A further explanation for different findings in male and female athletes could be that the general motor-performance component for males is not as important in the talent selection process as for female athletes because of factors that could be linked to technical aspects of the game. As mentioned before, technical actions such as shooting correlate with greater wingspan, but also with upper-body strength (11, 53). Because female athletes have smaller wingspan than male athletes, this could be a reason why chest-pass performance, which is part of the general motor-performance component and correlates with upper-body strength (68), is more important in female athletes than in male athletes. Furthermore, due to the increased number of shots in 3×3 basketball, the number of rebounds in 3×3 basketball is higher too (60). Because rebounds are considered to be a key performance indicator for predicting the outcome of the game (69), it is advantageous to be tall (11) and/or to jump high (70) to get these rebounds. Again, female athletes are smaller than male athletes, so jumping performance, which is a main part of the general motor-performance component, could have more relevance for them.

4.1 Limitations

To avoid overfitting the model, we included principal components from the PCA in the binomial logistic regression rather than using all variables in isolation. This allows to consider and include as much data as possible in an overall analysis. However, it does not allow conclusions about the exact contribution of specific variables.

The overall model of the binomial logistic regression statistically discriminated between the selection status of female and male athletes. Nevertheless, the success rate for predicting selected athletes was 56.7% for female athletes and only 26.5% for male athletes. This suggests that other factors such as coaches' assessments [often referred to as coach's eye (71)], tactical aspects [e.g., positioning (32)], technical skills (e.g., shooting qualities), or psychological factors (e.g., decision-making) might also play an important role for game performance. For homogeneous populations who have passed their APHV a longer time ago, these factors could have a greater impact on selection decisions (18, 72, 73) because all players have already reached a high degree of their maturational development. Thus, these variables should be considered in future investigations.

5 Conclusion

The aim of this study was to analyze predictors for selection in a 3×3 talent recruitment setting. For female athletes, the main predictors in 3×3 basketball talent selection are the anthropometric- and maturation-related and the general motor-performance components. For male athletes, in contrast, only the anthropometric- and maturation-related component seems to be relevant. Furthermore, early-matured female and male athletes show advanced anthropometric conditions compared to late-matured athletes. In this context, Soares et al. (10) assume that coaches probably tend to overvalue body height when selecting youth athletes. Therefore, coaches should raise their awareness to avoid deselecting late-matured athletes just because they have a temporal disadvantage in terms of their anthropometric conditions. Strategies such as bio-banding, in which athletes are matched with equivalent opponents in terms of maturity level (66) should be considered to retain late-maturing athletes in a competitive system. Arede et al. (74) suggest that in 5v5 basketball with bio-banded teams, the real and potential value of talented youth athletes could be better understood, and hence the accuracy of talent selection processes could be improved.

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 Prof. Dr. Klein, Ethics Board Faculty of Psychology and Sports Sciences, Goethe-University Frankfurt (2021-30). 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

TS: Data curation, Methodology, Writing – original draft. M-TF: Conceptualization, Data curation, Methodology, Writing – review & editing. KZ: Conceptualization, Data curation, Methodology, 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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Effects of hyperbaric oxygen therapy on recovery after a football match in young players: a double-blind randomized controlled trial

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Introduction: Football is a physically demanding sport that requires effective recovery strategies to maintain performance level and prevent injuries. This study investigated if a single 1-h hyperbaric oxygen therapy (HBOT) session affects recovery and performance after a football match in elite youth players.

Methods: Twenty elite youth football players (age 17.3 ± 0.5 years) were randomly assigned to a HBOT group or a control group (CON). They played a 90-min football game and underwent either a 60-min HBOT or placebo intervention. Before (T1), at the end of the match (T2), 1 h after HBOT or CON session (T3), and 12 h after HBOT session (T4), subjects underwent biochemical (serum samples (myoglobin (MB), creatine kinase (CK), lactate dehydrogenase (LDH), alanine aminotransferase (ALT), and aspartate aminotransferase (AST)) and performance measurements (linear speed at 5 m, 10 m and 20 m, squat jump (SJ), countermovement jump (CMJ) and countermovement jump with arm swing (CMJa)). The Hooper Index (HI) was collected and heart rate was measured during the game.

Results: The football match induced significant increases in all biochemical markers, but no significant differences were found between the HBOT and control group in biochemical or performance parameters at any time point. However, there was a significant interaction effect between time and group for HI (p = 0.012, $\eta 2$ = 0.124), with the HBOT group showing significantly lower HI values (8.6 ± 2.41) than the control group (11.0 ± 3.23) at 1 h post-HBOT.

Discussion: A single 1-h session of HBOT did not significantly affect recovery or performance parameters in elite youth football players, though it did show a moderate positive affect on the HI at 1 h post-HBOT. Further studies should explore the impact of either longer or sequential HBOT sessions on recovery.

KEYWORDS

hyperbaric oxygen therapy, football, performance, recovery, young athletes, blood analysis

1 Introduction

Football is a physically demanding, competitive sport that causes stress on various physiological systems (Reilly and Ekblom, 2005). Previous studies (Silva et al., 2013; Viana-Gomes et al., 2018) showed that a single match causes significant increases in oxidative stress and cellular damage indicators in the plasma of professional football players. This can lead to acute, albeit usually small, decrements in sprint and jump performance (Abaïdia and Dupont, 2018). The tight schedule, the intermittent nature of the sport, performing muscle-damaging actions, and limited time for recovery can lead to an increased risk of fatigue, delayed-onset muscle soreness (DOMS) and injuries (Barnett, 2006; Cheung et al., 2003). In addition, previous studies (Abaïdia and Dupont, 2018; Magalhaes et al., 2010) reported that complete recovery after one match requires up to 72 h. Therefore, effective and fast recovery is the key to uphold performance levels.

Considerable research attention has been given to strategies to accelerate acute recovery in football players. Nutrition and antioxidant supplements, sleep, cold water immersion, active recovery, and compression garments have been suggested (Dupuy et al., 2018; Nédélec et al., 2013; Santos et al., 2016) to reduce anti-inflammatory responses and fatigue immediately after the match, as well as to prevent further functional impairment. However, the area of effective recovery strategies remains unclear due to the limited number of studies that investigated elite players (Barnett, 2006) and the variety of modalities without empirical evidence of which one should be followed. Since the literature indicates the essential role of fast recovery, but lacks clear findings (Kellmann, 2010), an increased interest in hyperbaric oxygen therapy (HBOT) has emerged in recent years (Mihailovic et al., 2023). HBOT has been reported to accelerate cell regeneration and tissue repair, which should help eliminate fatigue and restore endurance capacity. More precisely, HBOT is a treatment in which 100% oxygen is supplied under elevated pressure. Such treatment increases dissolved oxygen levels in the blood and results in a high partial pressure of oxygen in peripheral tissues, which is beneficial for conditions associated with low oxygen environments, potentially stimulating the recovery process (Hodges et al., 2003). HBOT can improve the oxygenation of skeletal muscles, which accelerates the production of adenosine triphosphate (ATP) in addition to the metabolic purification of metabolites that cause fatigue (Sperlich et al., 2017). Moreover, HBOT is proven to be safe and effective in the non-athletic population as a treatment for accelerating the healing process and reducing local hypoxia and inflammation (Moghadam et al., 2020). Until now, HBOT has been applied in various ways, ranging from acute (single) sessions, such as 60-min interventions (Park et al., 2018; Branco et al., 2016), to more chronic protocols involving multiple sessions per week over extended periods (Hadanny et al., 2022; Mihailovic et al., 2023). The choice of protocol often depends on the goals, such as acute recovery or long-term adaptation.

HBOT administration has been proposed as an adjuvant treatment for improving muscle repair and recovery from exercise-induced muscle damage (Ishii et al., 2005). Surprisingly, although oxygen has the most important role during recovery, only two studies (Branco et al., 2016; Mihailovic et al., 2023) have investigated the post-exercise impact of HBOT on biochemical recovery parameters or performance in athletes. Branco et al. (2016) investigated the effects of a single session HBOT on hormonal and cell damage markers in professional jiu-jitsu athletes and failed to find a significant influence of HBOT, while Park et al. (2018) found positive effects of a single 60-min HBOT on the removal of peripheral fatigue symptoms induced by maximal exercise in college football players. Similarly, in terms of the acute effects of HBOT on performance, previous studies (Hadanny et al., 2022; Hodges et al., 2003; McGavock et al., 1999; Mihailovic et al., 2023) indicated equivocal findings. While early studies (Hodges et al., 2003; McGavock et al., 1999) suggested no effects of a single HBOT session on performance, later research (Mihailovic et al., 2023; Park et al., 2018) seems to indicate that HBOT was able to improve cardiac parasympathetic reactivation by HBOT applications over several weeks and recovery of peripheral fatigue by a single HBOT session.

The role of HBOT on recovery parameters and performance in elite football players is still poorly understood, and to date, no study has specifically examined the effects of a single session of HBOT after a football match. Since football is an intermittent sport with high physical, physiological, and metabolic demands, HBOT might be considered a promising post-exercise recovery treatment. Therefore, this study aimed to investigate the effects of a single HBOT session on recovery and performance after a football match in elite youth football players. We hypothesized that a single session of HBOT would significantly enhance recovery and improve performance compared to a placebo condition.

2 Methods

2.1 Participants

Twenty elite youth male football players (age: 17.3 ± 0.5 years; football experience: 10.2 ± 1.7 years) participated in the study, and informed consent was obtained from their parents or legal guardians. Participants were free of injuries and medical conditions contraindicated by HBOT. All participants were informed of the study procedures and provided written parental consent prior to participation. Participants were advised to refrain from severe physical activity for 24 h and to abstain from breakfast, caffeine, and alcohol prior to the first blood collection.

2.2 Study design and procedures

The study was conducted using a randomized, double-blind design. The participants were randomly assigned to either the HBOT group or the control (CON) group. All participants were evaluated for biochemical parameters, physical performance tests and Hooper index (HI). The participants were tested four times (Figure 1): at baseline, pre-match (T1), at the end of the match, post-match (T2), 1 hour after the HBOT session (T3), and 12 h after the HBOT session (T4). Fasted blood samples were collected before breakfast. After a standardized light meal and rest period, participants were evaluated for physical performance with the linear speed and vertical jump (VJ) height tests before playing a football match (T1). Participants were randomized in a 1:1 fashion into two groups

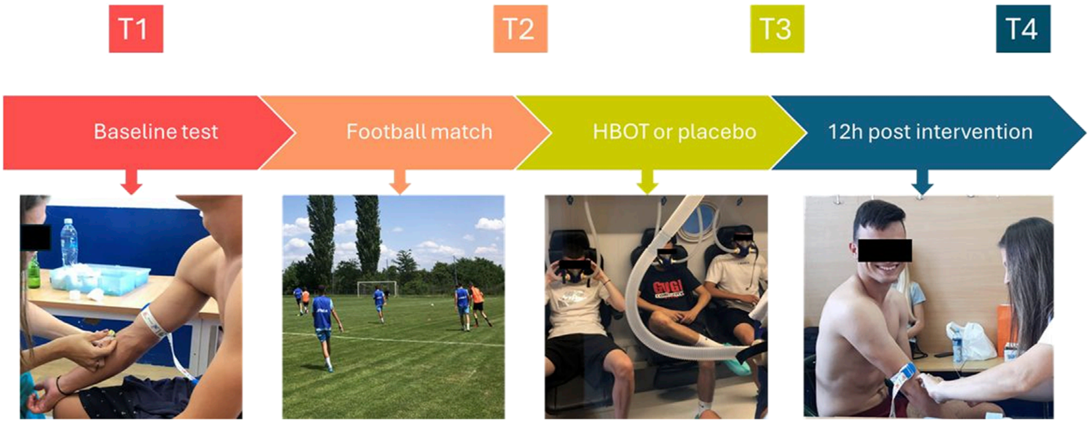

FIGURE 1
Study design.

based on their playing positions to play against each other. In the afternoon the match took place on an outdoor football field and lasted for 90 min at an average ambient temperature of 26°C. It was a simulated game replacing a regular training session, with 22 players. Both teams used a 5-three to two line up. Goalkeepers were excluded from the analysis because of the different physical demands of this position. The same examination was performed after the match (T2), followed by HBOT or CON treatment. Finally, blood samples and physical fitness were evaluated 1 h (T3) and 12 h (T4) after the intervention. In addition, heart rate (HR; Polar Team System H7 (Polar Electro Oy, Kempele, Finland)) was constantly tracked during the match to determine its intensity. Procedures were conducted with the requirements and approval of the Ethical Committee of Faculty of Sport and Physical Education, University of Niš (ref. 04–651/2; approval date 23 May 2022) and registered at ClinicalTrials.gov under NCT06112210.

2.3 Biochemical analysis

Blood samples were collected from the antecubital vein with participants in a seated position. A vacutainer tube was used to collect blood samples (Vacusera 5 mL Serum Gel and Clot Activator, Disera A.S. Izmir-Turkey) and centrifuged immediately at 3,000 rpm for 10 min to isolate the serum. Myoglobin (MB) was determined with Siemens IMMULITE 1000 (Siemens Healthcare Diagnostics, UK), while creatine kinase (CK), lactate dehydrogenase (LDH), alanine aminotransferase (ALT), and aspartate aminotransferase (AST) were analyzed using a biochemistry analyzer (A25 Biosystems Chemistry Analyzer).

2.4 Vertical jump (VJ) height

Squat jump (SJ), countermovement jump (CMJ) and countermovement jump with arm swing (CMJa) tests were performed to measure the VJ height. The Optojump system (Microgate, Bolzano, Italy) was used to determine vertical VJ height; its validity and reliability had previously been shown (Glatthorn et al., 2011). Previously, the procedure as well as the validity and reliability of the tests in football players were examined (Claudino et al., 2017; Garrett et al., 2020). Briefly, the SJ was executed in a semi squat position with the knees bent at 90° and the arms resting on the hips. Participants held this stance for one to 3 seconds before the maximal VJ. Moreover, the CMJ and the CMJa were evaluated while standing straight up, with equal weight distributed over both feet. The hands were free to move when the CMJa was conducted. Furthermore, the arms were secured to the hips during the CMJ to prevent their impact on jump height. Afterwards, participants squatted down to a 90-degree flexion and executed a maximal VJ without pausing at the moment of direction change. Each participant was provided with instructions to perform all jumps with maximal effort. Furthermore, each jump was attempted three times, with the best result being included in the statistical analysis.

2.5 Linear speed

Linear speed was measured from a standing position at 5 m, 10 m, and 20 m, as previously described (Buchheit et al., 2010; Dugdale et al., 2019). The Witty photocell system (Witty, System, Microgate, Bolzano, Italy) was used to assess the performance. In addition, to reduce the influence of the hand swing when passing through the gate, photocells were positioned at 10 m and 20 m from the starting line, 0.4 m above the ground, and with an accuracy of 0.001 m/s (Yeadon et al., 1999). Participants were instructed to exert full effort when passing through all gates.

2.6 Hyperbaric oxygen therapy (HBOT) procedure

Both the HBOT and placebo protocols were performed in a Barox HBOT chamber (Yaklasim Makina San. Ve Tic. Ltd. Sti). The participants were taken to the chamber immediately after the football match, where they sat in individual chairs and oxygen was delivered through individual masks. The HBOT group was exposed to 100% oxygen at 2.2 ATA (atmospheres absolute), while the CON group was exposed to normobaric ambient pressure (1 ATA). Both sessions lasted 60 min. This protocol was selected to follow current literature (Babul et al., 2003; Mekjavic et al., 2000; Shimoda et al., 2015; Webster et al., 2002).

2.7 Hooper index (HI)

HI was used for the subjective assessment of fatigue and players' wellbeing. Subjects were unfamiliar with the HI and therefore it was thoroughly explained before the start of the experiment. The HI is a summation of the four subjective ratings: sleep (concerning the night preceding the evaluation), fatigue, stress and DOMS on a scale of 1–7 (Hooper et al., 1995). Specifically, '1' represents "very, very good state", and '7' represents "very, very bad state". After the participants completed the questionnaire, the HI was calculated and used for analysis. Moreover, HI has been shown to be a valid and reliable tool for monitoring fatigue in professional football players (Clemente et al., 2017; Thorpe et al., 2015).

2.8 Data analysis

Data analysis was performed with the Statistical Package for the Social Sciences (v29.0; SPSS Inc., Chicago, IL, United States). The mean ± standard deviation (SD), Kolmogorov-Smirnov test to examine normality of distribution, and Levene's test to examine homogeneity of variance were determined for all outcome measures. Changes in biochemical parameters and physical fitness parameters were compared between subjects over four time points for the HBOT and CON group using a repeated measures analysis of variance (RM-ANOVA). Finally, to evaluate the magnitude of the observed differences, the effect size was calculated (*eta squared*, η^2) and interpreted as follows: <0.2 (small), >0.2 and <0.8 (moderate) and >0.8 (large) (Cohen, 1988). A power analysis was conducted using G*Power based on an effect size of 0.63 for CK levels from a similar study (Qu et al., 2024). With an α level of 0.05 and a desired power of 0.80, the analysis indicated that a total sample size of 22 participants would be required to detect statistically significant differences between the HBOT and CON group.

3 Results

The main characteristics of the participants (height, weight, fat mass, muscle mass and body mass index (BMI)) as well as time spent (%) in various heart zones during the match are summarized in Table 1 and Figure 2.

TABLE 1 Descriptive statistics of the main characteristics of the participants.

Variables	HBOT	CON
Height (cm)	181.4 ± 5.1	178.2 ± 6.6
Weight (kg)	71.0 ± 9.5	66.9 ± 6.5
Fat mass (%)	12.4 ± 3.1	13.2 ± 3.9
Muscle mass (%)	43.6 ± 1.7	43.7 ± 2.2
BMI (kg/m^2)	21.6 ± 2.6	21.1 ± 1.7

Legend: BMI, body mass index; HBOT, hyperbaric oxygen therapy group; CON, control group.

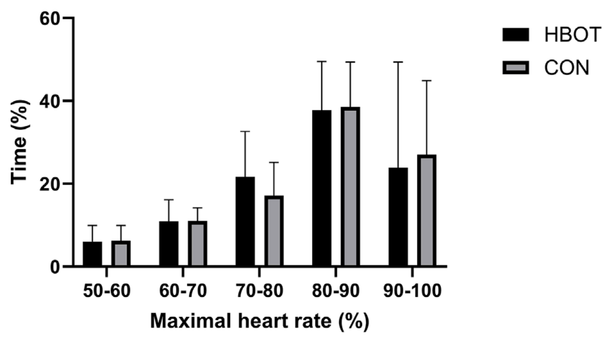

FIGURE 2
Time spent (%) in various heart rate zones as a percentage of maximum heart rate (HRmax) during the match. Note: comparisons are presented as HBOT vs. CON.

3.1 Biochemical parameters

Table 2 and Figure 3 shows descriptive data for both groups through four time points. The results indicated no significant differences between the HBOT and CON group in biochemical parameters at T1. Furthermore, there was no interaction effect between time and group for any of the measured variables ($p > 0.05$).

The match induced a significant increase (T1 vs. T2) in MB ($p = 0.003$), CK ($p < 0.001$), LDH ($p < 0.001$), ALT ($p < 0.001$), and in AST ($p < 0.001$).

3.2 Performance parameters

The results indicated no significant differences between HBOT and CON group in physical fitness tests at T1. Furthermore, there was no interaction effect between time and group for any of the measured variables ($p > 0.05$) (Table 3).

The match had no effect on most of the performance parameters except for SJ (T1 vs. T2; $p = 0.012$).

3.3 Hooper index

The results indicated no significant differences between HBOT and CON group in HI at T1. However, there was an interaction effect between time and group for HI ($p = 0.012$, $\eta^2 = 0.124$). More precisely, the HBOT group had significantly lower HI values (8.6 ±

TABLE 2 Results for biochemical parameters.

Serum samples	T1	T2	Δ T2 vs. T1	T3	Δ T3 vs. T2	T4	Δ T4 vs. T2	*p*-value, η^2
MB (ng/mL)								
HBOT	29.3 ± 7.9	92.9 ± 32.4	+218%	96.7 ± 36.9	+4%	36.3 ± 8.5	−61%	Group: $p = 0.783$, η^2: 0.004 Time: $p < 0.001$, η^2: 0.459 Interaction: $p = 0.591$, η^2: 0.020
CON	24.9 ± 5.5	137.4 ± 123.2	+451%	124.4 ± 102.1	−9%	44.9 ± 20.8	−67%	
CK (u/l)								
HBOT	195.5 ± 86	294.2 ± 110.2	+51%	378.0 ± 147.0	+28%	457.6 ± 194.8	+55%	Group: $p = 0.881$, η^2: 0.001 Time: $p < 0.001$, η^2: 0.504 Interaction: $p = 0.660$, η^2: 0.013
CON	210.3 ± 75.9	344.8 ± 95.9	+63%	526 ± 232.6	+53%	635.5 ± 354.5	+84%	
LDH (u/l)								
HBOT	391.5 ± 59.5	480.1 ± 59.2	+23%	430.6 ± 85.5	−12%	355.5 ± 77.5	−35%	Group: $p = 0.439$, η^2: 0.034 Time: $p < 0.001$, η^2: 0.568 Interaction: $p = 0.484$, η^2: 0.036
CON	397.6 ± 41.4	517.9 ± 43.8	+30%	469.4 ± 142.4	−9%	352.9 ± 41.6	−31%	
ALT (u/l)								
HBOT	16.0 ± 4.7	19.1 ± 4.9	+19%	18.5 ± 7.3	−3%	18.0 ± 5.7	−6%	Group: $p = 0.913$, η^2: 0.001 Time: $p = 0.001$, η^2: 0.270 Interaction: $p = 0.489$, η^2: 0.042
CON	16.2 ± 5.2	18.8 ± 3.9	+16%	17.1 ± 4.4	−9%	18.5 ± 5.8	−2%	
AST (u/l)								
HBOT	25.2 ± 5.9	35.2 ± 6.6	+40%	33.2 ± 8.2	−6%	32.5 ± 12.2	−8%	Group: $p = 0.793$, η^2: 0.004 Time: $p < 0.001$, η^2: 0.542 Interaction: $p = 0.754$, η^2: 0.011
CON	23.2 ± 4.6	34.8 ± 7.2	+50%	32.1 ± 6.6	−8%	32.6 ± 10.9	−6%	

MB, myoglobin; CK, creatine kinase; LDH, lactate dehydrogenase; ALT, alanine aminotransferase; AST, aspartate aminotransferase; HBOT, hyperbaric oxygen therapy group; CON, control group; T1 – pre-match; T2 – post-match; T3 – after HBOT; T4 – 12 h after η^2 – partial eta, effect size.

2.41) than the CON group (11.0 ± 3.23) at T3 (Figure 4). The match also presented a significant increase (T1 vs. T2) in HI ($p < 0.001$).

4 Discussion

The aim of this study was to determine the effect of a single session of HBOT on recovery parameters in elite youth football players. Briefly, the match clearly induced the anticipated biochemical changes indicating fatigue. However, the results indicated that there were no significant differences between the HBOT and CON group at T3 (after the intervention) for markers of muscle damage (MB, CK, LDH, ALT, and AST) and performance parameters (linear speed at 5 m, 10 m and 20 m, CMJ, CMJa, and SJ). Similarly, at T4, there were no significant differences between the groups for the same variables. Interestingly, the results revealed a significant difference between groups at T3 for HI, with a moderate positive effect of HBOT on this parameter.

Serum markers (MB, CK, LDH, ALT, and AST) have been extensively researched as parameters of muscle cell damage in elite football players (Ascensão et al., 2008; Ispirlidis et al., 2008; Meyer and Meister, 2011). The study's findings revealed that MB, CK, LDH, AST, and ALT concentrations increased in both groups immediately following the football match. Although the concentrations of LDH, AST and ALT decreased after HBOT and continued in the same manner 12 h after HBOT, the results demonstrated no statistically

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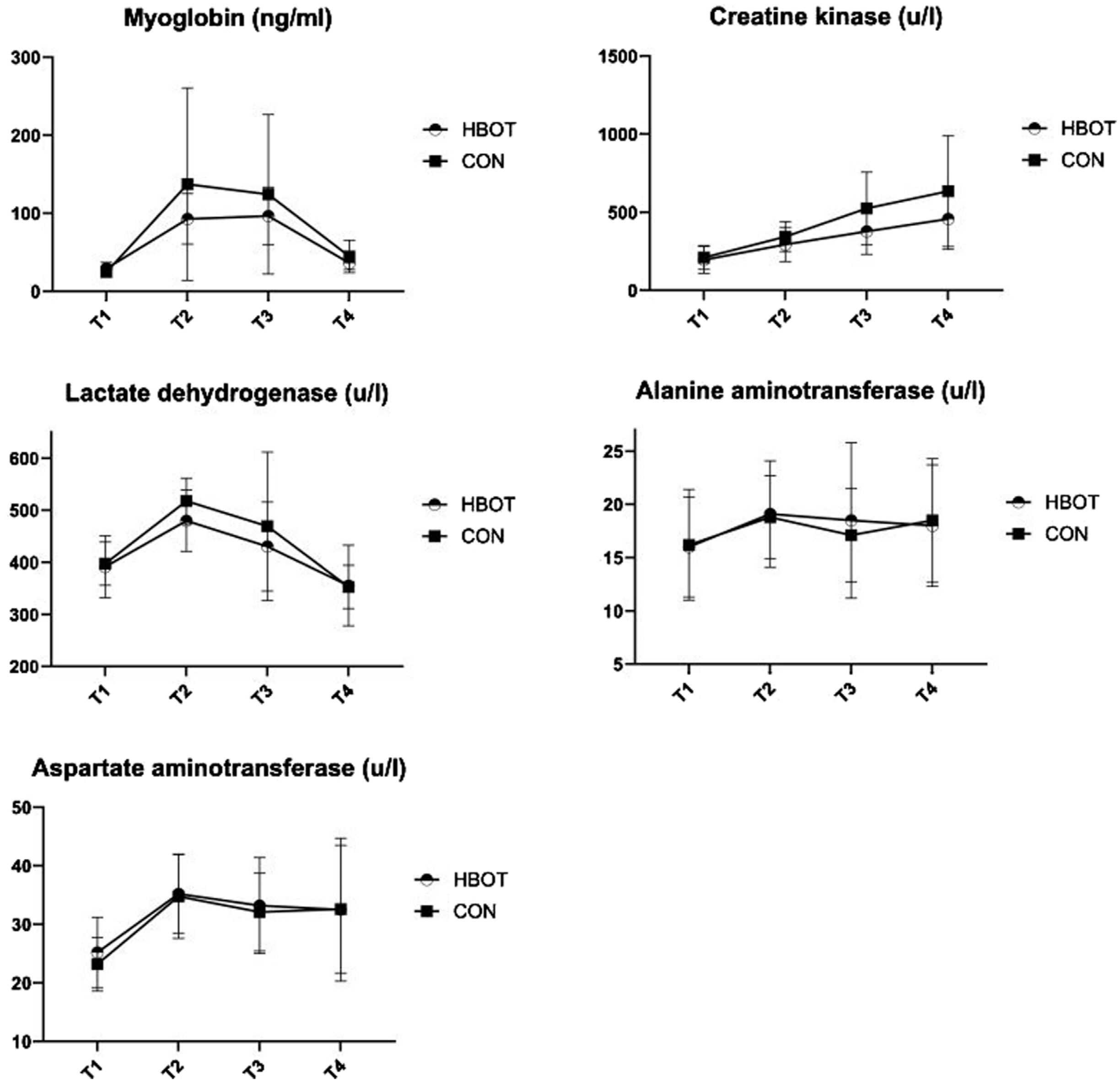

FIGURE 3
Biochemical parameters measured throughout four time points: pre-match (T1), post-match (T2), 1 hour after HBOT (T3) and 12 h after HBOT (T4).

significant effect of a single session of HBOT. Conversely, the most relevant marker of muscle damage, CK, had a drastic increase at all time points compared to baseline without a significant difference between groups. Existing studies (Branco et al., 2016; Harrison et al., 2001; Huang et al., 2021; Woo et al., 2020) examining post-exercise interventions have provided contradictory findings. While our findings are consistent with previous results showing no positive effect of HBOT on biochemical recovery parameters (Branco et al., 2016; Harrison et al., 2001; Huang et al., 2021), Woo et al. (2020) found that HBOT applied during the post-exercise recovery period is effective for treating exercise-induced muscle damage. It is noteworthy that none of these studies have assessed acute recovery using HBOT in elite youth football players immediately after a competitive match. Football is a very strenuous sport with high physiological and metabolic demands, where some markers of cell damage increase up to 72 h after the match and then return to their baseline values (Fatouros et al., 2010; Silva et al., 2013). More precisely, changes in direction and rapid accelerations and decelerations impose a significant eccentric load on the muscles, resulting in microinjuries and the release of CK and MB up to 72 h after a football match. In addition, their concentration depends on many factors, such as level of playing, period of season, individual responses, and previous activities (Brancaccio et al., 2007; Silva et al., 2013). In the present study, the participants were advised to refrain from stressful activities for 24h, which means that a certain concentration of CK remained in the blood. Furthermore, the participants evaluated in this study were in the off-season period, which probably resulted in higher

TABLE 3 Results for physical fitness (performance) parameters.

Physical Fitness	T1	T2	T3	T4	p-value, η^2
Linear speed at 5 m (s)					
HBOT	1.11 ± 0.07	1.1 ± 0.09	1.06 ± 0.08	1.05 ± 0.08	Group: $p = 0.850$, η^2: 0.002 Time: $p = 0.084$, η^2: 0.141 Interaction: $p = 0.374$, η^2: 0.055
CON	1.11 ± 0.11	1.08 ± 0.05	1.06 ± 0.05	1.09 ± 0.05	
Linear speed at 10 m (s)					
HBOT	1.83 ± 0.09	1.83 ± 0.10	1.81 ± 0.09	1.80 ± 0.09	Group: $p = 0.968$, η^2: 0.000 Time: $p = 0.187$, η^2: 0.089 Interaction: $p = 0.092$, η^2: 0.118
CON	1.81 ± 0.06	1.82 ± 0.06	1.79 ± 0.06	1.85 ± 0.07	
Linear speed at 20 m (s)					
HBOT	3.09 ± 0.10	3.12 ± 0.13	3.10 ± 0.10	3.13 ± 0.13	Group: $p = 0.813$, η^2: 0.003 Time: $p < 0.001$, η^2: 0.351 Interaction: $p = 0.370$, η^2: 0.059
CON	3.09 ± 0.10	3.13 ± 0.10	3.10 ± 0.10	3.18 ± 0.12	
SJ (cm)					
HBOT	32.70 ± 5.04	34.70 ± 5.31	35.60 ± 4.78	29.10 ± 8.32	Group: $p = 0.987$, η^2: 0.000 Time: $p = 0.005$, η^2: 0.279 Interaction: $p = 0.353$, η^2: 0.059
CON	31.30 ± 4.39	35.70 ± 3.10	34.30 ± 3.96	31.40 ± 3.20	
CMJ (cm)					
HBOT	34.40 ± 5.17	36.80 ± 4.99	36.80 ± 7.92	35.00 ± 7.24	Group: $p = 0.432$, η^2: 0.037 Time: $p = 0.002$, η^2: 0.258 Interaction: $p = 0.304$, η^2: 0.068
CON	33.60 ± 3.81	37.50 ± 3.56	35.50 ± 3.55	31.20 ± 2.76	
CMJa (cm)					
HBOT	40.30 ± 4.66	41.50 ± 2.80	43.20 ± 7.55	41.50 ± 9.27	Group: $p = 0.466$, η^2: 0.032 Time: $p = 0.049$, η^2: 0.141 Interaction: $p = 0.513$, η^2: 0.044
CON	38.90 ± 3.68	41.00 ± 5.23	41.50 ± 5.58	37.60 ± 6.52	

Legend: SJ, squat jump; CMJ, countermovement jump; CMJa, countermovement jump with arm swing; HBOT-hyperbaric oxygen therapy group; CON, control group; T1 – pre-match; T2 – post match; T3 – after HBOT; T4 – 12 h after HBOT; η^2 – partial eta, effect size.

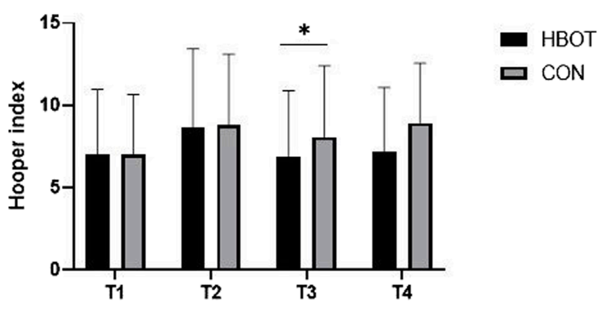

FIGURE 4
Hooper index (HI) values measured throughout four time points: pre-match (T1), post-match (T2), 1 hour after HBOT (T3) and 12 h after HBOT (T4). Note: comparisons are presented as HBOT vs. CON.

concentrations of CK in the blood after the match. Therefore, our study indicates that a single 60 min session of HBOT may not be sufficient to improve biochemical recovery parameters in elite youth football players. The similarity in blood parameters between the HBOT and CON group could be due to the short duration and single session of HBOT, the natural and effective recovery processes in elite youth athletes, the potential insensitivity of the measured biochemical markers, or the timing of the measurements. To better understand the effects of HBOT, future studies should consider multiple sessions, a larger sample size, and possibly more sensitive or additional markers of recovery.

HBOT increases dissolved oxygen levels in the blood and results in a high partial pressure of oxygen in peripheral tissues, it could potentially stimulate the recovery process (Hodges et al., 2003). Since HBOT improves the oxygenation of skeletal muscles, it may accelerate the production of ATP in addition to the metabolic purification of metabolites that cause fatigue (Sperlich et al., 2017). Therefore, we hypothesized that HBOT treatment would positively affect the main physical fitness indicators of performance such as linear speed and vertical jump height. However, the findings of our study indicate no effect of a single session on these parameters when compared to post-match measurements in youth elite football players. One reason for this finding could be that our simulated game did not affect these parameters in the first place. In general literature describes a modest deterioration of jump and speed performance (Abaïdia and Dupont, 2018), although this is not always the case (Krustrup et al., 2010). Several factors, such as fitness level, game status (winning vs. losing), potential rewards and environmental conditions, indeed make these parameters variable (Abaïdia and Dupont, 2018). One could also argue that the lack of impact is caused by a too low intensity during the game, although this is not substantiated through our heart rate data and the biochemical changes that occurred. The lack of effect after HBOT in the current study is congruent with the work of (McGavock et al., 1999; Hodges et al., 2003), who found no significant effect of acute HBOT treatment on performance. More precisely, previous studies (Hodges et al., 2003; McGavock et al., 1999) tried to determine the acute effects of HBOT at 2.5 ATA for 90 min on cardiorespiratory fitness and concluded that the experimental groups did not improve or deteriorate performance on the maximal and submaximal running tests. These findings contrast with a previous study (Mihailovic et al., 2023) reporting post-HBOT treatment as an efficient way to improve power output during cycling. However, the different parameters and populations assessed within studies investigating the single-session effect of HBOT on post-exercise performance make it difficult to compare the results. Although several studies have examined the acute effects of HBOT on performance, to date, no study has specifically examined the acute effects of HBOT on several parameters of physical performance in elite youth football players, who exhibit fewer performance impairments and metabolic disturbances than lower-level players. More precisely, the large muscle groups involved in running or jumping become more resistant in this population due to intense training (Reilly et al., 2008). Also, young elite players (U20) have a shorter and more efficient recovery. Nevertheless, it is crucial to draw attention to the beneficial findings of a recent study (Burgos et al., 2016) investigating the effects of 3 weeks of HBOT training on oxidative stress markers and endurance in young football players. Specifically, the authors (Burgos et al., 2016) found that 3 weeks of HBOT did not cause an increase in oxidative stress but improved endurance capacity. Therefore, if utilized for a long period of time, HBOT may have significant ergogenic effects in professional football players.

Our results showed a significant positive effect in HI after the HBOT compared to CON 1 hour after the treatment. Since the HI parameter is the most widely used parameter in football for subjective evaluation of match-induced fatigue, this indicates that although we were unable to induce significant differences in biochemical or performance parameters, we were successful in reducing the perception of fatigue after the match. The HI has been employed as a tool to detect changes in wellbeing in football players, with specific focus on fatigue, stress, sleep quality and DOMS, over the course of a season (Silva R. M. et al., 2022) or in the early-season *versus* in-season (Silva A. F. et al., 2022). Furthermore, this confirms previous findings that the HI index is more sensitive than physiological parameters, such as heart rate variability (Rabbani et al., 2019) or blood parameters as measured in our study, to track fatigue in a specific football population.

The major strength of this study is that it was the first double-blind randomized controlled study investigating the effects of a single session of HBOT on biochemical recovery and performance parameters in elite youth football players. Furthermore, the evaluation of an extensive range of parameters and the protocol used are strengths to consider. However, some limitations of our study should be acknowledged when interpreting the findings. First, the findings should be interpreted with caution due to the specific pool of participants included, representing a small sample size because of the methodological constraint of employing one football game and the size of the Barox HBOT chamber. Given the actual sample size in this study (n = 20), the study may have been underpowered to detect medium effect sizes for other outcomes. Second, the studies' comparison with current literature is difficult because of the limited number of studies investigating the acute effects of a single session of HBOT. Third, we advised the participants to refrain from any form of physical activity for a period of 24h, but we did not monitor or control their activities during the period of 48 h. Finally, although elite football players were recruited in our study, our findings are not generalizable to senior male professional football players, female football players, or athletes competing in other sports. Our research does not support the effectiveness of a single session of HBOT as a recovery model due to the absence of significant effects and the cost of treatment and equipment. However, large cohort studies examining acute effects on male and female football players and athletes competing across a wider range of sports should be conducted in the future. In addition, future research will have to further investigate acute HBOT protocols of different durations. Finally, future research will have to concentrate on the effects of sequential HBOT sessions on recovery and performance parameters.

5 Conclusion

In summary, our findings showed that a single session of HBOT did not have significant effects on selected biochemical recovery and performance parameters in elite youth football players. We did observe a lower HI score after the HBOT session compared to the placebo group, suggesting that HBOT may have a moderate positive effect on perceived recovery and wellbeing. Nevertheless, our findings may suggest a need for multiple HBOT sessions or a larger sample size to observe significant changes. Future studies are needed to confirm or refute our findings and to determine the optimal use of HBOT as a recovery intervention in football.

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 Ethical Committee of Faculty of Sport and Physical Education, University of Niš (ref. 04-651/2). 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 participant's legal guardians/next of kin. Written informed consent was obtained from the individual(s), and minor(s) legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

MG: Conceptualization, Investigation, Writing–original draft. TS: Conceptualization, Investigation, Supervision, Visualization, Writing–review and editing. AL: Methodology, Writing–original draft. SA: Conceptualization, Investigation, Resources, Writing–review and editing. BR: Formal Analysis, Methodology, Writing–review and editing. ŠB: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, 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.

Publisher's note

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Relationships between bone age, physical performance, and motor coordination among adolescent male and female athletes

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Biological maturity significantly impacts youth athletes' physical performance throughout adolescence. However, how this differs between male and female youth athletes remains unclear. Thus, the present study aimed to assess associations between maturity, physical performance and motor coordination in females and males. Sixty-eight youth athletes (mean age 13.9 ± 0.8 years, 26 females) were included in the present study. Participants performed a 40 m sprint, standing long jump (SLJ), push-ups and a 2,000 m run. Motor coordination was evaluated using the short form of the Körperkoordinationstest für Kinder test. Bone age (BA), assessed by x-ray of the left hand and analyzed with an automated software, was used as a biomarker of biological maturity. Results showed that BA was significantly associated with performance for males on 40 m sprint ($r = -.556$, $p < .001$), SLJ ($r = .500$, $p < .001$) and 2,000 m run ($r = -.435$, $p = .011$). No associations were found between BA and physical performance among females, nor between BA and motor coordination for either females or males. In conclusion, maturity is associated with exercises that require maximal speed, explosive leg strength and endurance in males, but not in females, with maturity showing no impact on the motor coordination in either sex.

KEYWORDS

puberty, skeletal age, physical capacity, motor skills, youth

Introduction

During adolescence, the physical performance of male and female youth athletes may be influenced by their biological maturity (1–3). This is linked to the development of lean body mass, which influences physical performance measures, such as strength, power, and speed (4). However, biological maturity may also impact motor coordination due to changes in limb length, muscle strength, and neuromuscular control (4, 5). While the evidence supporting the effect of biological maturity on the physical performance of males is growing, the evidence for females is less conclusive and lacks scientific support (6). This uncertainty also extends to the impact of biological maturity on motor coordination in both sexes.

It is likely that the impact of maturity on physical performance and motor coordination differs between males and females, as females experience relatively smaller gains in lean body mass and a greater accumulation of fat mass compared to males (7). The few studies on females have indicated that differences in biological maturity only had minor discrepancies in the performance of sprint, agility, jump, and intermittent-endurance (6), while others have found that maturity was associated with jump performance in females (8, 9). In contrast, studies in males have shown a stronger relationship between various measures of physical performance and biological maturity (2, 3). As noted, the difference is likely due to pubertal development, with males experiencing a higher secretion of anabolic hormones (such as testosterone), resulting in larger gains in muscle mass with increasing maturity (10). Still, whether maturity has an effect on motor coordination in males is not clear. One study found that youth soccer players performed slightly better in tasks such as jumping sideways and balancing backward compared to their less mature peers (11). Nevertheless, other studies on both males and females have shown the effect of maturity to be less pronounced, with maturity only having a minimal impact on motor coordination tasks (12, 13).

The current literature has a significant limitation in that it uses various markers of biological maturity, such as anthropometric measurements and age at menarche. This could cloud our understanding of how maturity affects changes in performance during adolescence, and may explain the different results between studies. It has been suggested that bone age (BA), measured using an x-ray image of the left hand and comparing the growth plates of several bones against images from a reference atlas (14), could be the most precise measure of biological maturity (15). Unlike anthropometric estimates of maturity using height and weight, which have shown significant limitations in both males and females, BA might improve the interpretation of maturity's effect on motor coordination and physical performance for both males and females.

Therefore, to further understand the connection between maturity and performance, we conducted tests on a group of young male and female athletes to assess their bone age, physical performance, and motor coordination. We hypothesised that maturity would be more closely linked to physical performance in males than in females, and that there would be no correlation between motor coordination and maturity level in either males or females. This information could contribute to our understanding of how biological maturity should be considered when evaluating physical performance and motor coordination in youth athletes.

Materials and methods

Data were collected in January and April 2023. All tests were conducted by experienced test personnel, and the same protocol was used on both test occasions. The study was approved by the Regional Committee for Medical and Health Research Ethics in Norway (551902) and the Norwegian Agency for Shared Services in Education and Research (SIKT) (870863) and it was conducted in accordance with the Helsinki Declaration. Since the participants were under the legal age of consent, their parents provided written informed consent for their participation.

Participants

A total of 26 females and 42 males aged 12–15 years participated in the study. All participants were involved in sport, and 60 out of 68 indicated their sport discipline on a questionnaire. Forty-three participants engaged in a single sport, while 17 were involved in multiple sports. Most participants were engaged in team sports, with football being the most common ($n = 35$), followed by handball ($n = 13$). Among individual sports, athletics was the most frequently practiced ($n = 8$), followed by swimming and gymnastics, each with four participants. Mean weekly training sessions were 4.70 ± 0.62 ($n = 37$). For an overview of the characteristics of the participants, see Table 1.

Anthropometric data

Anthropometric measurements included body height and weight. Height was measured with a stadiometer (Seca 206 and Seca 217, Hamburg, Germany), and recorded to the nearest 0.1 cm. Measurements were performed barefoot using standard procedures. Weight was assessed using the InBody 720 (InBody^{TM} 720, Biospace CO.).

Test regime of physical performance

All participants followed the same warm-up procedure. The order of the tests was the same for all participants: 40 m sprint, standing long jump (SLJ), jumping sideways (JS), push-ups, moving sideways (MS), balancing backwards (BB) and 2,000 m running. There was approximately 10 min of rest between each test. All tests, except for the 2,000 m run, were performed indoors. Due to logistical constraints, the 2,000 m run was performed on day 2 for some participants. The participants wore a T-shirt, shorts, and sports shoes during all the tests. Due to injuries, the number of participants for each test varied.

40 m sprint

A 40 m linear sprint test was conducted to measure the participant's speed. After the warm-up, all participants performed

TABLE 1 An overview of the participants characteristics.

	Females ($n = 26$)	Male ($n = 42$)
Chronological age (years)	14.0 ± 0.8 (12.6–15.1)	13.9 ± 0.8 (12.4–15.1)
Bone age (years)	13.8 ± 1.3 (11.4–16.8)	13.5 ± 1.5 (10.6–16.7)
Height (cm)	160.8 ± 6.8 (143.4–173.5)	164.1 ± 9.9 (149.3–185.4)
Weight (kg)	50.8 ± 6.9 (38.3–68.0)	51.7 ± 10.1 (34.4–85.8)

Data are represented as mean ± SD (min-max).

three maximal sprints of 40 m, separated by 2–3 min of rest. A portable photogate system (Witty, Microgate, Italy) was used to record running time. The first photogates were positioned 50 cm above the running surface, while the photogates at 40 m were positioned 120 cm above the running surface. All participants started from a standing position with split legs, with the toes of the front foot placed 60 cm behind the first photogates. The fastest sprint of three attempts was included in the analysis.

Standing long jump

SLJ was performed to measure explosive leg strength. Participants started with both feet placed behind a line marked on the ground and jumped as long as possible in a forward direction. The horizontal distance from the start line to the mark made by the heel was measured and used to determine the jumping length. The best of three attempts was used in the analyses.

Push-ups

Participants started in a plank position with their hands shoulder-width apart. They then bent their elbows until touching an object on the floor with their chest. The repetition was only counted when the chest touched the object. The spine had to be in a neutral position in each repetition, and the test lasted until they failed to complete a push-up. The maximum number of approved repetitions was used in the statistical analyses.

2,000 m running test

Participants were instructed to run 2,000 m as fast as possible. Each participant started every 10 s, and individual running time was registered using RaceSplitter (https://www.racesplitter.com/).

Tests of motor coordination

The Körperkoordinationstest für Kinder (KTK)

Motor coordination was assessed using the short form of the KTK developed by Kiphard & Schilling (16, 17). The short form KTK is comprised of three items (18): jumping sideways (JS), moving sideways (MS) and balancing backwards (BB).

Jumping sideways

JS evaluates the bilateral symmetrical motor coordination, speed, and dynamic balance of the lower limbs. Participants jumped over a square wooden slat (60 cm × 4 cm × 2 cm) with both feet horizontally from left and right as much as possible within 15 s, two times. All participants started on a self-selected side of the wooden slat and had to jump from and land on both legs. The test score added the number of jumps between the two tries.

Moving sideways

MS evaluates the coordination and agility of lateral movement. The test combines the velocity of the upper and lower limbs with fluidity of movement, laterality, and spatiotemporal structure. Participants stood on one of two platforms (25 cm × 25 cm × 5 cm) and moved the opposite platform by hand as fast as possible within 20 s Each participant was given two tries, one for each left and one for the right direction. The test score was the sum of the two trials.

The balancing backwards test

BB evaluates balance control and coordination. The test was performed barefoot, and there was no time limit. Participants stepped back three times on three balance beams of different widths, each 3 m long and 5 cm high, with widths decreasing as the test progressed (6.0, 4.5, and 3.0 cm, respectively). A maximum of eight steps could be taken for each beam in each test, and a maximum of 72 steps (eight steps × three times × three beams) could be taken for the total test score. The test score was the sum of the number of test steps. The sum of backward steps was used in the analyses. The maximum score was 72.

Skeletal maturity

Bone age (BA) was assessed using a posterior-anterior x-ray of the left hand and wrist, captured with a Siemens Ysio Max with integrated FLUORPSPOT Compacts imaging system (software version VE10; Siemens Healthineers). The x-ray field of view extended from the fingertips to 3 cm above the wrist joint, capturing the epiphyseal plates of the radius and ulna. Exposure settings were standardized at 50 kV, 1-1.5 mAs, and a 1 m tube-detector distance. No image processing or filtering was applied.

The BoneXpert standalone version 3.4.1.0 (Visiana, Holte, Denmark) was used to analyse the radiographs, based on the Greulich Pyle methodology (19). Gender as taken into consideration in the analyses. The system automatically performs 8–13 independent BA measurements from 8 to 13 different bones in the left hand. This automated process eliminates inter- and intra-observer variation. The root mean square error (RMSE) of BoneXpert is estimated to be 0.68 years in males and 0.52 years in females (20).

Statistical analyses

Descriptive data is shown as mean ± standard deviation (SD), 95% confidence interval (CI) and minimum and maximum values. To examine the distribution of the data and assess normality, the Shapiro-Wilk test was employed. One-way ANOVA was conducted to examine differences between males and females for variables that were normally distributed and Mann Whitney-*U* test was used for not normally distributed variables. Effect sizes (r) were calculated to quantify the magnitude of the differences. The relationship between variables was assessed using Pearson's correlation for normally distributed data, while Spearman's rho was applied for non-normally distributed data. An r-value between.01 and.29 was defined as a small correlation, between 0.30 and 0.49 as a medium correlation, and from 0.5 to 1.0 as a large correlation (21). The Statistical Products of Service Solution package (SPSS, version 29) was used for all statistical analyses, and p-values of $\leq .05$ were considered as statistically significant.

Results

Relationships between BA, physical performance and motor coordination

Among males, there was a strong negative correlation between BA and 40 m sprint time ($r = -.556$, $p < .001$, $n = 41$), a strong positive correlation between BA and SLJ performance ($r = .500$, $p < .001$, $n = 42$), and a moderate negative correlation between BA and 2000m run time ($r = -.435$, $p = .011$, $n = 33$). Among females, there was no significant correlation between BA and physical performance, nor between BA and motor coordination. No significant correlation was found between BA and motor coordination in males either (Table 2).

Physical performance between females and males

Males did significantly more push-ups ($U = 234.5$, $p = .001$, $r = .415$) and ran faster in the 2,000 m run test ($U = 124.5$, $p = .001$, $r = 0.452$) than females. There were no other significant differences in physical performance or motor coordination abilities between males and females. For an overview of scores on the tests of physical performance and motor coordination, see Table 3. Additionally, there was no significant difference between females and males in chronological age, BA, height and weight.

Discussion

The aim of the present study was to investigate linear relationships between biological maturity, physical performance and motor coordination in male and female adolescent athletes using seven different tests. We hypothesized that biological maturity would be more closely related to the physical performance of males than females, and that biological maturity would have less impact on motor coordination. Our results partly confirmed our hypothesis, showing that biological maturity was significantly related to maximal sprinting, jumping ability and 2,000 m endurance performance in males, but not to the number of push-ups. Furthermore, maturity was not related to any physical performance measures in females. Motor coordination performance did not show any relationship with maturity in either males or females.

The relationships between maturity and maximal sprinting and jumping performance among males align with previous findings (1–3, 22), confirming that maturity affects performance in exercises that require explosive leg power in males. Indeed, these findings are not surprising, given the hormonal changes

TABLE 3 An overview of the performances on the physical tests.

	Females	Males
Physical capasities		
40 m sprint test (sec)	6.06 ± 0.35 (5.29–6.50) ($n = 24$)	6.00 ± 0.41 (5.03–6.65) ($n = 41$)
Standing long jump (m)	1.97 ± 0.11 (1.80–2.25) ($n = 25$)	2.05 ± 0.19 (1.76–2.54) ($n = 42$)
Push-ups (n)	23.4 ± 12.5 (3–63) ($n = 23$)	32.9 ± 11.9 (1–62) ($n = 41$)
2,000 m run test (min)	9.04 ± 1.03 (8.09–9.52) ($n = 17$)	8.18 ± 0.32 (6.47–11.23) ($n = 33$)
Motor coordination		
Two-legged sideway jumps (n)	96.2 ± 10.2 (67–114) ($n = 24$)	98.0 ± 9.0 (71–116) ($n = 42$)
Side-way movement (n)	31.2 ± 5.7 (12–41) ($n = 26$)	31.6 ± 6.9 (14–41) ($n = 42$)
Balancing backward (score)	67.9 ± 5.3 (50–72) ($n = 26$)	64.3 ± 9.9 (20–72) ($n = 42$)

Data are presented as mean ± SD (min-max).

TABLE 2 An overview of the relationship between bone age (BA) and physical performance in females and male.

	40 m	SLJ	Push-ups	2,000 m	JS	MS	BB
Females							
BA	$r = -.372$	$r = .116$	$r = -.204$	$r = .168$	$r = -.064$	$r = .100$	$r = .041$
	$p = .073$	$p = .581$	$p = .351$	$p = .519$	$p = .766$	$p = .626$	$p = .843$
	[−.675, .036]	[−.292, .489]	[−.577, .240]	[−.340, .600]	[−.466, .359]	[−.319, .479]	[−.363, .432]
	($n = 24$)	($n = 25$)	($n = 23$)	($n = 17$)	($n = 24$)	($n = 26$)	($n = 26$)
Males							
BA	$r = -.556$	$r = .500$	$r = .049$	$r = -.435$	$r = -.202$	$r = .144$	$r = .196$
	$p < .001$	$p < .001$	$p = .760$	$p = .011$	$p = .198$	$p = .364$	$p = .214$
	[−.738, −300]	[.231, .698]	[−.262,.351]	[−.683, −.097]	[−.477, .108]	[−.177, .436]	[−.124, .479]
	($n = 41$)	($n = 42$)	($n = 41$)	($n = 33$)	($n = 42$)	($n = 42$)	($n = 42$)

SLJ, standing long jump; JS, two-legged sideway jumps; MS, side-way movement; BB, balancing backward.

associated with the growth spurt, which result in increased lean body mass, muscle strength, and performance in males (23). However, our research did not find any correlation between maturity and performance in push-ups among our male participants, which may be attributed to the test's procedure, as it resembles upper-body endurance performance more than maximal strength and power. This outcome aligns with a prior study on young male soccer players conducted in our lab (2).

However, the significant association we found between 2,000 m performance and maturity contrasts with other studies that have examined intermittent-endurance performance and maturity (1, 2). This relationship might be somewhat unclear. For instance, Gundersen et al. (22) found that more mature U14 soccer players (but not U15 players) performed better when results were adjusted for players height (i.e., shorter individuals with higher maturity showed better endurance performance). This may be related to the Yo-Yo IR1 intermittent-endurance performance test, which requires participants to make a 180° turn for each lap. In contrast, in our study, the 2,000 m run test was performed without turns. In general, improvements in endurance performance may be attributed to higher maximal oxygen uptake, enhanced running economy, or superior anaerobic capacity. As maximal oxygen uptake relative to body mass remains stable throughout adolescence for male youth athletes (24), it is plausible that the increased maturity observed in the males in our study has contributed to better running economy and/or anaerobic capacity, thereby translating to improved performance in the 2,000 m event (1, 2, 25). We did not find any significant relationship between maturity and physical performance in females. Only a few previous studies have investigated the relationship between maturity and physical performance in females. Two studies have found that both vertical jump performance (4, 24) and standing long jump (26) were significantly related to maturity in youth female athletes, based on equations from anthropometric variables to estimate peak height velocity (PHV). Similar findings were also observed for 30 m sprint performance (27). Based on these studies, more mature females performed better in jumping and sprinting tasks, which contradicts our findings. However, the physical performance differences between females and males may be attributed to the methods used to estimate maturity. Estimates of PHV for females are less accurate, and utilizing BA improves our interpretation of the relationship between maturity and physical performance. While it is likely that neuromuscular function changes during growth and maturation contribute to improved jumping and sprinting performance (28), the gains in fat mass for females may obscure physiological changes during weight-bearing activities like running and jumping. Previous studies using longitudinal data suggest that jump and sprint performance in females peaks around 13–14 years of age before leveling off (29–31). This is also evident in the development of maximal oxygen uptake (relative to body mass), which has been shown to decrease as females mature throughout adolescence (25). More research utilizing BA as a maturity marker is necessary to better understand how maturity impacts females' physical performance.

Our study found no correlation between biological maturity and motor coordination in either males or females, indicating that maturity is not linked to motor coordination. Our results align with a recent study that explored the relationship between bone age and motor performance in females. That study found that bone age accounted for only 1.8% and 5.8% of the variance in motor performance among females aged 10–12 and 13–15, respectively (32). Meanwhile, a previous study of male soccer players aged 5–19 showed that the development of motor competence occurred before the adolescent growth spurt in males (33). This suggests that motor coordination may develop at an earlier age in males than in our study population. As the JS test involves hopping and jumping, which may also require skills such as strength and speed to perform well, we might have expected a relationship between maturity level and the two-legged sideway jump test. On the other hand, the jumping sideway test lasts 2×15 s and is not a measure of maximal explosive strength, which previously was associated with maturity level in males. Furthermore, it is possible that the age of the participants and the athletic experience of our research subjects limited the potential influence of BA on motor coordination assessment. This is supported by findings from a study conducted by O'Brien Smith and colleagues in 2019 (34), which revealed that motor coordination abilities may be a persistent trait among highly skilled adolescent athletes. To explore this further, future studies should also include younger athletes in their cohort.

This study aimed to comprehensively assess physical performance and motor coordination in both male and female subjects. However, certain limitations must be considered. Firstly, the age of our sample may have been too high to reveal strong relationships between biological age and physical performance and/or motor coordination, especially in females who reach puberty earlier than males. In line with this, the females in our study likely had a bone age reflecting that they had already gone through menarche. As this is a late maturational event, it may have affected the relationship between physical performance and biological maturation in the females. Additionally, the sample size on some tests was small, particularly for females, which could have limited the statistical power. Future studies should aim to include younger age groups to represent the entire maturity continuum.

Our findings confirmed the hypothesis that biological maturity has a greater influence on physical performance in young males than in young females. However, no significant correlation was found between motor coordination and maturity level in either sex.

Practical implications

This study highlights the significance of accounting for biological maturity in evaluation of physical performance, particularly for activities that require strength and explosive effort in adolescent males. Conversely, our results suggest that the biological maturity in females requires a different level of consideration. However, biological maturity does not affect motor coordination tasks in either sex, implying that these assessments can be conducted without the influence of biological maturity. The results of this study and previous research suggest that motor coordination tests could prove useful in identifying the motor skills of young adolescent athletes, irrespective of biological maturity. Thus, these assessments may have practical implications for coaches and practitioners seeking to identify promising young athletes and facilitate their development.

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 Regional Committee for Medical and Health Research Ethics in Norway (551902) and the Norwegian Agency for Shared Services in Education and Research (SIKT) (870863). 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

HG: Conceptualization, Data curation, Formal Analysis, Project administration, Writing – original draft, Writing – review & editing. KK: Conceptualization, Data curation, Writing – review & editing. MV: Data curation, Formal Analysis, Software, Writing – review & editing. CR: Data curation, Formal Analysis, Software, Writing – review & editing. HG: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

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Investigating the effects of previous injury on subsequent training loads, physical fitness, and injuries in youth female basketball players

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Background: Previous studies have shown that athletes accustomed to higher chronic workloads are less susceptible to injury than those exposed to lower chronic workloads. However, few studies have evaluated whether previous injury influences them. Therefore, this study investigated the impact of previous injuries on subsequent training loads, physical fitness, and injury rates in female youth basketball players.

Methods: Training load, physical fitness, and injuries of 18 young female basketball players (age 16.8 ± 1.4 years) were monitored. Previous injury status was clustered using the K-means clustering algorithm to separate players into high-risk and low-risk groups. Linear mixed models were used to analyze the effects of previous injury status on subsequent training load and physical fitness. Meanwhile, the differences between the players' injury groups were analyzed.

Results: Previous injury status can significantly impact a player's subsequent training loads, including acute loads, chronic loads, skill-based training loads, training monotony, and training strain (all $p < 0.05$). The two groups had no significant differences in physical fitness (all $p > 0.05$). Furthermore, the incidence of non-contact injuries was significantly higher in the high-risk group than low-risk group, which would result in more training time lost (all $p < 0.05$).

Conclusion: This study identified the impact of previous injury status on subsequent training load, physical fitness, and injuries in youth female basketball players. These findings provide valuable insight for coaches to optimize training loads according to previous injury status, aiming to minimize the likelihood of subsequent injuries.

KEYWORDS

training load, physical fitness, injury, youth, basketball

1 Introduction

In recent years, there has been a growing emphasis on specialization in elite youth sports, leading to a level of competitiveness akin to adult sports (Bergeron et al., 2024). While this approach may help identify young athletes with the potential to become elite athletes, it is important to recognize that an overemphasis on early professional success may lead to a series of health problems. For example, Hall and colleagues found that female adolescents who engaged in early sports specialization exhibited a markedly higher risk of knee health problems (Hall et al., 2015). Additionally, previous experience has indicated that during periods of rapid growth, long bones lengthen more quickly than the muscle-tendon complex, which can create tension on the tendon apophysis and potentially lead to traction injuries on the growth plate (Nguyen and Caine, 2024). Consequently, these adverse outcomes not only hinder subsequent training and impede physical fitness development but also interfere with the healthy growth of youth athletes (Bahr, 2014).

High training volume, intensity, and competition frequency are critical to improving competitive performance in young athletes, but they also raise concerns about sports-related injuries (Visnes and Bahr, 2013). It is commonly believed that higher training loads lead to more injuries. However, recent research suggests that athletes accustomed to high training loads experience fewer injuries than those with lower training loads, which contradicts conventional wisdom (Hulin et al., 2016). For instance, Gabbett and colleagues found that rapid increases in training load significantly raised the likelihood of injuries in team sports (Gabbett et al., 2016). Then, they introduced the concept of the acute-to-chronic workload ratio (ACWR) to measure these rapid changes in training loads and proposed the training-injury prevention paradox (Gabbett, 2016). They suggest that players who experience high chronic loads have developed sports-matched physical fitness, which reduces the risk of injury associated with a sudden increase in training load. Despite the appeal of this paradox, the conflicting findings of the available investigations make determining the relationship between training load and injury remains an open question (Mohr et al., 2023; Impellizzeri et al., 2020). Consequently, these findings prompt the interesting question: "What factors contribute to individual differences in tolerance for rapid spikes in load? (Gabbett, 2020)"

Previous injury, which is a significant risk factor with strong evidence in elite youth sports, can lead to problems such as reduced muscle strength, altered muscle recruitment patterns and proprioceptive deficits (Fulton et al., 2014). For instance, Røksund and colleagues demonstrated that football players who experienced hamstring strains exhibited a significant decrease in speed during a repetitive sprint test (Røksund et al., 2017). Similarly, Buhmann and his team found that hamstring injury history was associated with long-term deficits in autonomic activation during maximal centrifugal contraction, stretch reflex, and tendon reflex amplitude (Buhmann et al., 2020). This evidence highlights that previous injuries can significantly alter internal risk factors, thereby directly or indirectly impacting an athlete's training tolerance and physical fitness (Alonso-Muñoz et al., 2023; Steib et al., 2013). Although most existing research on previous injury history has investigated factors that may influence new injuries, such as changes in kinematics and motor skills, few studies have focused on the impact of previous injuries on subsequent training, which may blur the association between training load and injury (Sedeaud et al., 2020). Hence, it is necessary to investigate the impact of previous injuries on subsequent training.

With this in mind, this study utilizes metadata from previously published research to preliminarily investigate the effects of previous injuries on subsequent training load, physical fitness, and injury in young female basketball players (Huang et al., 2022). It was hypothesized that players with a higher injury burden would be characterized by an inability to withstand higher training loads (both accumulation and variability), poorer fitness, and a higher incidence of injuries than players with a lower injury burden.

2 Materials and methods

2.1 Ethics statement

This study was conducted following the guidelines of the Declaration of Helsinki and was approved by the Fujian Provincial Basketball and Volleyball Sports Management Center (protocol number: FJBVSM2020101001).

2.2 Participants

Eighteen youth female basketball players (age: 16.8 ± 1.4 years, height: 175.7 ± 6.0 cm, weight: 66.1 ± 6.0 kg, training years: 3.4 ± 1.7 years) were recruited. Training load, physical fitness, and injury monitoring data were collected from participants over 20 weeks. The team's weekly schedule consisted of 5–6 skill-based basketball sessions lasting 80–120 min, emphasizing skills development and game-based conditioning. Additionally, the participants engaged in 2–3 physical training sessions lasting 60–80 min per week, focusing on metabolic conditioning, strength/power, and agility development. Before the commencement of the study, all participants were provided with written and oral information about the study and were required to sign an informed consent form.

2.3 Training load

The Borg-10 ratings of perceived exertion (RPE) scale was used to monitor the perceived exertion experienced by the players following each training session, which has been confirmed for its validity (Foster et al., 1995; Chen et al., 2002). Then, the duration between the start and end of the training was recorded. The internal training load was quantified by calculating the session rating of perceived exertion (sRPE) using Equation 1.

$$\boldsymbol{sRPE} = \boldsymbol{duration} \times \boldsymbol{RPE} \tag{1}$$

The unit of measurement for the duration was minutes, while the RPE was expressed in arbitrary units (AU). This study assessed the training load information of the athletes by calculating acute training load (ATL), chronic training load (CTL), acute chronic workload ratio (ACWR), monotony, and

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strain. ATL is the rolling average of sRPE or duration for the last week, and CTL is the rolling average of sRPE or duration for the past 4 weeks. The ACWR, monotony, and strain were calculated as shown in Equations 2–4.

$$\boldsymbol{ACWR = \frac{ATL}{CTL}} \tag{2}$$

$$\boldsymbol{Monotony = \frac{Average\ of\ weekly\ training\ load}{Standard\ deviation\ of\ weekly\ training\ load}} \tag{3}$$

$$\boldsymbol{Strain = Average\ of\ weekly\ training\ load \times Monotony} \tag{4}$$

2.4 Physical fitness

This study used several field-based tests to assess physical fitness according to the testing protocols available in Sports Injury Management (Joyce and Lewindon, 2016). In detail, the squat one-repetition maximum (1 RM) test was utilized to assess the maximal strength of the lower extremities, while the bench press 1 RM test was employed to evaluate the maximal strength of the upper extremities. Agility was evaluated using the 5.8 m × 6 rounds shuttle run, and repeated sprint performance was measured through the 15 m × 17 rounds shuttle run. The run-up vertical jump (RVJ) test measured the explosive and jumping ability.

2.5 Injury surveillance

Injury was defined as an event during training or a match that resulted in the player's absence from subsequent sessions, and injury data were collected according to a standardized collection procedure (Bahr et al., 2020; Fuller et al., 2006). The injury records included details on the injury's location, nature, time loss, type, occurrence of injury (contact, non-contact), and diagnosis mode. According to the Strengthening the Reporting of Observational Studies in Epidemiology Sports Injury and Illness Surveillance (STROBE-SIIS), this study defined non-contact injuries as injuries caused by indirect contact mechanisms, including overuse and chronic injuries (Bahr et al., 2020). Among them, the upper extremity included the shoulder, upper arm, elbow, forearm, wrist, and hand; the lower extremity included the hips, thighs, knees, calves, ankles, and feet; the trunk included the chest, thoracic spine, lumbosacral, and abdomen. The injury incidence during the investigation was calculated using the following Equation 5:

$$\boldsymbol{Incidence = \frac{number\ of\ injuries}{training\ exposure} \times 1000\,h} \tag{5}$$

The injury record in the year before the research started was considered the previous injury. Six indicators were incorporated as analysis variables for the cluster, which encompassed the count of upper extremity injury (UEI), the count of lower extremity injury (LEI), the count of trunk injury (TI), loss of time due to upper extremity injuries (LT-UEIs), loss of time due to lower extremity injuries (LT-LEIs), and loss of time due to trunk injuries (LT-TIs).

2.6 Statistical analysis

In this study, the K-means clustering algorithm was used to analyze the previous injury history. Prior to clustering, scaling was performed using the median and interquartile range. The optimal number of clusters (k-value) is determined by silhouette coefficient maximization, where the k-value ranges from 2 to 5. Differences in categorical variables were analyzed using the Chi-squared test, while differences in continuous numerical variables were analyzed using Welch's t-test or Welch's analysis of variance (It depends on the optimal number of clusters). Linear mixed models were used to assess the effects of time and previous injury history status on dependent variables, treating time and group as fixed effects and player as a random effect. Since this investigation focused on the impact of previous injuries on each indicator of players, only the main and interaction effect of previous injury status on the dependent variable was reported. Post-hoc analyses with Bonferroni correction were conducted for statistically significant main and interaction effects. All hypothesis tests were two-tailed with a significance level (α) of 0.05, and p-values greater than 0.1 were considered insignificant, p-values less than 0.1 were marginally significant, and p-values less than 0.05 were considered significant. The data were analyzed using Jamovi software (version 1.8.1) and Python 3.6 programming environment.

3 Results

3.1 Previous injury grouping

The clustering results indicate that the maximum silhouette coefficient (0.398) was achieved when the number of clusters (k) was set to 2. As a result, this study divided the players into two clusters. The descriptive statistics for these two clusters are presented in Table 1. It is clearly seen that the two clusters are significantly different in terms of training years, LEI count, LT-LEIs, UEI count, and LT-UEIs ($p < 0.05$), while there were no significant differences in terms of position, age, height, weight, BMI, TI count, and LT-TIs ($p > 0.05$). Consequently, this study named the clusters as high-risk and low-risk groups.

3.2 Training load

The player's previous injury status did not significantly affect their weekly fitness-based training load and skill-to-fitness training load ratio ($p > 0.05$). However, it did significantly reduce the player's ATL ($p = 0.033$, Bonferroni corrected), CTL ($p = 0.021$, Bonferroni corrected), and total weekly skill-based training load ($p = 0.031$, Bonferroni corrected). Similar findings were also observed in the analysis of training duration, which showed that previous injury status would significantly decrease a player's ATL ($p = 0.034$, Bonferroni corrected), CTL ($p = 0.018$, Bonferroni corrected) and total weekly skill-based training session duration ($p < 0.001$, Bonferroni corrected).

There was no significant interaction between previous injury status and time on training load indicators ($p > 0.05$). However, it is important to note that both training monotony (sRPE-based

TABLE 1 The descriptions and differences in the basic information between the high-risk and low-risk groups.

	High risk	Low risk	*p*	MD	95% CI of MD	Cohen's d effect size
Position						
Forward Center Guard	5 (45.5) 3 (27.3) 3 (27.3)	5 (71.4) 1 (14.3) 1 (14.3)	0.557	—	—	
Age (years)	16.91 ± 1.14	16.57 ± 1.90	0.682	0.338	−1.472 to 2.147	0.216
Height (cm)	177.00 ± 6.40	174.00 ± 5.50	0.421	2.351	−3.711 to 8.413	0.394
Weight (kg)	68.10 ± 5.90	62.90 ± 5.10	0.065	5.234	−0.378 to 10.845	0.951
BMI (kg/m^2)	21.80 ± 1.80	20.70 ± 1.50	0.156	1.144	−0.489 to 2.777	0.707
Training Years (years)	3.55 ± 0.69	2.29 ± 1.25	**0.040***	1.260	0.075 to 2.444	1.246
LT-TIs (days)	1.73 ± 2.57	0.86 ± 2.27	0.464	0.870	−1.607 to 3.347	0.359
LT-LEIs (days)	4.19 ± 1.00	0.29 ± 0.76	**< 0.001****	3.905	3.023 to 4.787	4.419
LT-UEIs (days)	2.82 ± 1.54	1.00 ± 1.73	**0.043***	1.818	0.066 to 3.570	1.110
TI Count	0.64 ± 0.81	0.29 ± 0.76	0.367	0.351	−0.457 to 1.159	0.448
LEI Count	2.55 ± 1.29	0.14 ± 0.38	**< 0.001****	2.403	1.502 to 3.304	2.522
UEI Count	1.36 ± 0.92	0.43 ± 0.79	**0.037***	0.935	0.064 to 1.807	1.089

Abbreviations: BMI, body mass index; TI, trunk injury; LEI, lower extremity injury; UEI, upper extremity injury; LT-TIs, loss of time due to trunk injuries; LT-LEIs, loss of time due to lower extremity injuries; LT-UEIs, loss of time due to upper extremity injuries; MD, mean difference.
Note: The Chi-squared test was used to compare the position of the two groups; a Welch's t-test was used to compare age, height, weight, BMI, training year, TI, count, LT-TIs, LEI, count, LT-LEIs, UEI, count, and LT-UEIs.
Bold indicates statistically significant values ($p < 0.05$).
*$p < 0.05$.
**$p < 0.01$.

monotony: p = 0.004, Bonferroni corrected, duration-based monotony: p = 0.002, Bonferroni corrected) and training strain (sRPE-based strain: p = 0.008, Bonferroni corrected, duration-based strain: p = 0.001, Bonferroni corrected), which were calculated based on sRPE or duration, were significantly lower in the high-risk group (Table 2).

3.3 Physical fitness

It was found that previous injury status had no significant main effect on the squat 1RM (p = 0.388), bench press 1RM (p = 0.629), 5.8 m × 6 rounds shuttle run (p = 0.168), and RVJ (p = 0.299). However, there was a slightly significant effect on the 15 m × 17 rounds shuttle run (p = 0.065). Further analysis revealed that the low-risk group performed significantly better than the high-risk group on the third (p = 0.034, MD = 1.41, 95% CI: 0.12–2.71) and fourth tests (p = 0.019, MD = 1.59, 95% CI: 0.30–2.88) of the 15 m × 17 rounds shuttle run. Additionally, no significant interaction was found between previous injury status and time on physical fitness indicators (p > 0.05).

3.4 Injuries

It was found that the incidence of injuries (p = 0.032, MD = 6.69, 95% CI: 0.68–12.70) and non-contact injuries (p = 0.034, MD = 6.11, 95% CI: 0.52–11.70) was significantly higher in the high-risk group (Table 3). There was no significant difference in the incidence of contact injury between the two groups (p > 0.05). Notably, players in the high-risk group were more prone to losing training time due to non-contact injuries (p = 0.026, MD = 4.46, 95% CI: 0.64–8.27).

4 Discussion

This study retrospectively investigated the impact of previous injuries on subsequent training loads, fitness, and injury. Our findings revealed the following characteristics among players classified in the high-risk group compared to the low-risk group: (i) ATL, CTL, skill-based training load, training monotony, and training strain were significantly lower in the high-risk group. (ii) Players in the high-risk group took longer to complete the 15 m × 17 rounds shuttle run test, but this difference did not reach statistical significance. (iii) Incidence of injury, particularly non-contact injury, was significantly higher in the high-risk group. Meanwhile, players in the high-risk group experienced more training time lost due to non-contact injury.

The findings of this study provide evidence supporting that previous injuries not only increase players' susceptibility to subsequent injuries but also adversely affect their training tolerance, which aligns with the basic hypothesis of this study (Mandorino et al., 2023). It is widely acknowledged that players who maintain high chronic workloads usually achieve the necessary fitness for competition, reducing their likelihood of injury (Windt and Gabbett, 2017). Conversely, players with low chronic workloads

TABLE 2 Linear mixed model results for the effect of previous injury status on training load and physical fitness.

Dependent variables			Independent variables					
			Time		Group		Time × group	
			F	*p*	F	*p*	F	*p*
Training load	sRPE based	ATL (au)	2.974	**<0.001****	5.473	**0.033***	0.909	0.568
		CTL (au)	2.018	0.018*	6.610	**0.021***	1.627	0.075
		ACWR (au)	1.382	0.164	0.088	0.767	1.208	0.271
		skill-based session (au)	17.976	**<0.001****	5.671	**0.030***	0.891	0.591
		fitness-based session (au)	36.177	**<0.001****	3.031	0.100	0.791	0.710
		skill-to-fitness ratio (au)	28.206	**<0.001****	1.023	0.327	0.869	0.616
		Monotony (au)	12.412	**<0.001****	11.182	**0.004****	0.394	0.988
		Strain (au)	10.975	**<0.001****	9.364	**0.008****	0.574	0.916
	Duration based	ATL (au)	2.853	**<0.001****	7.756	**0.013***	0.781	0.723
		CTL (au)	2.910	**<0.001****	6.934	**0.018***	1.312	0.203
		ACWR (au)	1.632	0.073	0.158	0.691	1.235	0.252
		skill-based session (au)	18.729	**<0.001****	8.849	**0.009****	0.892	0.589
		fitness-based session (au)	47.207	**<0.001****	3.171	0.093	0.600	0.899
		skill-to-fitness ratio (au)	36.998	**<0.001****	0.824	0.365	1.250	0.222
		Monotony (au)	12.734	**<0.001****	14.369	**0.002****	0.380	0.990
		Strain (au)	10.780	**<0.001****	15.299	**0.001****	0.443	0.977
Physical fitness	Squat 1RM (kg)		2.745	0.055	0.788	0.388	0.798	0.502
	Bench press 1RM (kg)		9.893	**<0.001****	0.243	0.629	0.261	0.853
	Run-up vertical jump (cm)		0.365	0.779	1.150	0.299	0.228	0.876
	5.8M × 6 rounds shuttle run (seconds)		12.270	**<0.001****	2.083	0.168	1.179	0.329
	15M × 17 rounds shuttle run (seconds)		0.214	0.886	3.933	0.064	0.772	0.516

Abbreviations: sRPE, session rating of perceived exertion; ATL, acute training load; CTL, chronic training load; ACWR, acute chronic workload ratio; RM, repetition maximum.
Note: Bold indicates statistically significant values ($p < 0.05$).
*$p < 0.05$.
**$p < 0.01$.

TABLE 3 The descriptions and differences in the incidence of injuries and time loss between the high-risk and low-risk groups.

	High risk	Low risk	*p*	MD	95% CI of MD	Cohen's d effect size
Injury Incidence (per 1,000 training hours)	11.70 ± 6.01	5.01 ± 5.63	**0.032***	6.690	0.682 to 12.697	1.150
NCI Incidence (per 1,000 training hours)	9.38 ± 6.32	3.27 ± 4.80	**0.034***	6.110	0.517 to 11.703	1.090
CI Incidence (per 1,000 training hours)	2.32 ± 2.40	1.74 ± 1.89	0.577	1.017	−1.587 to 2.746	0.269
LT-Injury (days)	9.09 ± 5.74	8.29 ± 15.05	0.896	0.805	−13.204 to 14.814	0.071
LT-NCIs (days)	4.96 ± 5.54	0.50 ± 1.32	**0.026***	4.455	0.644 to 8.266	1.106
LT-CIs (days)	4.14 ± 5.33	7.07 ± 15.56	0.645	−2.935	−17.389 to 11.519	−0.252

Abbreviations: NCI, non-contact injury; CI, contact injury; LT-NCIs, loss of time due to non-contact injuries; LT-CIs, loss of time due to contact injuries; MD, mean difference.
Note: Bold indicates statistically significant values ($p < 0.05$).
*$p < 0.05$.

may lack the fitness reserves needed to handle the demands of intense competition, resulting in a higher risk of injury (Gabbett, 2016; Windt et al., 2017). However, some investigations yielded conflicting findings, leading to ongoing debate (Mohr et al., 2023; Impellizzeri et al., 2020; Suarez-Arrones et al., 2020; Myers et al., 2020). It is important to note that existing research has ignored the impact of previous injuries on training load and injury, which could be a crucial factor in explaining these inconsistencies (Sedeaud et al., 2020). Our findings revealed that players with a higher burden of previous injuries exhibited lower training loads (both acute and chronic workloads) and a higher incidence of subsequent injuries. Meanwhile, these players had lower training monotony and strain, which may mean that they could not withstand rapid changes in training load. To our knowledge, training monotony and strain are strongly associated with increased risk of injury, overtraining syndromes, and illness (Curtis et al., 2021). For instance, Brink and colleagues identified a significant correlation between higher monotony and an increased likelihood of injury (Brink et al., 2010). Nevertheless, our findings observed that players with a higher injury burden generally had lower levels of monotony and strain, but still had a high incidence of subsequent injury. These findings prompt the question: Does frequent exposure to higher chronic workloads reduce players' risk of non-contact injuries? We propose that players with lower chronic workloads may have higher injury burdens than those with higher chronic workloads, making them more susceptible to maladaptation due to training intolerance and compensatory movement patterns (Opar et al., 2012; Croisier, 2004; Blyton et al., 2023; Hodges and Tucker, 2011; Desai and Gruber, 2021). As Howe and colleagues found, exercise-induced fatigue can exacerbate compensatory strategies, elevating the risk of injury to the affected limb (Howe et al., 2021). This vulnerability increases the susceptibility of these players to non-contact injuries, perpetuating a detrimental cycle. The debate will continue as existing research remains insufficient to provide a simple and definitive answer to this question.

Contrary to expectations, this study did not find an effect of previous injuries on the players' strength, agility, or jumping ability. In theory, previous injuries should impair a player's motor function, especially proprioception and neuromuscular control, leading to poorer fitness (Mandorino et al., 2023; Ritzmann et al., 2022). For example, Areia and associates found deficits in muscle activity, proprioception, and functional asymmetry in individuals with a history of hamstring strain during eccentric testing (Areia et al., 2019). Similarly, Bramah and colleagues observed differences in running kinematics among male runners with recurrent calf muscle strain injuries, possibly due to neuromuscular deficits (Bramah et al., 2021). However, contrary to earlier findings, no effect of previous injury on physical fitness was detected. One possible explanation is that players who have experienced previous injuries can maintain their performance through compensatory movements. For instance, youth basketball players with a history of injury exhibited similar peak mean vertical ground reaction forces during jump landings compared to uninjured players (Louw et al., 2006). However, players with a history of injury demonstrated smaller hip and knee flexion angles and greater eccentric activity during landing. Another possible explanation is that variations in test selection may have led to inconsistent results. A recent systematic review found that inter-limb strength asymmetry, measured by isometric knee extensor strength testing, correlates with higher injury risk (Guan et al., 2022). However, this correlation was not observed in unilateral jump test measures (Brumitt et al., 2020). Therefore, future observations will take into account the differences between the tests.

Notably, this study found that previous injuries slightly affected players' repetitive sprint performance, similar to earlier findings (Røksund et al., 2017). Since repeated sprinting ability is important for basketball success and demands a high level of neuromuscular resistance to fatigue (Gottlieb et al., 2021; Charron et al., 2020), it was speculated that players with higher injury burdens would be more susceptible to neuromuscular fatigue. The research by Norte and colleagues supports our speculation (Norte et al., 2018). They found that patients who had experienced anterior cruciate ligament reconstruction (ACLR) exhibited impaired quadriceps strength and corticospinal excitability at each time point of knee extension. Frank and others found that neuromuscular fatigue may influence the increased risk of future injuries in women with a history of ACLR by altering lower extremity biomechanics and postural control (Frank et al., 2014). Despite lacking clinical information on neuromuscular fatigue, our study revealed significant differences between high-risk and low-risk groups in the third and fourth tests. Considering the effect of training intensity schedules on physical fitness, training-induced neuromuscular fatigue could be crucial in the relationship between previous injuries and a player's ability to repeat sprints.

In summary, although previous injuries do not significantly affect the physical performance of young female basketball players, they can hinder training tolerance and increase the risk of further injuries. These findings suggest that coaches should adjust the training load composition based on previous injuries to improve players' training tolerance and reduce the likelihood of additional injuries caused by neuromuscular fatigue, such as increasing the neuromuscular training, improving movement patterns and developing a fitness-fatigue model to manage the training load effectively (Paravlic et al., 2024; Šiupšinskas et al., 2019; Imbach et al., 2022). Nevertheless, given the information available, this study cannot offer more detailed recommendations for future training until the following limitations are addressed. Firstly, although the implemented sRPE-based training load quantification method is widely used in sports practice and research, it is a general indicator and does not differentiate between specific physiological response changes and intensity (Dhahbi et al., 2024). Secondly, this study was conducted within a sports management center, generalisations beyond this specific cohort should be treated with caution. While using data from a single centre can help avoid confounding factors such as youth maturity, coaching leadership styles, and match demands (whether in-season or off-season), it also limits the possibility that these findings can be extrapolated to all youth populations. Further research is needed to investigate the effects of the above-mentioned confounders on the findings (Silva et al., 2022; Giuriato et al., 2023). Finally, it would have been interesting to evaluate the effect of previous injury status on physiological responses following physical fitness testing, such as electromyography during strength testing and blood lactate during repetitive sprint performance testing (Kubo et al., 2019; Zebis et al., 2022).

5 Conclusion

The findings of this preliminary study revealed that while previous injuries do not substantially impact the physical fitness performance of young female basketball players during field-based assessments, they can impair subsequent training loads and lead to further injuries. These findings offer valuable insights into optimizing training loads based on previous injuries. Nevertheless, this study still has some flaws. Future research should include more comprehensive neuromuscular tests to investigate how previous injuries impact subsequent training loads and injuries, which could help develop injury prevention strategies based on training load management.

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 Fujian Provincial Basketball and Volleyball Sports Management Center. 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

YH: Conceptualization, Data curation, Methodology, Software, Writing–original draft, Writing–review and editing. SW: Conceptualization, Writing–original draft, Writing–review and editing. CL: Data curation, Resources, Writing–original draft, Writing–review and editing. YW: Methodology, Software, Writing–review and editing. ZB: Methodology, Software, Writing–review and editing. BL: Methodology, Writing–review and editing. YG: Data curation, Resources, Writing–review and editing. ZW: Conceptualization, Writing–original draft, Writing–review and editing.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2025.1506611/full#supplementary-material

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Acute effect of technique modification training on 180° change of direction performance and kinematics in adolescent male soccer players

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Introduction: Change of direction (COD) maneuvers are frequently performed during soccer games and are critical for performance. Adolescent players often display immature COD maneuvers, suggesting that COD technique modification training may be a more effective approach for adolescent athletes. This study investigated the acute effects of COD modification training on COD performance and kinematics in male adolescent soccer players.

Methods: Twenty-nine male junior high school soccer players participated in this study and were divided into two groups: 16 players underwent 15-min COD technique modification training (COD group), while 13 players engaged in 15-min linear sprint training. The participants performed Pro-Agility and 20-m sprint tests before and after the intervention, and the total times were measured. COD deficit (CODD) was calculated as the difference between these times. Center of mass (COM) velocity and trunk and lower limb kinematics were computed from three-dimensional kinematic data collected during the Pro-Agility test using a markerless motion capture system. Each section of the Pro-Agility test was divided into acceleration and deceleration phases based on the COM velocity; Stop marks the moment of direction change. Two-way (group and time) mixed ANOVA was conducted with Bonferroni corrections for *post-hoc* comparisons.

Results: No significant interactions were observed in the total time of the Pro-Agility test, CODD, 20-m sprint time, or average acceleration and deceleration in each phase ($p > 0.05$). On the other hand, the COD group showed significant interactions and improvements in average deceleration from final foot (FF) contact to Stop ($p = 0.012$, $g = 0.639$), penultimate foot hip flexion angle at Stop ($p = 0.042$, $g = 0.496$), COM-FF horizontal distance at Stop ($p = 0.008$, $g = 0.650$), and FF ground contact time ($p < 0.001$, $g = 0.803$).

Conclusion: A 15-min COD technique modification training led to partial, immediate improvements in kinematic parameters among adolescent soccer players but did not enhance overall COD performance or acceleration/deceleration ability.

KEYWORDS

intervention, agility, turning, deceleration, acceleration, motion analysis, Pro-Agility

1 Introduction

Change of direction (COD) maneuvers are often performed during soccer. Soccer players perform approximately 100 COD maneuvers in the 90–180° range per match (1), requiring substantial deceleration during COD. These maneuvers are common in situations involving opponents (2) and are essential for gaining temporal and spatial advantages. Consequently, improving COD performance is one of the primary goals of performance coaches who implement targeted training interventions. COD performance is typically assessed by the total time required to complete a COD task (CODTT). However, for a more detailed analysis, COD maneuvers can be broken down into four components: initial acceleration, deceleration, turning, and reacceleration (3). Previous studies have shown that deceleration before and after turning affects CODTT (4, 5), and elite soccer players complete COD tasks faster than their non-elite counterparts (6, 7).

Moreover, because CODTT is greatly influenced by linear sprint ability (8, 9), the concept of COD Deficit (CODD), calculated as the difference between the CODTT and linear sprint time over the same distance, has been proposed (8). CODD reflects time loss owing to deceleration, direction change, and reacceleration relative to linear sprinting ability, independent of linear sprint ability (8, 10). Harper et al. further divided the deceleration phase during the deceleration test into early and late halves (11). They found that a large deceleration was associated with superior physical fitness (11). Another study used a three-dimensional (3D) motion capture system to evaluate the center of mass (COM) velocity-time curve during the 505 Test, revealing significantly larger deceleration from the penultimate foot (PF) in the faster group than in the slower group (4). Therefore, examining the training effect on acceleration and deceleration in COD maneuvers in detail is essential.

Various training methods, including resistance and plyometric training, are commonly employed to improve COD. A meta-analysis by Chaabene et al. suggested that improvements from resistance training may stem from neural factors, such as increased motor unit recruitment and synchronization, as well as morphological factors, including increased muscle fiber size (12). Similarly, a meta-analysis by Asadi et al. indicates that plyometric training enhances COD performance through neuromuscular adaptations, improves motor unit recruitment, and increases eccentric strength in thigh muscles (13).

Moreover, COD techniques that optimize horizontal force orientation are essential for COD performance (4, 14). For example, a lower COM achieved through PF triple flexion and trunk inclination toward the intended direction increases stability and facilitates a more horizontal application of the braking force (4). In the turning phase, a wider final foot (FF) contact position relative to the COM plays a key role in applying propulsive force (15, 16). Dos'Santos et al. indicated that the CODTT of the 505 Test was significantly correlated with PF hip flexion angle, PF knee flexion angle, and the vector of propulsive force in FF (4). To modify such techniques, previous studies have investigated the impact of COD technique modification training on these aspects (17–19). This method involves implementing drills that incorporate various COD maneuvers, teaching technical points, and providing live feedback. A previous study reported that a 6-week COD technique modification training program in adult populations improved the CODTT of the 505 Test, as well as the PF maximum hip flexion angle and FF contact time (18). Furthermore, such technical improvements can potentially decrease the load on the FF knee, thereby mitigating the risk of severe non-contact knee injuries (17, 19, 20). For example, the increase in PF hip maximum flexion angle promoted deceleration with PF, which is associated with reducing FF knee abduction moment (17). Similarly, trunk inclination toward the intended direction, a characteristic observed in athletes with faster CODTT (4), has also been associated with a reduced risk of knee injuries (17, 20). This indicates that COD technique modification training may be effective for both performance enhancement and, in some aspects, injury prevention (17–19).

COD ability is trainable across various adolescent-age players (21, 22), who tend to exhibit immature COD maneuvers (23). Therefore, COD technique modification training may be a more effective approach for improving the COD ability in these athletes, potentially leading to immediate positive changes. Such acute changes in COD maneuvers can lead to long-term performance enhancement and injury prevention. When adolescent athletes experience injuries, their training and match participation are often limited, negatively impacting future performance and restricting their athletic development (24). Therefore, more research on training interventions for skill learning and adaptation in COD performance is needed for adolescent athletes (25).

Consequently, this study investigated the acute effects of COD technique modification training on COD performance and kinematics in male adolescent soccer players. We hypothesized that COD technique modification training would acutely improve the kinematics of COD maneuvers, enhancing deceleration ability and overall COD performance.

2 Materials and methods

2.1 Research design

This randomized controlled trial employed a pre-test/post-test design to investigate the acute effects of COD technique modification training on COD performance and kinematics in adolescent male soccer players. This study measured the 20-m sprint time, CODTT, and kinematic data in the Pro-Agility test and calculated the CODD before and after the intervention. Participants were categorized into two groups, each undergoing a different training program between the pre- and post-test. The COD technique modification training group (CODG) underwent COD technique modification training focused on refining basic COD skills (Table 1), whereas the control group (CONG) engaged in linear sprint training, excluding COD (Table 2). The training duration (15 min) and running distance (190 m) were matched between CODG and CONG to ensure comparability. 3D motion analysis was conducted using a markerless motion

TABLE 1 Fifteen-minute intervention program of COD modification training.

	Exercises	Intensity (perceived speed)	Total distance (m)	Number of decelerations and CODs	Repetitions	COD emphasis
1	5 m running—Stop—10 m running—Stop	80%	15	2	2	- Decelerate at PF
2	5 m running—90° COD—5 m sidestep—Stop	80%	10	2	2 (1 each side)	- Decelerate at PF - Push the body in the next direction at FF
3	5 m sidestep ×2–5 m running	100%	15	2	2 (1 each side)	- Decelerate at PF and drop COM - Push the body in the next direction at FF - Incline the trunk toward the next direction
4	5 m running—90° COD—5 m running—135° COD—5 m running—Stop	80% and 100%	15	3	4 (1 each side and intensity)	- Decelerate at PF - Push the body in the next direction at FF - Incline the trunk toward the next direction
5	5 m shuttle run (including 2 180° COD)	100%	15	2	2 (1 each side)	- Decelerate at PF and drop COM - Push the body in the next direction at FF - Incline the trunk toward the next direction
6	Pro-Agility run	100%	20	2	1	- Decelerate at PF and drop COM - Push the body in the next direction at FF - Incline the trunk toward the next direction
	Total		190	30		

COD, change of direction; PF, penultimate foot; FF, final foot; COM, center of mass.

TABLE 2 Fifteen-minute intervention program of linear sprint training.

Exercises	Intensity	Total distance (m)	Number of decelerations and CODs	Repetitions
10 m running	80%	10	0	2
15 m running	80%	15	0	4
15 m running	Gradually increase to maximum speed	15	0	2
15 m running	100%	15	0	4
20 m running	100%	20	0	1
Total		190	0	

capture system to explore joint kinematics and the COM velocity-time curve during the Pro-Agility test to examine the effectiveness of the intervention.

2.2 Participants

A minimum sample size of 12 per group was determined based on a prior power analysis using G*Power (version 3.1; University of Dusseldorf, Germany), assuming an effect size of 0.33, indicating a power of 0.8 and a type 1 error (alpha level) of 0.05 (26). Consequently, 32 junior high school male soccer players from a regional-level soccer team participated in this study, with 16 participants randomly assigned to either the CODG or the CONG. However, due to scheduling conflicts on the day of the study, three participants from the CONG dropped out. Therefore, 16 players were recruited for the CODG [mean ± standard deviation (SD); age: 14.0 ± 0.6 years, height: 162.8 ± 8.6 cm, and body mass: 51.9 ± 6.1 kg], and the other 13 players acted as the CONG (age: 14.1 ± 0.7 years, height: 165.8 ± 5.5 cm, and body mass: 55.2 ± 6.4 kg). No significant differences in age, height, or body mass were observed between the groups ($p = 0.190–0.765$). This study was approved by the Ethics Review Committee on Research with Human Subjects of Waseda University (approval no. 2022-308), and all participants and their parents were informed of the benefits and risks of the investigation before signing the consent forms. None of the participants had lower limb injuries that could affect measurements or training. They had no experience with systematic physical training but regularly participated in soccer, completing four 90-min training sessions or playing one competitive match per week.

2.3 Procedure

All measurements were completed on the same day between 18:00 and 21:00. Participants underwent anthropometric measurements wearing shorts, a T-shirt, and socks. After a standardized 10-min warm-up consisting of forward and backward jogging, sidestepping, dynamic stretching, and sprints, participants performed the pre-tests, including the 20-m sprint and Pro-Agility tests in a random order, with times measured using a timing gate system. A rest period of at least 2 min was allowed between trials or measurements to minimize fatigue. Then, participants completed a 15-min intervention program, and after 4 min of passive recovery, they performed the 20-m sprint and Pro-Agility tests in a random order as the post-tests. These tests and training sessions were conducted on a synthetic turf pitch while wearing soccer shoes.

2.3.1 Anthropometric measurements

Height was measured to the nearest 0.1 cm using a portable stadiometer (Seca 213, Hamburg, Germany). Body mass was measured to the nearest 0.1 kg using a body composition analyzer (HD-660, TANITA, Japan). Leg length was measured twice, from the greater trochanter to the lateral malleolus, using a measuring tape while the participant stood. The average values for both legs were used in the analysis. This measurement showed high intra-rater reliability, with an intraclass correlation coefficient ($ICC_{2,2}$) of 0.998–0.999.

2.3.2 20-m sprint

The 20-m sprint time was measured using a timing gate system (VoltOnoSprint; S-CADE, Tokyo, Japan), positioned at the start and goal lines and set to a height of approximately 0.8 m. Participants adopted a two-point stance 0.5 m behind the start line and started with the examiner's verbal signal. They were instructed to start without countermovement and sprint as quickly as possible. The test was performed twice during the pretest, and the average time was calculated. The post-test was performed only once.

2.3.3 Pro-Agility test

A Pro-Agility test was performed in three trials after sufficient familiarization. Participants adopted a two-point stance 0.5 m behind the start line and started with the examiner's verbal signal. They were instructed to perform the test as quickly as possible, using their dominant (kicking) leg to turn, ensuring they either touched or crossed the line at each turn. The CODTT was measured using a timing gate system (VoltOnoSprint, S-CADE, Tokyo, Japan) positioned at the start and goal line and set at approximately 0.8 m. 3D kinematic data were obtained using a markerless motion capture system (Theia3D, v2023, Theia Markerless, Kingston, ON, Canada) and 13 cameras (Sony RX0 II, Sony Corporation, Tokyo, Japan) at 120 fps. Trials were repeated for premature direction changes or slips after rest until three valid attempts were recorded, and the average value of the three trials was adopted for analysis.

2.4 Data analysis

2.4.1 CODD

CODD was calculated by subtracting the 20-m sprint time from the Pro-Agility CODTT (CODTT—20-m sprint time).

2.4.2 3D kinematic data

Video data were processed using the Theia3D software to obtain 3D pose estimates of the participants using the default inverse kinematics model. The 3D pose estimates for each body segment were exported for further analysis using Visual3D (x64 Professional v2023.03.1; C-Motion Inc., Germantown, MD) (27). Kinematic variables were smoothed using generalized cross-validation spline smoothing with a 10 Hz cut-off frequency. Lower limb joint angles were calculated using the standard Cardan rotation sequence (X-Y-Z) equivalent to the joint coordinate system (28). The trunk inclination angle was defined as the angle relative to the global coordinate system.

In this study, we focused on the 10-m interval and the subsequent reacceleration phase, as it is the most demanding part of the Pro-Agility test (10). The phases were defined from the velocity-time curve of the COM (Figure 1). The point at which the COM velocity approached closest to zero was defined as the "Stop." The 10-m interval was designated as the acceleration and deceleration phases, and each phase was further divided into two sub-phases of equal duration, defined as the "Early" and "Late." Additionally, the phase from the 2nd Stop to the toe-off of the FF was defined as the reacceleration phase.

To evaluate the rate of acceleration and deceleration, we calculated the average acceleration (Acc) and deceleration (Dec) for each phase. Additionally, we specifically calculated the Dec for PF and FF contact (PFC and FFC, respectively) events during the deceleration phase (i.e., PFC-FFC, FFC-Stop, and PFC-Stop). Foot contact was defined as the first occurrence of a peak in either heel or toe vertical acceleration (29). Toe-off was defined as the toe peak vertical jerk, which is the first derivative of acceleration with respect to time (29). To evaluate the trunk and lower body kinematics during deceleration, the PF hip and knee flexion angles, trunk inclination angle, COM height, and horizontal separation distance between the COM and FF (the midpoint of the toe and heel) were calculated. The COM height was normalized to the individual leg length.

2.5 Intervention program

After the pretest, participants underwent approximately 15 min of training (either COD modification training or linear sprint training). Each training session was classified into two groups of approximately eight participants, led by the principal researcher, a physical fitness coach certified by the Japan Football Association.

The COD technique modification training included drills at various angles, distances, efforts, and focuses based on previous studies (18, 19) (Table 1). The training focused on three technical aspects based on previous studies: (1) "Decelerate at the penultimate foot and drop COM" (to increase deceleration in PF and PF hip and knee flexion and to the lower COM); (2) "Push the body in the next direction at FF" (to increase horizontal propulsive force, resulting in getting larger COM velocity for next direction); (3) "Incline the trunk toward the next direction" (to align COM in a more effective position to apply the braking and propulsive force horizontally and minimize COM displacement relative to the turning line). Participants were provided with verbal coaching on the aforementioned points before the drill to ensure they understood the key aspects of the

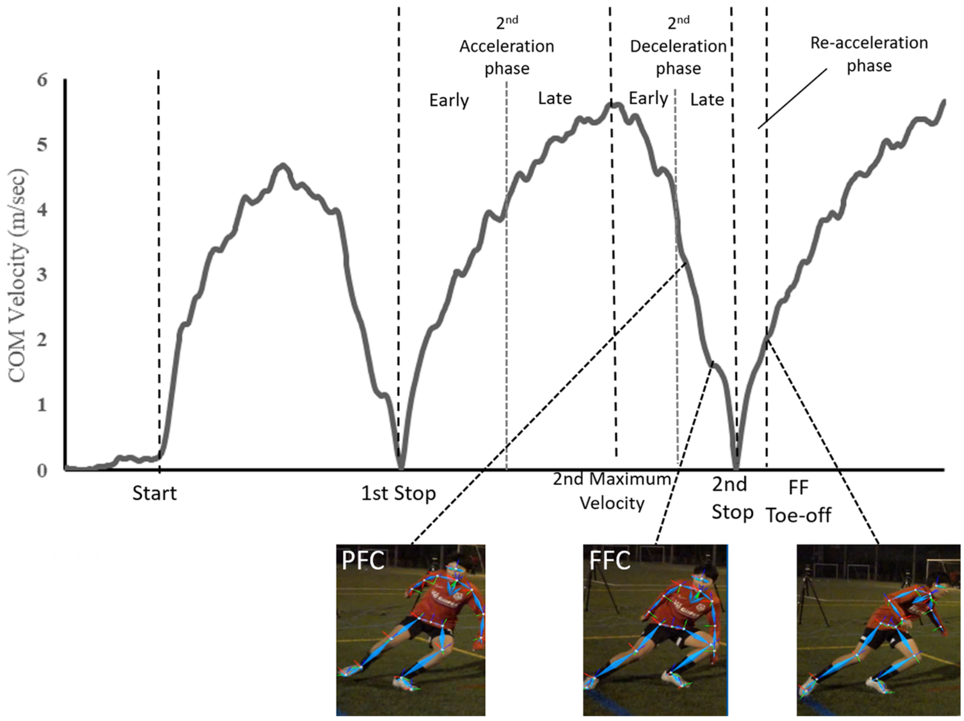

FIGURE 1
Phase division of the Pro-Agility test based on COM velocity.

upcoming drill. During the drills, coaching on these points was performed using short phrases at appropriate times. After each trial, participants received verbal feedback specifying the aspects that were performed well and the areas needing improvement concerning the aforementioned points.

The CONG conducted linear sprint training without COD maneuvers to eliminate differences caused by increased muscle temperature and post-activation potentiation. The training was designed to match the duration and total distance of the COD technique modification training (Table 2). No special instructions were given to the CONG, except for explaining the distance and intensity of the exercises.

2.6 Statistical analysis

All statistical analyses were performed using SPSS software (v28, SPSS, Inc., Chicago, IL, USA). The normality of all variables was assessed using the Shapiro–Wilk test. The reliability of the kinematic data from the Pro-Agility test was assessed using $ICC_{2,k}$, and the coefficient of variation (CV) was calculated using data from all 29 participants. Minimum acceptable reliability was determined with an ICC ≧ 0.7 and CV ≦ 15%, and variables demonstrating low reliability were removed from further analysis (4).

A two-way mixed analysis of variance (ANOVA), with a between-subject factor (CODG and CONG) and a within-subject factor (pre- and post-intervention measures), was used to identify significant interactions (group × time) for outcomes. A Bonferroni-corrected pairwise comparison was used for further analyses when significant interactions were observed. Partial eta squared (partial η^2) effect sizes were calculated for all ANOVAs and evaluated as follows: small (0.010–0.059), medium (0.060–0.149), and large (≧0.150). Pre-to-post changes in variables for each group were assessed using a paired-sample t-test, and the magnitudes of differences were evaluated using Hedges' g effect sizes, interpreted as trivial (≦0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (2.00–3.99), and extremely large (≧4.00). Statistical significance was set at $p < 0.05$ for all analyses.

3 Results

Almost all measurements and analysis variables demonstrated high intra-session reliability (Pre: $ICC_{2,k}$ = 0.701–0.850, CV = 1.0–14.3%; Post: $ICC_{2,k}$ = 0.707–0.934, CV = 1.4–13.8%) except for Early Dec, Late Acc, PF hip flexion angle at PFC, PF knee flexion angle at PFC and Stop, FF hip flexion angle at Stop, and FF knee flexion angle at FFC and Stop (Table 3). These variables showed low reliability and were excluded from further analysis.

Based on the two-way mixed ANOVA, no significant interaction was observed in CODTT, CODD, or 20-m sprint time. No significant interactions were observed in any of the Acc or Dec in each acceleration and deceleration phase (Table 4).

TABLE 3 Reliability of completion times and phase- and event-specific variables.

Variables	Event	$ICC_{2,k}$		CV (%)	
		Pre	Post	Pre	Post
Completion times					
CODTT	—	0.850	0.934	1.8	1.4
20 m sprint	—	0.955	—	1.0	—
Variables at 2nd turn					
Early Acc	—	0.851	0.856	4.0	4.0
Late Acc	—	0.611	0.531	10.7	11.8
Early Dec	—	0.493	0.189	22.4	24.9
Late Dec	—	0.758	0.792	6.5	6.2
Re-Acc	—	0.718	0.770	6.1	7.5
Dec	PFC-FFC	0.773	0.840	12.3	13.8
	FFC-Stop	0.701	0.734	10.7	11.4
	PFC-Stop	0.788	0.766	5.8	9.3
Contact time	FF	0.768	0.709	14.3	13.2
PF hip flexion angle	PFC	0.575	0.635	10.0	10.9
	FFC	0.831	0.797	7.9	6.7
	Stop	0.856	0.783	7.2	7.5
PF knee flexion angle	PFC	0.485	0.482	21.3	20.1
	FFC	0.744	0.750	8.5	5.2
	Stop	0.826	0.647	6.5	5.4
FF hip flexion angle	FFC	0.814	0.789	13.3	13.3
	Stop	0.831	0.778	19.7	20.0
FF knee flexion angle	FFC	0.506	0.554	16.4	14.1
	Stop	0.650	0.333	12.0	12.1
COM height	PFC	0.830	0.920	3.1	3.6
	FFC	0.910	0.928	3.4	2.9
	Stop	0.880	0.861	4.0	3.9
COM—FF horizontal distance	FFC	0.770	0.845	3.3	2.4
	Stop	0.710	0.707	6.8	6.1
Trunk inclination angle	PFC	0.771	0.790	11.6	12.2
	FFC	0.835	0.859	9.4	8.6
	Stop	0.840	0.788	9.9	11.0

CV, coefficient of variation; CODTT, total time required to complete a COD task; Acc, mean acceleration of center of mass during the acceleration phase; Dec, mean deceleration of center of mass during the deceleration phase; COM, center of mass; PF, penultimate foot; FF, final foot; PFC, penultimate foot contact; FFC, final foot contact.

A large, significant interaction for Dec in PFC-Stop was observed ($p = 0.023$, Partial $\eta^2 = 0.178$) without a significant increase in either group (Table 5). A medium, significant interaction for Dec in FFC-Stop was observed ($p = 0.048$, Partial $\eta^2 = 0.137$), with CODG showing a significant, moderate increase ($p = 0.012$, $g = 0.639$) (Table 5). A large, significant interaction for FF contact time was observed ($p = 0.036$, Partial $\eta^2 = 0.152$), with CODG showing significant moderate reduction ($p < 0.001$, $g = 0.803$) (Table 5).

A large, significant interaction for the PF hip flexion angle at Stop was observed ($p = 0.021$, Partial $\eta^2 = 0.183$) with CODG showing significant small increase ($p = 0.042$, $g = 0.496$) (Table 5). A medium, significant interaction for COM height at FFC was observed ($p = 0.041$, Partial $\eta^2 = 0.145$) without significant improvement in either group (Table 5). A large, significant interaction for COM-FF horizontal distance at Stop was observed ($p = 0.006$, Partial $\eta^2 = 0.248$), with CODG showing a significant, moderate increase ($p = 0.008$, $g = 0.650$) (Table 5). No significant interactions or pre-to-post changes were observed for the other kinematic variables (Table 5).

4 Discussion

This study aimed to investigate the acute effect of a 15-min COD technique modification training with verbal instruction on COD performance and kinematics in adolescent male soccer players. The primary findings were that, although no acute enhancement of CODTT and CODD was observed, the intervention partially but immediately improved kinematics, including a shorter FF contact time, greater Dec in FFC-Stop, a greater PF hip flexion angle at Stop, and a longer COM-FF horizontal distance at Stop. These acute kinematic improvements may be the first step toward long-term adaptation in COD performance and injury risk reduction in adolescent athletes.

CODTT, CODD, and 20-m sprint time did not change after the 15-min intervention in either group. This suggests that fatigue did not influence the results. A previous study reported that a 6-week COD technique modification training program consisting of 12 sessions improved CODTT in the 505 Test (18). While no studies examined the acute effect of training aimed at improving COD performance, another study on adult sprinters reported an acute effect of a 10-min mini-hurdle drill, which increased step frequency while maintaining step length, resulting in improved linear sprint time (30). Nevertheless, no significant improvements in CODTT or CODD were observed in this study. COD maneuvers comprising multiple elements—initial acceleration, deceleration, turning, and reacceleration (3)—require complex motor control at high speed, and adolescent players tend to exhibit immature COD maneuvers (23). Indeed, considerable variability was observed in joint kinematics at the FF during the pre-test (CV > 15%), suggesting that participants may have had immature COD techniques. Improving such complex maneuvers requires repeated closed drills with conscious effort (25). While the training session in this study emphasized decelerating with the PF, lowering the COM, and pushing the body at the FF, a single 15-min training session may not be sufficient to optimize these techniques. Additionally, it should be noted that similar to previous studies, this training incorporated not only 180° COD but also COD at various angles required in soccer (31) for long-term progression (17–19). Therefore, by repeatedly performing such training, gradual changes in kinematics can be expected, which may lead to long-term enhancement in performance.

Conversely, the average deceleration significantly increased only during the FFC to Stop. This is interesting because no direct instructions were provided for deceleration in the FF. Indeed, some kinematic variables during the FFC changed after the intervention, one of which was the reduction in FF contact time. A previous study indicated a significant correlation between an increased PF hip flexion angle and reduced FF contact time (16). The reduction in FF contact time indicates a shorter turning phase and represents one of the key components of COD performance (18, 32).

TABLE 4 ANOVA and *post-hoc* results for COD performance and average acceleration and deceleration in each acceleration and deceleration phase.

Variables	Group	Pre	Post	Interaction		*Post-hoc*	
		Mean ± SD	Mean ± SD	*p*	Partial η^2	*p*	Hedges' *g*
CODTT (s)	COD	5.32 ± 0.36	5.32 ± 0.33	0.077	0.112	—	—
	CON	5.18 ± 0.15	5.24 ± 0.19			—	—
20-m Sprint (s)	COD	3.42 ± 0.32	3.42 ± 0.23	0.956	0.000	—	—
	CON	5.18 ± 0.15	5.24 ± 0.19			—	—
CODD (s)	COD	1.90 ± 0.14	1.89 ± 0.18	0.137	0.080	—	—
	CON	1.83 ± 0.14	1.89 ± 0.12			—	—
Early Acc (m/s^2)	COD	5.00 ± 0.63	4.91 ± 0.56	0.990	0.000	—	—
	CON	5.10 ± 0.42	5.01 ± 0.38			—	—
Late Dec (m/s^2)	COD	9.49 ± 1.14	9.33 ± 0.80	0.556	0.013	—	—
	CON	9.60 ± 1.17	9.25 ± 1.42			—	—
Re-Acc (m/s^2)	COD	6.47 ± 0.75	6.33 ± 0.87	0.914	0.000	—	—
	CON	6.51 ± 0.40	6.32 ± 0.86			—	—

CODTT, total time required to complete a COD task; CODD, change of direction deficit; Acc, average acceleration of center of mass during the acceleration phase; Dec, average deceleration of center of mass during the deceleration phase.

TABLE 5 ANOVA and *post-hoc* results for kinematic variables at 2nd turn.

Variables	Event	Group	Pre	Post	Interaction		*Post-hoc*	
			Mean ± SD	Mean ± SD	*p*	Partial η^2	*p*	Hedges' *g*
Dec (m/s^2)	PFC-FFC	COD	7.54 ± 1.35	7.33 ± 1.36	0.432	0.023	—	—
		CON	8.91 ± 2.51	8.16 ± 2.63			—	—
	FFC-Stop	COD	14.7 ± 2.36	16.3 ± 2.64	0.048*	0.137	0.012*	0.623
		CON	14.3 ± 2.57	14.0 ± 2.22			0.707	—0.121
	PFC-Stop	COD	10.7 ± 1.06	11.2 ± 1.16	0.023*	0.178	0.097	0.439
		CON	11.3 ± 1.92	10.8 ± 2.38			0.100	—0.224
Contact time (s)	FF	COD	0.32 ± 0.07	0.27 ± 0.06	0.036*	0.152	0.000**	—0.748
		CON	0.30 ± 0.08	0.29 ± 0.06			0.638	—0.137
PF hip flexion angle (°)	FFC	COD	83.2 ± 13.7	87.7 ± 10.8	0.099	0.098	—	—
		CON	86.0 ± 10.8	84.1 ± 11.0			—	—
	Stop	COD	83.7 ± 16.1	90.5 ± 9.89	0.021*	0.183	0.042*	0.496
		CON	90.4 ± 13.0	85.5 ± 15.0			0.178	—0.338
PF knee flexion angle (°)	FFC	COD	106.2 ± 16.1	106.9 ± 9.39	0.749	0.004	—	—
		CON	106.1 ± 13.4	105.4 ± 11.6			—	—
FF hip flexion angle (°)	FFC	COD	39.6 ± 10.0	39.3 ± 7.04	0.779	0.003	—	—
		CON	37.0 ± 8.54	36.0 ± 9.84			—	—
COM height (m/leg length)	PFC	COD	0.92 ± 0.05	0.92 ± 0.05	0.279	0.043	—	—
		CON	0.93 ± 0.09	0.94 ± 0.09			—	—
	FFC	COD	0.81 ± 0.05	0.79 ± 0.04	0.041*	0.145	0.307	—0.431
		CON	0.81 ± 0.09	0.83 ± 0.09			0.062	0.215
	Stop	COD	0.80 ± 0.05	0.79 ± 0.05	0.112	0.091	—	—
		CON	0.79 ± 0.10	0.81 ± 0.09			—	—
COM—FF horizontal distance (m)	FFC	COD	0.67 ± 0.05	0.68 ± 0.05	0.187	0.064	—	—
		CON	0.68 ± 0.03	0.67 ± 0.03			—	—
	Stop	COD	0.56 ± 0.06	0.60 ± 0.06	0.006**	0.248	0.008**	0.650
		CON	0.61 ± 0.06	0.59 ± 0.04			0.237	—0.380
Trunk inclination angle (°)	PFC	COD	36.4 ± 7.05	39.9 ± 8.07	0.256	0.047	—	—
		CON	35.3 ± 9.01	35.7 ± 4.60			—	—
	FFC	COD	48.2 ± 9.29	50.2 ± 10.5	0.297	0.040	—	—
		CON	47.9 ± 10.4	46.9 ± 6.82			—	—
	Stop	COD	56.8 ± 9.94	56.0 ± 9.46	0.434	0.023	—	—
		CON	57.1 ± 12.8	54.3 ± 12.8			—	—

COM, center of mass; PF, penultimate foot; FF, final foot; PFC, penultimate foot contact; FFC, final foot contact.
$^{**}p < 0.01$; $^{*}p < 0.05$.

Furthermore, the CODG maintained its COM further from the FF after the intervention. Extending the COM-FF horizontal distance is believed to enable a more horizontally applied ground reaction force, which is beneficial for COD performance (15, 16). Although the CODTT did not improve in this study, the training successfully achieved rapid deceleration and an acute reduction in turn duration. Therefore, these acute kinematic changes induced by the 15-min intervention may positively influence phase-specific performance.

These kinematic changes may also contribute to the prevention of severe knee injuries, which are more commonly associated with COD maneuvers than with other movements (33). High-intensity deceleration, a key component of COD, can cause tissue damage and increase the risk of injury (34), highlighting the importance of improving braking mechanics. In this study, a significant increase in the PF hip flexion angle was observed, which may enhance stability and support braking force production during PFC (3, 4), potentially reducing FF knee abduction moment indirectly without compromising performance. Although previous studies have reported that greater trunk inclination toward the intended direction during the FFC is associated with smaller knee abduction moments (35, 36), the absence of significant changes in the trunk inclination angle after the intervention leaves this relationship unclear. Nevertheless, a scoping review by Dos'Santos et al. (2019) indicates that long-term COD technique modification training is an effective strategy for reducing knee joint loading (37). Consequently, incorporating this training continuously (e.g., into warm-up routines) over an extended period may benefit subsequent athletic performance and lead to definitive improvements in injury prevention.

While the improvement in deceleration during FFC and the longer COM-FF horizontal distance at Stop were observed, no significant changes were found in subsequent acceleration phases (Re-Acc and Early Acc). Although many drills in the training program emphasized pushing the body in the next direction at the FF, this did not translate into expected outcomes. A previous study indicated that a more horizontally oriented propulsive force vector in the FF is related to enhanced exit velocity after turning (18), and one strategy to achieve this is to incline the trunk toward the next direction (4, 38). Despite emphasizing trunk inclination toward the next direction, no significant improvement was observed in the trunk inclination angle at Stop. Achieving meaningful improvements in this kinematic variable may demand an extended focus, highlighting the importance of integrating such targeted exercises into a broader training regimen.

Similarly, despite emphasizing deceleration in the PF during training, no improvement was observed in deceleration or kinematic variables from PFC to FFC. During the entire phase from FFC to Stop, the PF remained in contact with the ground, and hip joint of the PF remained flexed. This suggests that the instruction "Decelerate at the penultimate foot and drop COM" was reflected not during the PF single-limb support phase but rather in the double support phase of the FF and PF. Furthermore, to achieve greater deceleration, it is crucial to incline the trunk toward the next direction and lower the COM at PFC (3, 4), but no changes were observed in these kinematic variables. Considering the findings of Dos'Santos et al. (2021), who reported no changes in trunk angle during deceleration even after twelve sessions of technique modification training (18), implementing drills specifically focusing on trunk posture might be more effective.

This study had a few limitations. First, because the measurements and interventions were conducted in a practical setting, the kinetics of the Pro-Agility test were not measured. A previous study reported significant improvements in braking and propulsive force vectors after a 6-week COD modification training (18). Therefore, further research should investigate acute effects on the kinetics of Pro-Agility tests. Second, the 15-min training duration may have resulted in fewer repetitions, making the progression more challenging. Further research should consider extending the duration of training interventions to increase repetitions and progress the drill, and investigate the differences in acute effects. Finally, the participants were male adolescent soccer players, and it can be inferred that they included players at various stages of maturity. However, since the participants were not categorized by maturity, the investigation of acute effects is limited to overall male junior high school players. The training effects may vary depending on maturation (39); however, the present study did not compare effects based on maturity. Moreover, it remains unclear whether these findings in the present study can be generalized to athletes of different ages and sexes. Therefore, further research is needed to investigate the differences in the acute effects of COD modification training according to maturity levels, ages, and sexes.

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 Review Committee on Research with Human Subjects of Waseda University (approved No. 2022-308). 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

HN: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing, Project administration, Software, Validation, Visualization. DY: Conceptualization, Data curation, Investigation, Methodology, Resources, Software, Writing – original draft, Writing – review & editing. DN: Investigation, Writing – review & editing. NN: Investigation, Writing – review & editing. NH: Conceptualization, Project administration, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

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

Publisher's note

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Passing-skill training vs. small-sided games for improvement of side-foot kick accuracy among youth female soccer players

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This study compared the effectiveness of a passing-skill training (PST) concept (theory lectures, passing-skill training, and external- and internal-focus feedback) and three-a-side small-sided games (SSG) on improving side-foot kick accuracy among youth female soccer players. Seventeen youth female soccer players (age: 12.7 ± 0.8 years) completed the pre-post-intervention study, where the pre- and post-tests included three 10-m passing accuracy tests with increasing level of complexity: (1) stationary ball with a fixed target (SBFT), (2) rolling ball with a fixed target (RBFT), and (3) rolling ball with a moving target (RBMT). Based on the pre-tests, the participants were matched into the PST group or the SSG group. The training consisted of nine 30-min sessions for both groups during a period of 4.5 weeks. During the intervention, the PST group significantly improved the side-foot kick accuracy across all three tests. In contrast, the SSG group showed no significant change in passing accuracy in either the RBFT test or the RBMT test; however, their side-foot kick accuracy was significantly reduced in the SBFT test. There were significant between-group differences in side-foot kick accuracy across all three tests after the intervention, where the PST group had a greater side-foot kick accuracy than the SSG group. In conclusion, results indicate that the PST concept significantly enhances passing accuracy across all tested variables, unlike SSG, suggesting PST's superiority in technical skill development.

KEYWORDS

football, performance, test, skill acquisition, adolescents

Introduction

Short on-the-ground passes has previously been found to be the most frequently used passing activity in elite soccer (1–3). Execution of accurate side-foot kicks is essential for retaining possession of the ball by the team (4), and analyses of games of the group stages of FIFA World Cup 2014 showed that match statistics variables related to passing, such as ball possession, number of short passes, and average pass streak, had a positive effect on the probability of winning (5). In line with these findings, the ability to execute an accurate pass has been accentuated in elite soccer, where the percentage of successful passes increased between seasons 2006–07 and 2012–13 in the English Premier League (6), and the percentage of successful passes was significantly higher in Premier League than the leagues closest under (i.e., Championship and League 1) (7). Another approach to establish the passing effectiveness is to investigate the variables "space control" (i.e., teammate's distance to the closest defender when he/she receives the pass) and "number of outplayed players" (i.e., decrease of the number of defenders between the teammate that receives the pass and the goal) during matches; it was found that teams scoring more goals on average also outplayed more players and were more successful in increasing space control in the attacking third through passing (8). To achieve these advantages of greater space control and number of outplayed players by effective passing, it is necessary to have a great passing accuracy within the team. The importance of having a high passing effectiveness within a team was emphasised in a previous study, where the team was approximately 24% more likely to win games if their mean percentage of successful passes was improved by 1% (9). Therefore, it is of paramount importance to improve the soccer players' side-foot kick accuracy to improve the performance capacity of the team.

The ability to execute accurate side-foot kick passes has been found to differentiate both male (10) and female (11) soccer players with regard to competitive standard. Competitive-standard differences in passing accuracy has also been found within different age groups of youth male soccer players (12). Recently, it was reported that passing skills in soccer develop with age between the age of 10 and 14 years; however, the passing skills differed between genders in all age groups, where boys had a superior skill compared to girls (13). Advanced biological maturity status has been shown to be associated with slightly better performance in some technical-skill tests (e.g., ball control with the body and head, and dribbling with a pass), but maturity was not a predictor of passing accuracy (14). Previously, it was reported that U-13 players slightly later in maturation but with better soccer skills had a higher prevalence of being an active soccer player 10 years later than their more matured and less skilled counterparts (15). Moreover, they also showed that the U-15 players' soccer skills (i.e., ball control and passing accuracy) at baseline were indicators of later playing status (regional vs. national level) (15). The importance of being technical skilled as a youth soccer player is also emphasize by the results in a study where the variables net hope, motor abilities, technical skills and biological maturity were analysed once a year for three years from the age of twelve; the researchers found that players with a technical skill classified as "high", and scoring above average for the other three variables, were more likely to reach the highest level of performance (16). Technical skill in youth soccer players has also been highlighted as one potential predictor of adult high performance (17). Based on the results presented above, it appears that soccer players should acquire fundamental technical skills at a relatively high level at an early stage. A key basic skill for youth soccer players to master independent of level of expertise (elite or novice) is short passes (≤11 m) (18), and to develop this technical skill it is necessary to focus on passing-skill training.

An advantage in this sense is the great trainability of young soccer players' motor performance and technical skills. A study including 600 elite young soccer players found that the greatest improvements of motor performance were observed in the age group 11–13 years old (19). In line with this finding, coordinative abilities can be trained particularly well in the period before puberty (20). At this age period, which is considered as the "golden age for motor development", training should be oriented towards the technical aspects (21). The number of hours spent in individual practice as 11 years of age was a predictor of the competitive level they reached in their careers (22). When it concerns improvement of the passing skill, a 22-week training intervention focused on improving motor abilities and specific skills in 12 years old male soccer players found that execution time in a passing test decreased significantly in the intervention group (23); the differentiated training intervention they used were a combination of technical drills (e.g., passing, receiving and dribbling), small-sided games (SSG), game situations, and free play. Because of the large variation of the training program, it is difficult to point out which exercise(s) that gave the largest contribution to positive effect on the passing-skill acquisition.

In a recently published review, it was concluded that training using SSG has a positive effect on soccer players' short-passing abilities (24). Previously, training using 14 sessions focused on modified SSG significantly improved execution of passes during match play in youth male soccer players aged 10–12 years (25, 26). A key factor to improve the passing skill in youth soccer is the number of ball contacts and passes, and by using SSG with 3 or 4 players in each team a significantly increased number ball contacts and passes was registered compared to SSG teams with 6 or 8 players (27, 28). It appears that SSG, with few players, is a training context that potentially could improve passing skills in youth female soccer players. In contrast to training using SSG, where the players are being challenged to acquire movement solutions in side-foot kick passing technique appropriate for match conditions, soccer training using decontextualized exercises aims to improve important aspects of performance using structured and repetitive tasks starting with low-complexity exercises and thereafter transit to more complex and challenging contexts. Previously, we designed a passing-skill training (PST) concept consisting of five side-foot kick exercises and a theory lecture focusing on key factors for a side-foot kick with high accuracy; the elite female soccer players that were assigned to the intervention group improved their side-foot kick accuracy, whereas the control group did not show any improvements (29).

Despite the known benefits of SSG in skill development, limited research has been done on their comparative effectiveness against structured passing-skill training (PST) in youth female soccer players. This study aims to fill this void by evaluating the specific impact of these training modalities on passing accuracy. Therefore, the purpose of the study was to compare the effectiveness of a PST concept and three-a-side SSG on improving side-foot kick accuracy among youth female soccer players.

Materials and methods

Participants

Twenty youth female soccer players volunteered to participate in the study and the participants' legal guardian(s) gave their written informed consent to the players' participation in the study. Seventeen of the participants [age: 12.7 ± 0.8 years (mean ± standard deviation); body mass: 52.2 ± 7.9 kg; stature: 162 ± 5 cm; experience in soccer: 6.6 ± 1.6 years] completed the study. All participants belonged to the same team, which was ranked among the top 10 in Sweden within their age group. The team maintained a year-round training schedule, practicing three times per week. The test procedures were performed in accordance with the World Medical Association's Declaration of Helsinki—Ethical Principles for Medical Research Involving Human Subjects 2008, and the study was approved by the Regional Ethical Review Board, Uppsala, Sweden.

Study design

To investigate the effects of the two training regimes, a pre-post-intervention study was implemented. Before the start of the training intervention, three side-foot kick tests were performed (pre-tests). Based on the results of the pre-tests, the participants were matched into two groups. The results in each test gave the participant a ranking from 1 to 20. The ranking points from the three tests were added and the sum was used for the subsequent matching procedure. The top ranked participant was assigned to group A. The participants ranked second and third were assigned to group B. The participants with ranking number 4, 6, 7, 9, 12, 14, 15, 17, and 20 were assigned to group A and consequently, participants ranked 5, 8, 10, 11, 13, 16, 18, and 19 were assigned to group B. Hence, both groups ranking sum is 105. Thereafter, the groups were randomly assigned to follow either the PST concept or training using three-a-side SSG in addition to their regular training. During the 4.5-week conditioning period, both groups performed nine 30-min training sessions as a part of the 75-min regular training that was organized twice a week. The remainder of the training had the focus to develop the functional technique, where decision-making was an important role in both attacking and defensive play. However, the regular training sessions during the intervention did not contain training using SSG. After the training intervention, the participants performed the three side-foot kick tests (post-tests) once more. A total of 17 participants (9 in the PST group and 8 in the SSG group) fulfilled the training requirements of at least 8 out of 9 training sessions and carried out the post-tests. The test results are based on the participants who completed the study.

Testing procedures

The pre- and post-tests included three 10-m side-foot kick passing-accuracy tests with increasing level of complexity: (1) stationary ball with a fixed target (SBFT), (2) rolling ball with a fixed target (RBFT), and (3) rolling ball with a moving target (RBMT).The tests were performed at an indoor soccer field with artificial grass turf (XM 40, Fieldturf Tarkett, Nanterre, France). The same set of 15 pressured controlled balls (0.9 atm) of size 5 (Beau Jeu, Adidas AG, Herzogenaurach, Germany) was used. Each side-foot kick was preceded by a 3 s countdown (Stopwatch, Fitlb, San Jose, CA, USA) with one beep every second. The first beep was regarded as the start of the test and the last beep, with a higher tone, was regarded as the intended time of the kick. The computer program was set to have 10 s between kicks in each series. All three tests consisted of 20 side-foot kicks (4 series with 5 kicks/series) and the rest period between series was 40 s. All tests were recorded using video cameras (HC-V750, Panasonic, Osaka, Japan), that were positioned 3.5 m above the turf, to allow subsequent analyses of the side-foot kick passes' accuracy and speed (Dartfish TeamPro version 8, Dartfish HQ, Fribourg, Switzerland).

SBFT test

In the first test, the participant's ability to accurately pass a stationary ball towards a fixed target (i.e., a 1.7 m high target stick with a diameter of 35 mm) was tested (Figure 1A). The run-up started 5 m from the pre-determined ball-strike position, with a fixed run-up angle of 40°. The participant was instructed to perform the side-foot kick within 3 s from the beep that started the countdown. The aim of each side-foot kick was to hit the target stick positioned 10 m from the position of the ball strike. To be considered as an acceptable kick, the ball had to roll on the artificial grass turf the whole 10-m distance. The first series was started with the right foot as striking foot; thereafter, the participant alternated between feet in each series. Hence, in the second series started with the participant performing the side-foot kick with the left foot. The accuracy was defined as the distance between the centre of target stick and the centre of the ball when it passed the target line (i.e., the line perpendicular to the fictive line between the ball's position at the kick and the target stick). Ball speed was calculated based on the ball's registered time between a marked line 2 m in front of the target line and the target line.

RBFT test

In the second test, the participant's ability to accurately pass a rolling ball (i.e., a ball on the move) towards a fixed target was tested (Figure 1B). The run-up with the ball started 5 m from the pre-determined ball strike position. The participant was instructed to move the ball in a straight path, from the start position to the ball-strike position, and execute the side-foot kick within 3 s from the beep that started the countdown. The rest of the execution and analyses of the RBFT test followed the same procedure as in the SBFT test.

RBMT test

In the third test, the participant's ability to accurately pass a rolling ball (i.e., a ball on the move) towards a moving target was tested (Figure 1C). The start position for the run-up was aligned with the start of the strip of light emitting diodes (LED) and positioned 8.7 m perpendicular to the straight 20-m LED-strip. The run-up with the ball started 3 m from the pre-determined ball-strike position during which the participant was instructed to move the ball in a straight path. The shorter run-up distance, compared to the RBFT test, was set to allow the participant to

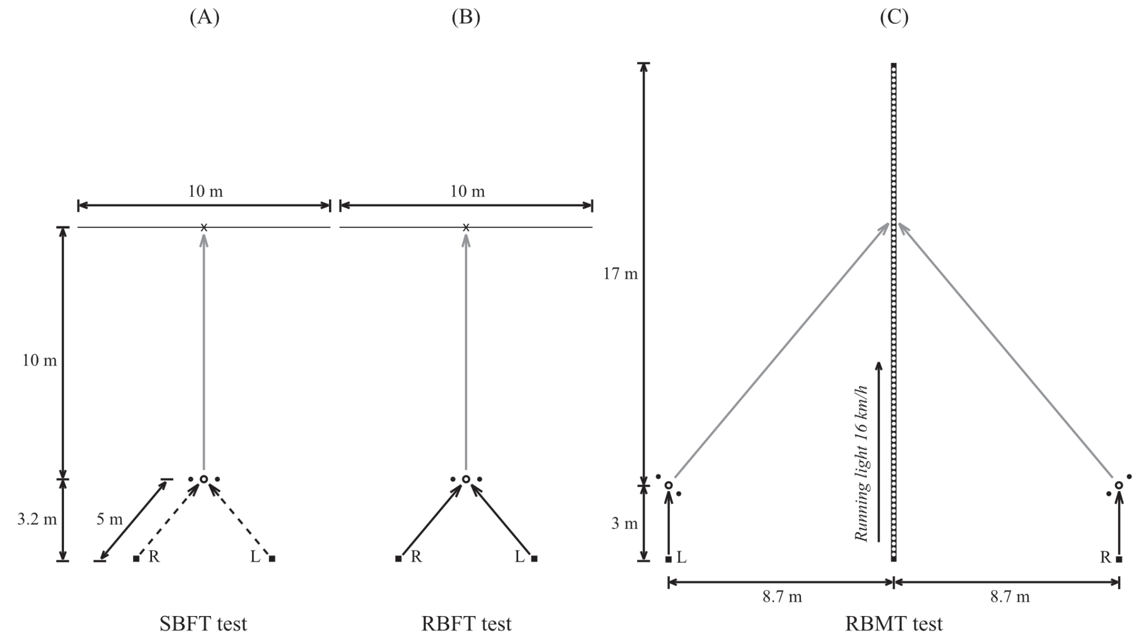

FIGURE 1
The arrangement of the three side-foot kick tests: **(A)** stationary ball with a fixed target (SBFT), **(B)** rolling ball with a fixed target (RBFT), and **(C)** rolling ball with a moving target (RBMT). Black dashed arrow represents the participant running without the ball; grey arrow represents the intended trajectory of the ball; black arrow represents the participant running with the ball; the cross sign represents the fixed target (i.e., the target stick with the diameter 35 mm and the length 1.7 m); R, start position when the side-foot kick was executed with the right foot; L, start position when the side-foot kick was executed with the left foot; and black rectangle with white dots represents the LED-strip.

identify the moving target of a 0.2-m section (i.e., emulating the length of a teammates foot) of the lit LED-strip. The "running-light section" was started on the second countdown beep and its constant speed was set to 4.44 m/s (i.e., 16.0 km/h) simulating a running teammate. The starting time of the moving target were chosen with the intention that the passes are executed with approximately the same angle between run-up direction and ball trajectory as well as a passing length of approximately 10 m as in the preceding two tests. The participant was instructed to execute the side-foot kick within 3 s from the beep that started the countdown with the aim to hit the centre of lit-up section when the ball passed the LED-strip. In contrast to the other two tests, the first series of five side-foot kicks was performed using the left foot and thereafter the participant alternate striking foot between series. The accuracy was defined as the distance between the centre of the 0.2-m lit-up section and the centre of the ball when it crossed the LED-strip, and this position was also used to calculate the passing length (i.e., the distance from position of the ball strike to the position where the ball crossed the LED-strip). Mean ball speed was calculated as the quotient between passing length and the ball's registered time between ball strike and the LED-strip passage.

PST concept

Before the start of the first training session included in the intervention, the participants in the PST group underwent a 30-min theory lecture focusing on key factors (e.g., position and direction of the support foot, the path of the kicking foot before the ball strike, foot angle at the ball strike, and point of the ball that should be hit) for a side-foot kick with high accuracy. During the lecture, they were also educated about potential faults that could influence the accuracy of the pass negatively. A repetition of the basics of the theory lecture was held before the fifth training session. Based on the content in the theory lectures, the participants were encouraged to reflect on misdirected passes under the training and what caused the poor accuracy. All participants in the PST group were given a printed version of the pictures included in the theory lecture as support in the reflection process. The participants brought the compendium to all training sessions.

The intervention consisted of nine 30-min training sessions, that was scheduled before the start of the regular training. For each training, the participants executed five training exercises (5 min/exercise and 1 min rest between exercises) (Figures 2A–E), which were supervised by the same two coaches that gave internal-focus feedback on the execution of the side-foot kicks based on the content in the compendium. In all exercises, the participants were instructed to alternate between striking feet.

In the first exercise, all participants in the PST group were included simultaneously. The exercise consisted of four sections, where the ball is passed on the move by the participant to a teammate that receives the ball (Figure 2A). In section S1 and S3, the participant used a side-foot kick to pass the ball between two disc cones. In section S2 and S4, the participant that

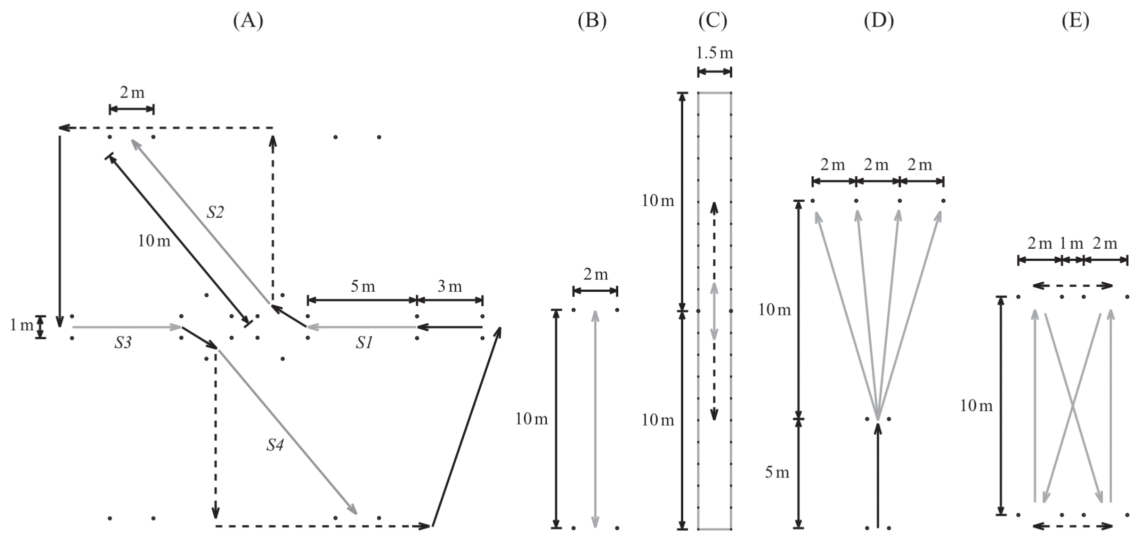

FIGURE 2
Graphical description of the five side-foot kick exercises **(A–E)** that were included in the passing-skill training (PST) concept. Black dashed arrow represents the participant running without the ball; grey arrow represents the trajectory of the ball; black arrow represents the participant running with the ball; and dots represent disc cones.

received the ball in the preceding section takes the ball with her and passes the ball between two disc cones to a teammate that is running on a straight line. At half time, the direction of the exercise was changed to alternate striking foot of the passes.

In the second exercise, two participants kicked the ball 10 m back and forth to one another, and they aimed to pass the ball between two disc cones that were 2 m apart (Figure 2B). Initially, the participants stopped the ball so that the side-foot kick was performed with a stationary ball. As the participants progressed, they used two-touch passing from training session five.

In the third exercise, two participants passed the ball between each other with one touch, trying to keep the ball within a 1.5-m wide corridor, where the lateral boundary lines were represented by ropes (Figure 2C). The participants started 2 m apart, and after each ten completed passes both participants backed 1 m (e.g., after 30 completed passes the participants were 8 m apart). If the ball crossed one of the ropes, the participants had to go back to the start position and make another try. Before training session five, the width of the corridor was reduced to 1.2 m.

In the fourth exercise, four 4-cm high disc cones were placed 2 m apart on a line 10 m from the position of the kick (Figure 2D). A ball was placed on each cone and the participant was instructed to hit the balls off the cones with as few side-foot kicks as possible. During the first four training sessions, the side-foot kicks were executed with a stationary ball. During the subsequent five training session, the distance from the start position to the ball-strike position was 5 m and the participant executed the side-foot kicks with the ball on the move.

In the fifth exercise, two pairs of disc cones with a 2-m gap between the cones in each pair were placed on two parallel lines 10-m apart (Figure 2E). There was a spacing of 1 m between the innermost cones in each pair. The two participants were positioned behind the cones on each side. One of the participants aimed to pass the ball straight between the two outer cones on each side. The receiver used two-touch side-foot kicks to pass the ball diagonally between the other participant's two outer cones on the opposite side. After the delivery of a pass, the participant moved sideways to receive the next pass. When one of the participants failed to pass the ball between the intended pair of cones, the participants switched tasks and the participant who kicked diagonally went to straight passing and vice versa. To increase the level of complexity, the players were instructed to use one-touch passing from training session five.

Three-a-side SSG

The SSG group completed nine 30-min training sessions, that was scheduled before the start of the regular training, consisting of five 5-min blocks of three-a-side SSG with 1 min rest between blocks. The pitch size was 16 m × 8 m and the width of the goals was 0.8 m. The participants were instructed by the coach to focus on accurate passing and controlled receiving of the ball during the SSG. The coach also encouraged the participants to "use movement", "support play", and "create space".

Statistical analyses

Test results are presented as the means and standard deviations. The agreement of test variables with a normal distribution was assessed with the Shapiro–Wilk test. Paired and independent *t*-tests were employed to analyse within-group and between-group differences, respectively, providing a robust framework for

TABLE 1 Results for side-foot kick tests before and after the 4.5-week training intervention.

Test	Variable	PST group		SSG group	
		Pre	Post	Pre	Post
SBFT	Δ	0.56 ± 0.14	0.43 ± 0.10**	0.52 ± 0.12	0.71 ± 0.17**
	v	8.4 ± 2.0	7.8 ± 1.2	7.9 ± 1.9	8.2 ± 1.5
RBFT	Δ	0.68 ± 0.24	0.48 ± 0.14*	0.66 ± 0.16	0.65 ± 0.14
	v	8.0 ± 1.7	7.9 ± 1.5	7.7 ± 1.5	7.9 ± 1.4
RBMT	Δ	0.97 ± 0.34	0.73 ± 0.27**	1.05 ± 0.34	1.20 ± 0.40
	v	9.6 ± 1.8	10.3 ± 2.0*	9.1 ± 1.1	9.9 ± 1.0*
	l	11.4 ± 0.8	11.2 ± 0.9	10.9 ± 1.2	11.7 ± 0.8

Values are expressed as mean ± standard deviation for the 10-m side-foot kick tests before (pre) and after (post) the 4.5-week training intervention. PST group, passing skill training group ($n = 9$); SSG group, small-sided game group ($n = 8$); SBFT, stationary ball with fixed target; RBFT, rolling ball with fixed target; RBMT, rolling ball with moving target; Δ, absolute deviation from the centre of the target (m); v, ball speed (m/s); l, passing length i.e., the distance from position of the ball strike to the position where the ball crossed the LED-strip (m). Paired-samples Student's *t*-test were used to investigate within-group differences between pre- and post-tests and the differences are reported as *for $P < 0.05$, **for $P < 0.01$.

detecting significant changes in passing accuracy. The effects size (η^2) was calculated for each analysis and was interpreted as: small effect for $0.01 \le \eta^2 < 0.06$, moderate effect for $0.06 \le \eta^2 < 0.14$, and large effect for $\eta^2 \ge 0.14$ (30). All statistical analyses were assumed to be significant at an alpha level of 0.05. The statistical analyses were conducted using IBM SPSS Statistics software, Version 29 (IBM Corporation, Armonk, USA).

Results

Within-group differences

Results for the three side-foot kick tests before and after the training intervention are presented in Table 1. The paired-samples *t*-tests revealed that the PST group improved the accuracy for all three side-foot kick tests, SBFT ($t = 4.59$, $P = 0.0018$, $\eta^2 = 0.72$), RBFT ($t = 2.38$, $P = 0.044$, $\eta^2 = 0.41$), and RBMT ($t = 3.55$, $P = 0.0075$, $\eta^2 = 0.61$), during the training intervention. No significant improvements in side-foot kick accuracy were found in the SSG group in the RBFT ($t = 0.45$, $P = 0.67$, $\eta^2 = 0.028$) and RBMT ($t = -1.22$, $P = 0.26$, $\eta^2 = 0.18$) tests; however, a significantly reduced accuracy was found for the SBFT test ($t = -4.29$, $P = 0.0036$, $\eta^2 = 0.72$) in the SSG group.

There was an increased ball speed in the RBMT for both groups (PST: $t = 2.57$, $P = 0.033$, $\eta^2 = 0.49$; SSG: $t = 3.21$, $P = 0.015$, $\eta^2 = 0.56$) during the training intervention. However, there was no ball-speed differences for either group in the SBFT (PST: $t = -0.96$, $P = 0.37$, $\eta^2 = 0.12$; SSG: $t = 0.92$, $P = 0.39$, $\eta^2 = 0.096$) or RBFT (PST: $t = -0.47$, $P = 0.65$, $\eta^2 = 0.031$; SSG: $t = 0.64$, $P = 0.55$, $\eta^2 = 0.049$) test.

Between-group differences

At the pre-tests, no between-group difference was found for side-foot kick accuracy for either SBFT ($t = -0.60$, $P = 0.56$, $\eta^2 = 0.023$), RBFT ($t = -0.14$, $P = 0.89$, $\eta^2 = 0.0013$), or RBMT ($t = 0.65$, $P = 0.46$, $\eta^2 = 0.027$) test. However, there were significant between-group differences for all three tests after the intervention, SBFT ($t = 4.33$, $P < 0.001$, $\eta^2 = 0.56$), RBFT ($t = 2.46$, $P = 0.027$, $\eta^2 = 0.29$), and RBMT ($t = 2.82$, $P = 0.015$, $\eta^2 = 0.35$), where the side-foot kick accuracy was consistently better for the PST group (Figure 3).

No between-group difference was found for ball speed for either SBFT (pre: $t = -0.51$, $P = 0.62$, $\eta^2 = 0.017$; post: $t = 0.57$, $P = 0.58$, $\eta^2 = 0.021$), RBFT (pre: $t = -0.46$, $P = 0.65$, $\eta^2 = 0.014$; post: $t = 0.057$, $P = 0.96$, $\eta^2 = 0.00022$), or RBMT (pre: $t = -0.69$, $P = 0.50$, $\eta^2 = 0.031$; post: $t = -0.55$, $P = 0.59$, $\eta^2 = 0.020$) test. In the RBMT test, there were no between-group differences in passing length, either at pre-test ($t = -1.08$, $P = 0.30$, $\eta^2 = 0.072$) or post-test ($t = 1.18$, $P = 0.25$, $\eta^2 = 0.085$).

Discussion

The purpose of the study was to compare the effectiveness of a PST concept and three-a-side SSG on improving side-foot kick accuracy among youth female soccer players. The results of the current study demonstrate that the participants in the PST group improved their side-foot kick accuracy significantly across all three passing tests, but no significant improvements in passing accuracy were found in the SSG group during the nine 30-min training sessions included in the 4.5-week training intervention.

Previously, we showed that short technique-intense training period focused on side-foot kick performance improved elite female soccer players' passing accuracy in the tests where the ball strike was performed on a moving ball (29); however, they did not improve the fundamental skill of passing a stationary ball towards a fixed target. In the current study, the participants in the PST group improved their side-foot kick performance in both tests where the task was to pass a stationary or moving ball towards a fixed target (Table 1). Worth noting is that after the intervention, the accuracy of the PST group in the SBFT test (0.43 ± 0.10 m) was in accordance with the accuracy reported for the elite female players (0.84 ± 0.19 m), because the distance from the ball-strike position to the target was twice as long for elite female players (20 m vs. 10 m). This observation was somewhat unexpected given that the elite female players were older and part of a Swedish first league team; however, the potential for improvement of the isolated skill of passing a stationary ball towards a fixed target is greater for youth female players as a

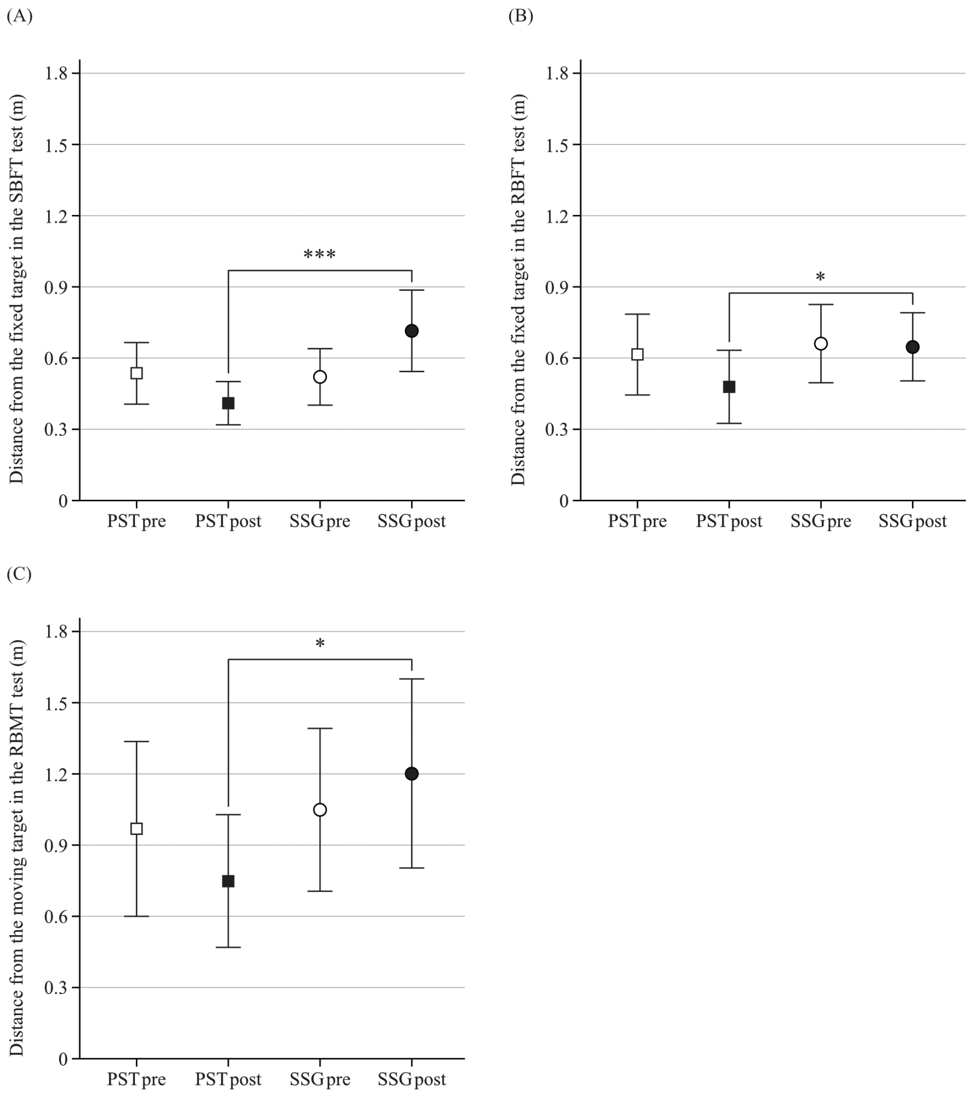

FIGURE 3
The accuracy of the three side-foot kick tests: **(A)** stationary ball with a fixed target (SBFT), **(B)** rolling ball with a fixed target (RBFT), and **(C)** rolling ball with a moving target (RBMT). The side-foot kick accuracy of each test is represented by the absolute distance between the target's centre and the ball's centre before (pre) and after (post) the 4.5-week training intervention, where filled/open squares and circles represent mean values of the passing-skill training (PST) group and small-sided games (SSG) group, respectively. Error bars represent ± 1 standard deviation. Significant between-group differences between training regimes are reported as: *P < 0.05, and ***P < 0.001.

result of their enhanced trainability of motor performance, coordinative abilities, and technical skills (19, 20).

The significant improvement of the accuracy of the PST group in both tests with higher complexity (i.e., where the participants passed a moving ball) is probably to some extent related to, the previously mentioned, enhanced trainability of the fundamental motor skills in youth soccer players. Development of basic fundamental motor skills serves as building blocks allowing for acquisition of more complex and difficult soccer-specific motor skills (31); therefore, it is suggested that youth soccer coaches should include training of fundamental motor skills before puberty with an emphasis on the quality of movement (31, 32). To develop motor skills, augmented feedback could be an important factor to improve an athlete's performance, and it should therefore be applied in sports training (33). In general, augmented feedback could be provided as external-focus feedback which is movement-effect related (also referred to as "knowledge of results") or as internal-focus feedback which instead is body-movement related (also referred to as "knowledge of performance"), and previously it was showed that experienced soccer players' execution of lofted passes showed a greater accuracy after the external-focus feedback condition compared to the condition where the internal-focus feedback was used (34). In line with this finding, it was reported that external-focus feedback was more effective in learning of soccer "head kick" among youth female soccer players (35). In the current study we used a combination of internal-focus and external-focus feedback; the coaches provided internal-focus feedback based on the participants' side-foot kick performance during the passing-skill training, whereas the participants in the PST group received direct external-focus feedback on their passing accuracy using the task constraints (i.e., cones and ropes) as reference. A recent review supports the use of a combination of prescriptive external-focus feedback (including information about what to do next to improve) and internal-focus feedback if the aim is to enhance motor-skill learning (36). Hence, the feedback given to the PST group could be one contributing factor to the significant improvement of the side-foot kick accuracy.

Training using SSG is a frequently used method with the aim to improve physiological abilities and technical skills in youth soccer (37). In the current study we used SSG with 3 vs. 3, and previously three-a-side SSG resulted in higher mean heart rate, greater involvement with play, more dribbling, and more short and medium passes than five-a-side SSG in youth male soccer players (38). An 8-week training intervention, consisting of SSG with 3 vs. 3, improved youth male soccer players' maximal aerobic power and overall soccer-specific technical skills (i.e., sum of juggling, dribbling, heading, passing, and shooting skills) (39). It has been reported that SSG simulate the overall movement pattern in elite women's soccer matches and the players are, therefore, challenged to practise their short-passing skills during SSG (40). Therefore, it can be expected that the SSG group would improve their general short-passing abilities. However, in contrast to the PST group, the SSG group did not improve the passing accuracy for any of the three tests (Table 1). In a recent review, it was stated that SSG has a positive impact on soccer players' short-passing abilities (24), but this statement was based on the results from only two studies which used the Loughborough Soccer Passing Test (LSPT) to analyse the short-passing ability (41, 42). Both these studies used the overall skill performance time (i.e., execution time + penalty time) to verify the SSG's positive impact on short-passing abilities. The "execution time" is the time to complete 16 passes against target areas attached on four benches that are placed different directions and perpendicular to the player that is tested. For the variable "penalty time", time is added for missing the bench, missing the target area, handling the ball, passing the ball from outside the designated area, ball touching a cone, and performing the test over 43 s. Only the two first two penalty components, together with a bonus time awarded if the player hit the middle 10-cm strip of the target area, reflect the side-foot kick accuracy. Consequently, none of the three variables that normally are reported for LSPT performance is fully appropriate to detect side-foot kick accuracy of soccer players. A previous study highlighted this limitation, where it was shown that execution time of the LSPT did not differentiate selected and de-selected male youth soccer players (10–18 years), but the talented players were generally more accurate in their passing and ball control (i.e., a reduced penalty time) compared to their less-skilled counterparts (43); the authors concluded that having superior passing accuracy is eventually a good predictor for future performance level.

Based on the enhanced trainability of motor skills in youth soccer players, it is concerning that the fundamental ability to execute accurate side-foot kicks on a stationary ball towards a fixed target in the SBFT test declined significantly in the SSG group and possibly due to the training using SSG. Short passes during SSG are generally executed on a moving ball, but this should not be a reasonable explanation to the demonstrated decline in passing accuracy. One potential explanation to this result is that the main focus in SSG is not the accuracy; instead, the aim is to keep the ball within the team and the teammates compensate for an inaccurate pass by adjusting their movement direction and/or speed. Moreover, the general passing length during three-a-side SSG using a small pitch is relatively short (27), therefore, a somewhat inaccurate pass will not negatively affect the teammate's chance to receive the ball. The visual feedback the player may receive from the situation is that the teammate successfully received the pass, and the pass's accuracy was sufficient. Conversely, the participants in the PST group receive instant external-focus feedback on the accuracy of every single side-foot kick through the task constraints (cones or boundary lines) that are a part of the setup in all five exercises (Figures 2A–E). As previously argued in the study with elite female soccer players, the external-focus feedback based on the outcome of each side-foot kick could be one of the key factors behind the improvements of the side-foot kick accuracy (29). Also, the self-reflection of the passing quality, based on the information in theory lectures and the compendium, may have contributed to the significant improvements in the PST group. Hence, passing-quality reflections are rarely a conscious part of daily training, because the teammates adapt to the ball's trajectory and speed, filtering out inaccurate passes.

The previously developed and to the current study refined training concept had a positive effect on the PST group's side-foot kick accuracy in the RBMT test, which is the most complex and match-like test where the LED-strip's "running light" simulates a running teammate. The importance of a player's ability to accurately pass the ball to a running teammate was previously shown in a study analysing passing actions; they found that the efficiency of the pass, the trajectory of the receiver, and where on the pitch the pass was received were the main performance indicators for success in completing the play by a shot (44). Training using SSG with few players in each team induces many ball contacts and short passes (27, 28), which should entail that the ability to perform accurate side-foot kick passes on a rolling ball to a teammate who is moving is challenged. However, the SSG group did not improve the side-foot kick accuracy in the RBMT test. On the contrary, the improvement of the accuracy in the PST group was somewhat unexpected since their main training focus were not to pass teammates on the move, and an interesting finding in this context is that the improved accuracy was accompanied with an increased ball speed (Table 1). This finding is in contrast to the previously reported speed/accuracy trade-off in soccer, which leads to a reduced ball speed when an accuracy demand is introduced (45, 46). Hence, the PST concept appears to have a positive influence on the ability to accurately pass the ball on the move to a moving target with a significantly increased ball speed, which definitely is an important factor for success in soccer as reflected by a continuous increase of passing ball speed in the World Cup during the period 1966–2010 (47).

Consistent with prior studies (23, 29), our findings suggest that targeted technical training like PST can offer more controlled and focused skill enhancement than SSG, aligning with literature emphasizing the importance of deliberate practice in skill acquisition (22). Hence, the results of the current study advocate for soccer coaches to integrate more PST sessions into their regular training schedules, especially when the aim is to enhance passing accuracy among youth female players.

The current study investigates the impact of a 4.5-week long training period on passing accuracy among youth soccer players and the relatively short duration of the intervention is a limitation. Therefore, it would be valuable to investigate whether a prolonged training period leads to further improvements in passing accuracy. To make the test with the LED-strip even more authentic to a match situation, where the player should time the direction and speed of the pass to an imagined running teammate, a possibility to vary the speed of the "running light" to simulate teammates with different movement speeds would be preferrable. The abilities to adapt the face angle of the kicking foot and the applied force to the ball are key factors for soccer players to master and these factors place high demands on the coordinative skills. Therefore, passing-skill training should be a natural part of the regular training among youth soccer players, that have great opportunities develop the side-foot kick accuracy as a consequence of the high trainability of their coordinative abilities (20). Because of the significant improvements the PST group displayed, it would have been of interest to try to quantify the impact of each of the key elements in the PST concept (i.e., theory lectures, passing-skill training, external-focus and internal-focus feedback during training). Further studies are also warranted to investigate the influence of sex, retention of the training effect, and dose-response relationship between training volume and improvement of side-foot kick accuracy. In this context, it would naturally have been of great interest to investigate the impact of the PST concept on match performance to analyse if, for example, the passing success rate improves with passing-skill training or not.

Conclusions

Results in the current study indicate that the PST concept significantly enhances passing accuracy across all tested variables, unlike SSG, suggesting PST's superiority in technical skill development. It appears that passing exercises with task constraints (i.e., cones and ropes) in addition to theory lectures focusing on key factors for a side-foot kick with high accuracy, gives players the foundation to do self-reflections on their passing accuracy and consider plausible causes to misdirected passes. Therefore, soccer coaches should integrate the PST concept into their regular training schedules, especially when the aim is to enhance passing accuracy among female players.

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 Regional Ethical Review Board, Uppsala, Sweden. 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

TC: Conceptualization, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. JB: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. JI: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. MC: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing.

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Does inter-limb asymmetry matter in adolescent speed skaters?

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Inter-limb asymmetry (IA) has been shown to impact athletic performance, but its relationship with speed skating performance is not yet clear. To investigate the effect of IA in lower limb strength on skating time in adolescent speed skaters, 17 male adolescent speed skaters (age: 16.65 ± 0.79 years, height: 176.63 ± 6.45 cm, weight: 63.08 ± 9.51 kg) underwent body composition, isokinetic knee strength, multi-direction (vertical, horizontal and lateral) single-leg squat jump and single-leg drop jump tests (from a 20 cm box) at the end of the season to assess the IA. The results showed that most lateral single-leg squat jump (LSJ) related variables such as relative lateral peak force (7.40 ± 0.67 N/kg vs 7.03 ± 0.61 N/kg, $P < 0.001$, ES = 1.32), relative lateral impulse (Imp-L) (2.67 ± 0.23 Ns/kg vs 2.45 ± 0.24 N/kg, $P = 0.043$, ES = 0.94) and take-off velocity (2.81 ± 0.20 m/s vs 2.59 ± 0.30 m/s, $P = 0.001$, ES = 0.83) showed a significant left-sided dominance, and increased corresponding asymmetry prolonged 100m and 500 m skating times. Furthermore, increased asymmetry in single-leg vertical drop jump (VDJ) height also prolonged 100 m skating time. For adolescent speed skaters, the LSJ and VDJ tasks exhibit good sensitivity to the lower limb strength asymmetry, and increases in corresponding asymmetries may have negative effects on speed skating performance.

KEYWORDS

inter-limb difference, limb dominance, squat jump, drop jump, isokinetic testing

1 Introduction

Inter-limb asymmetry (IA) refers to the differences in morphological structure and functional performance between contralateral limbs. It is commonly quantified as the percentage difference in performance between limbs during specific tasks, which serves to describe and assess the degree of asymmetry (Bishop et al., 2018). Early applications of such concept were focused on injury prevention and risk assessment (Bishop et al., 2016). Prolonged exposure of contralateral limbs to asymmetric loads and tasks can lead to the development of IA. Consequently, IA is a widespread phenomenon in sports, and its relationship with athletic performance has received considerable attention (Maloney, 2019).

Based on the bilateral coordination control strategies, movements in sports can be categorized as bilateral symmetric (in-phase or out-of-phase) and asymmetric movements (Maloney, 2019). Previous evidence suggests that excessive IA can impair performance in symmetric movements such as sprinting and bilateral vertical jumps (VJ). Despite the inherent bilateral asymmetrical loading due to the nature of movement patterns, long-term repetitive execution of asymmetrical tasks, such as table tennis strokes, can lead to a specific increase in IA, but without negatively impacting performance. Therefore, this is considered a benign structural and functional adaptation of the body to these types of movements (Bishop et al., 2018). Furthermore, for team sports such as football and ice hockey, the specialized technical actions exhibit a mixture of bilateral symmetric and asymmetric characteristics. Repeated exposure to asymmetrical tasks, such as change of direction can lead to an increase in IA in the lower limbs of athletes, potentially affecting performance in symmetric movements like sprinting (Maloney, 2019). Therefore, athletes participating in events with multiform technical actions are more susceptible to the negative effects of IA on performance, and previous studies have primarily focused on team sports with typical related characteristics (Loturco et al., 2019; Madruga-Parera et al., 2020; Bishop et al., 2021a; Nicholson et al., 2022; Espada et al., 2023; Twible et al., 2024).

Nevertheless, unlike team sports, where athletes perform asymmetrical tasks with randomness, speed skaters (specifically refer to the long-track speed skating in the present study) must lean their bodies to the left while executing asymmetrical lower limb movements in the turns (De Koning et al., 1991). This results in significantly higher power output and blood oxygen saturation in the left leg compared to the right leg during turns (De Koning et al., 1991; Hettinga et al., 2016). Therefore, asymmetrical loading is an inherent characteristic in speed skating, long-term training may lead to an increased lower limbs asymmetry of athletes, potentially affecting the symmetric push-off movements of both legs during straight-line skating. Speed skating training is predominantly conducted on land, with land training accounting for over 50% of the total training time. Consequently, land-based specific strength training methods can also replicate the technical characteristics of ice skating in some extent, and the associated testing methods also demonstrate high ecological benefits (Stuart and Cochrane-Snyman, 2022). The horizontal and lateral single-leg squat jump (SLSJ) has been shown to closely resemble the neuromuscular patterns of the skating push-off movements, and the peak take-off velocity is highly correlated with the results (Zukowski et al., 2023b). However, it has been shown that there are no significant differences in peak velocity between legs in the horizontal and lateral single-leg jump for speed skaters. Given that the outcome measure of take-off velocity in the study may have relatively poor sensitivity to the IA index (Virgile and Bishop, 2021), the results should be interpreted with caution. Alongside SJ, drop jump (DJ) are also widely incorporated into the strength training programs of speed skating, as the speed skating starting technique shares similarities with on-land starting techniques, where both require rapid stretch-shortening cycle (SSC) contractions of the lower limbs and demand a high level of reactive strength (Song et al., 2017). Despite the fact that DJ performance can evaluate or train the SSC capacity of the lower limbs, and it exhibits directionality, such as horizontal DJ performance being superior in predicting sprinting performance compared to vertical direction (Schuster and Jones, 2016). According to the author's limited knowledge, there is currently no study analyzing the impact of the DJ performance on speed skating performance, and the related IA characteristics remains unknown.

Long-term specialized training has been shown to induce specific changes in brain tissue, which can affect limb coordination strategies and neuromuscular function (Nakata et al., 2010). Therefore, it is necessary to clarify the relationship between IA and athletic performance during adolescence and implement timely interventions, as researchers have done across various sports (Pontaga and Zidens, 2014; Pardos-Mainer et al., 2020; Blagrove et al., 2021; Pamuk et al., 2023). Neuro-plasticity have been observed in speed skaters (Park et al., 2013), however, reports of lower limb strength performance asymmetry among adolescent speed skaters is scarce, and the relationship between it and results remains unclear.

Considering that IA is highly task-specific, there are differences in the same metric across different tasks and between different metrics within the same task. Therefore, IA assessment should be based on tasks that closely resemble the technical action and neuromuscular patterns of the sport-specific technique (Bishop et al., 2018). However, previous studies comparing the correlation between land tests and on-ice performance have primarily focused on adult athletes (Zhang and Xia, 2011; Zukowski et al., 2023b), it remains unclear how effective land tests are in predicting on-ice performance in adolescent athletes. Therefore, the objectives of this study include: (1) assessing the characteristics of bilateral lower limb strength performance in adolescent speed skaters; and (2) examining the impact of critical strength performance variables asymmetries that are significantly related to the results on skating time. We hypothesize that the left lower limb strength performance is superior to the right side, and increases in critical variables asymmetries are associated with prolonged skating time.

2 Materials and methods

2.1 Subjects

17 professional male adolescent speed skaters from the Heilongjiang Ice Training Center voluntarily participated in the study (age: 16.65 ± 0.79 years, height: 176.63 ± 6.45 cm, weight: 63.08 ± 9.51 kg), who participated in the National Junior Speed Skating Championships or National U17 Speed Skating League. All participants had maintained regular training over the past year and had at least 3 years of prior training experience, with no athletic injuries occurred in the past 6 months and were in good health during the testing period. This study adhered to the Declaration of Helsinki and was approved by the institutional ethics committee (code: 2024013). Informed consent was obtained from all participants and their guardians prior to the experiment.

2.2 Procedures

Testing was consisted of four sessions (Figure 1), and conducted during the speed skating competition season (February to March). Participants were instructed to abstain from alcohol and caffeine intake 3 hours prior to each test session. Each test session was separated by at least 48 h, and no high-intensity training was performed on the day before strength session. The first session included the body composition measurements. In addition, the participants were informed about the jump test protocol and performed at least five repetitions of various types of jumps to familiarize. During the second session, isokinetic knee strength was measured. In the third and fourth sessions, single-leg drop jumps (SLDJ) were performed, and SLSJ were measured in the vertical, horizontal, and lateral directions. In the fourth session (SLSJ), three participants withdrew due to personal reasons, resulting in a sample size of n = 14 for the fourth session. Prior to the isokinetic and jump testing, a standardized warm-up was conducted, which included a 5-min cycling bout at 60 W, followed by 3 min of dynamic stretching, and 3 min of familiarization with the testing procedures. To minimize the influence of circadian rhythms, all testing was conducted during the same time slot each day (8:00 a.m. to 11:00 a.m.) (Pradhan et al., 2024). The best performance from the most recent two public competitions for each athlete was selected for correlation analysis, with results reported to two decimal places. The skating time data were obtained from the official website of the Chinese Skating Association (https://www.chinacsa.net.cn). All competitions were held between January and March, a period during which athletes generally achieve their peak athletic levels (McCarthy, 2003), and the altitudes of the competition venues were similar (140–200 m).

2.2.1 Body composition measurements

The InBody770 bioelectrical impedance analyzer (InBody Co., Seoul, South Korea) was used to measure the body fat, and muscle mass of participants. This method has been shown to have high retest reliability and validity (r^2 = 0.96; CV = 0.15%; ICC = 0.96) and can serve as an effective alternative to dual-energy X-ray absorptiometry (DXA) for measuring body composition (McLester et al., 2020; Lee et al., 2021).

2.2.2 Isokinetic knee strength testing

The isokinetic knee strength testing was conducted using the Con-Trex MJ isokinetic dynamometer (Con-Trex AG, Dubendorf, Switzerland). The reliability of this instrument has been previously validated (Maffiuletti et al., 2007). The backrest of the seat was adjusted to 85°, participants crossed their arms over chests, and the trunk was secured to the backrest with straps. The rotational axis of the dynamometer was aligned with the lateral epicondyle of the tested knee, and the distal end of the rotational arm was attached approximately 2–3 cm above the ankle joint. The tested thigh was strapped with a magic tape for stabilization (Figure 2A). The range of motion for the knee was set to 0°–80°, and gravitational corrections were applied prior to testing. Prior to the formal testing, participants performed five sub-maximal knee flexion-extension movements for warm-up. The testing protocol was conducted at angular velocity of 60°/s and 180°/s, with the order of leg testing randomized. A total of four sets of tests were conducted, each set consisted of five repetitions of knee flexion-extension, with a 2-min rest period between sets. Verbal encouragement was provided to the participants throughout the testing.

2.2.3 Single-leg drop jump

Kinetic data during the take-off phase were collected using a Kistler 3-D force platform (Kistler Instrument AG, Winterthur, Switzerland) at a sampling frequency of 1,000 Hz. Three cameras (SONY HDR-FX1000E, Tokyo, Japan) were positioned 5 m in front of, to the left of, and to the right of the participant to capture the take-off action at a frame rate of 50 Hz for kinematic analysis. The principal axes of the left and right cameras were oriented perpendicular to the sagittal plane of participants, while the principal axis of the front camera was oriented perpendicular to the frontal plane of participants. A PEAK (3 m × 3 m × 3 m) radial calibration frame (composed of 24 points) was used to calibrate the 3-D motion space around the force platform (Figure 2D). Participants stood on a 20 cm high jump box (20 cm away from the force platform) with their hands placed on their hips (Holm et al., 2008). Upon the experimenter's command, participants stepped forward with the tested limb, landing naturally on the force platform and then performing a rapid jump in the vertical, forward, and lateral directions. Throughout the test, participants kept hands on the hips, and landed with both feet (with the feet touching down sequentially in the lateral direction) (Figure 2B). Prior to testing, participants were instructed to jump as high or as far as possible while minimizing the take-off time. Each direction of the SLDJ

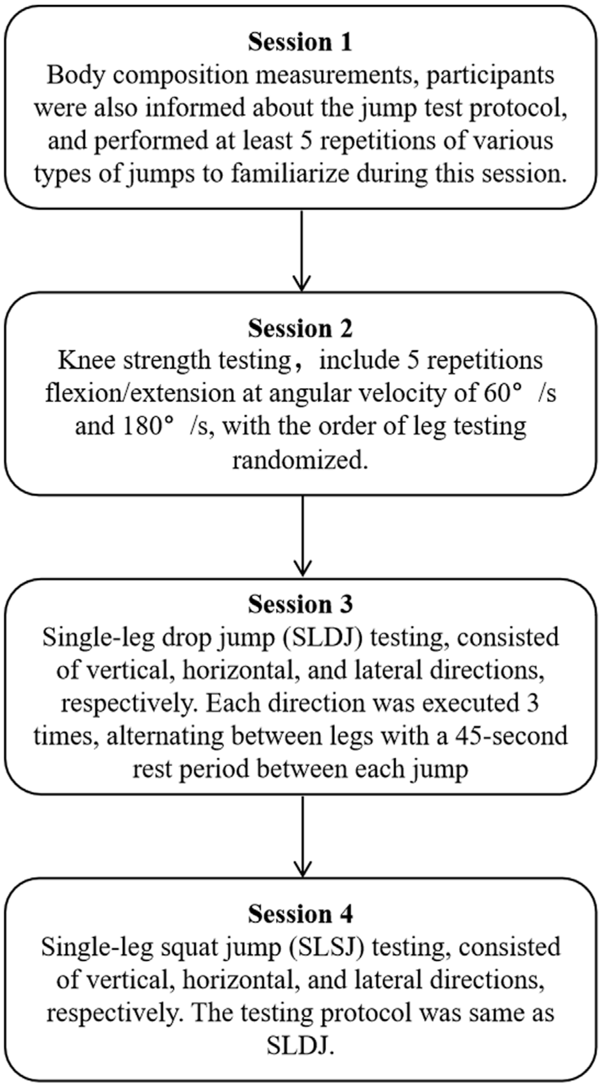

FIGURE 1
Testing procedures.

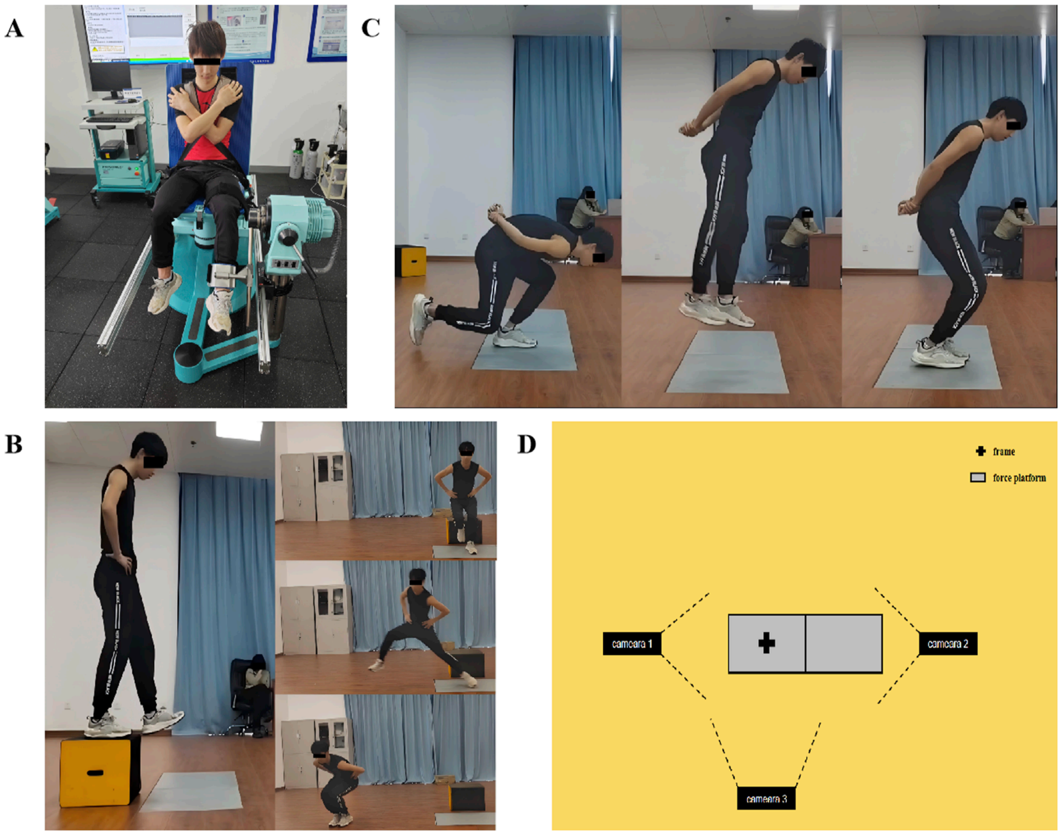

FIGURE 2
Diagrams of the Isokinetic knee strength testing **(A)**, Single-leg drop jump **(B)**, Single-leg squat jump **(C)**, Plan of the jump testing site **(D)**.

task was executed 3 times, alternating between legs with a 45-s rest period between each jump (Dobbs et al., 2015). After completing all jumps in the same direction (6 jumps in total), changed the direction with a 2-min rest period between directional changes. The order of directions was randomized. Participants were required to repeat the test if any of the following occurred: jumping rather than naturally falling onto the force platform; not keeping hands on the hips throughout the take-off; failing to maintain balance after landing.

2.2.4 Single-leg squat jump

The kinetic and kinematic data collecting method was same as the SLDJ test. Participants stood on one leg on the force platform, with the supporting knee flexed to approximately 90°, and another leg bent the knee with the foot tip off the ground. Meanwhile, participants leaned forward and kept hands behind their back, simulating the starting position of skating push-off. Participants held this position for 2–3 s before receiving the command to perform a jump in the vertical, horizontal, and lateral directions. Throughout the test, participants kept hands behind their back, and landed with both feet (with the feet touching down sequentially in the lateral direction) (Figure 2C). The testing sequence and rest intervals were same as SLDJ. Participants were required to repeat the test if any of the following occurred: non-supporting leg touched the ground before take-off; not keeping hands behind their back throughout the take-off; failing to maintain balance after landing.

2.3 Data processing

The video files were imported into SIMI Motion 8.0 (SIMI Reality Motion Systems, Germany) for kinematic analysis. The raw data were smoothed using a low-pass digital filter, residual analysis indicated a cut-off frequency of 6–10 Hz (Winter 2009). In the SLSJ, manual digitization was performed to mark the foot tip, heel, medial aspect of the first metatarsal, and lateral aspect of the fifth metatarsal. The horizontal SLSJ jump distance was defined as the distance from the foot tip of the support leg at take-off to the heel of the posterior foot after landing. The lateral SLSJ jump distance was defined as the distance from the medial aspect of the first metatarsal of the support leg at take-off to the lateral aspect of the fifth metatarsal of the same leg after landing. Both horizontal and lateral jump distances were normalized by height (Holm et al., 2008), and the vertical jumping height was calculated from the force-time curve. In the SLDJ, 21 anatomical points were manually digitalized for analyzing, including the head, bilateral hands, elbows, shoulders, hips, knees, ankles, toes, heels, medial aspect of the first metatarsal, and lateral aspect of the fifth metatarsals. The body center of gravity (BCoG) were calculated based on the Hanavan human mechanics model (Hanavan, 1964). The jumping distances and heights in the SLDJ were calculated and processed similarly to the SLSJ, and the velocity of the BCoG at the first touch-down moment was also recorded. The event synchronization technique (take-off moment) was applied to achieve multi-camera synchronization through the SIMI Motion Twin. The Direct Linear Transformation (DLT) algorithm was used to establish the three-dimensional coordinates, and the intra-class correlation coefficient (ICC) of 0.97 for the BCoG velocity indicates reliable manual digitization (Atkinson and Nevill, 1998). The kinetic data were imported into MATLAB for analysis, and smoothed at 75 Hz. The vertical force exceeding 10 N above the body weight (BW) were defined as the start of the SLSJ, and values below 25 N were defined as the moment of take-off (Hunter et al., 2005). In the SLSJ, the impulse and peak forces (PF) in the X (horizontal), Y (lateral), and Z (vertical) directions were calculated and recorded from the force-time curve, along with the rate of force development (RFD) and take-off velocity. For better comprehension, the vertical take-off velocity was converted to height. The horizontal and lateral impulse were calculated as the area under the force-time curve (Figure 3C), while the net impulse was calculated in the vertical direction according to Hunter et al. (2005) (Figures 3A, B), the PF and impulse were normalized by BW. The RFD (Equation 1), take-off velocity (Equations 2–4), and jump height (Equation 5) were calculated according to the methods presented by Ebben et al. (2010) and Guo et al. (2020):

$$RFD = \frac{F_{peak} - F_{initial}}{\Delta T_{peak}} \tag{1}$$

F_{peak} = Peak GRF, $F_{initial}$ = Initial GRF on landing, ΔT_{peak} = Time from the initiation to the peak GRF.

$$V_{take-off} = \sqrt{{V_v}^2 + {V_{h/l}}^2} \tag{2}$$

$$V_v = \int_0^{T_o} (F_v/m - g)dt \tag{3}$$

$$V_{h/l} = \int_0^{T_o} \left(F_{h/l}/m\right)dt \tag{4}$$

$$H = {V_v}^2/2g = \left(\int_0^{T_o} (F_v/m - g)dt\right)^2/2g \tag{5}$$

$V_{take\text{-}off}$ = take-off velocity, V_v = vertical take-off velocity, $V_{h/L}$ = horizontal/lateral take-off velocity, T_o = take-off time, F_v = vertical GRF, m = body mass, g = gravitational acceleration, $F_{h/L}$ = horizontal/lateral GRF, H = vertical jump height.

In the SLDJ, the change in BCoG velocity (including the take-off velocity) was calculated based on the method of McMahon et al. (2021) by combining the first touch-down BCoG velocity (Equations 6–8). Similarly, the vertical SLDJ take-off velocity was converted to jump height using the same method as for the vertical SLSJ. The formula for calculating BCOG velocity is as follows:

$$V_{rb} = \sqrt{{V_{vb}}^2 + {V_{hb/lb}}^2} \tag{6}$$

$$V_{vb} = \left(\int_0^{T_o} (F_v/m - g)dt\right) - V_{vt} \tag{7}$$

$$V_{hb/lb} = \left(\int_0^{T_o} \left(F_{h/l}/m\right)dt\right) + V_{ht/lt} \tag{8}$$

V_r = resultant velocity of BCOG, V_{vb} = vertical velocity of BCOG, $V_{hb/lb}$ = horizontal/lateral velocity of BCOG, T_o = take-off time, F_v = vertical GRF, m = body mass, g = gravitational acceleration, V_{vt} = vertical touch-down velocity of BCOG, $F_{h/l}$ = horizontal/lateral GRF, $V_{ht/lt}$ = horizontal/lateral touch-down velocity of BCOG.

The moment when the BCOG velocity reached 0 m/s was defined as the instant of transition from eccentric to concentric action of the support leg, the period from this moment to the take-off was defined as the propulsive phase. The net impulse and PF in the X, Y, and Z directions during the propulsive phase were calculated and recorded (Figures 3B,C), also normalized by BW. Additionally, considering the time as a critical performance variable affecting the SSC, we normalized variables in the SLDJ using the reactive strength index (RSI) based on the take-off time (Holm et al., 2008).

2.4 Statistical analysis

SPSS 21.0 (IBM, Armonk, NY) was used for statistical analysis, results are presented as mean ± standard deviation (SD). For the SLSJ and SLDJ tests, following González-García et al. (2024) recommended, the first jump was excluded, and the mean values of the relevant variables from the subsequent two jumps were used for analysis. The normality of data distribution was evaluated using the Shapiro-Wilk test. For normally distributed data, Pearson correlation analysis and paired samples t-tests were used to examine the relationships between dominance side variables, IA and the results, and the inter-limb differences for variables. For non-normally distributed data, Spearman rank correlation analysis and Wilcoxon signed-rank tests were used for the aforementioned analyses. In addition, quartile splits were performed for IA variables without significant correlations with the results, and independent samples t-tests or Mann-Whitney U tests were used to compare the skating time differences between the lowest quartile (Q1) and highest quartile (Q4) asymmetry group of IA. Cohen's d effect size was used to assess the magnitude of inter-limb or group differences, where: ES < 0.20 = trivial, 0.20–0.49 = small, 0.50–0.79 = medium, and ≥0.8 = large. And the correlations magnitude were defined according to Hopkins (2002): r = 0–0.1 (trivial), 0.1–0.3 (small), 0.31–0.5 (moderate), 0.51–0.7 (large), 0.71–0.9 (extremely large) and 0.91–1.0 (almost perfect). For the SLSJ and SLDJ tests, within-session reliability of test measures were quantified using a two-way random intra-class correlation coefficient (ICC) with absolute agreement inclusive of 95% confidence intervals (CI) and the coefficient of variation (CV). Interpretation of the reliability followed the recommendations of Bradshaw et al. (2010): ICC >0.67 and CV < 10% = good, ICC <0.67 or CV > 10% = moderate, ICC <0.67 and CV > 10% = poor. The IA was quantified using the formula from Bishop et al. (2021b) (100 - (100/maximum value × minimum value)) to express the degree of asymmetry as a percentage. An IF function was added to indicate the direction of asymmetry (left < right, −1, 1), with positive values indicating left-sided dominance and negative values indicating right-sided dominance. In addition, the Kappa coefficient was calculated to evaluate the consistency of asymmetry direction across tests. Consistency levels were interpreted according to Viera and Garrett (2005) as follows, where Kappa values: 0.01–0.20 = slight, 0.21–0.40 = fair, 0.41–0.60 = moderate, 0.61–0.80 = substantial, 0.81–0.99 = almost perfect. Furthermore, given the scarcity of relevant previous studies, a *post*

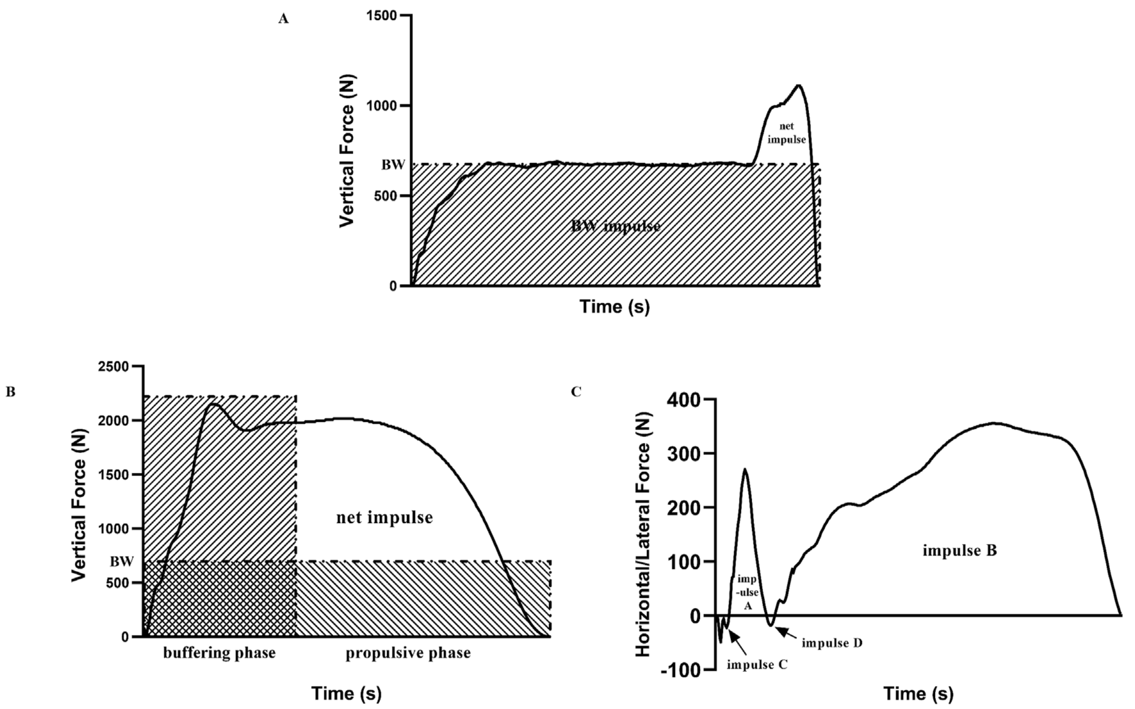

FIGURE 3
Schematic diagram of the vertical net impulse during the SLSJ take-off phase **(A)**, BW = body weight, the net impulse is calculated as the total impulse minus the BW impulse. Vertical net impulse during the SLDJ propulsive phase **(B)**, the vertical net impulse was calculated as the total vertical impulse during the propulsive phase minus the BW impulse during the same phase. Horizontal/lateral net impulse during the SLDJ propulsive phase **(C)**, the horizontal/lateral net impulse is calculated as the sum of impulse A and impulse B minus the sum of impulse C and impulse D

hoc power analysis was conducted (G*Power v. 3.1.9.7) based on the sample size in this study, the results indicated an average statistical power of 0.864 for the relevant variables (alpha level set at 0.05).

3 Results

3.1 Feature of IA

The general characteristics of all tests can be found in Supplementary Tables S1–S4. Except for vertical net impulse, the retest reliability of other variables was moderate to good. In isokinetic testing, significant right-side dominance was observed in relative knee extension PT ($t = -3.403$, $P = 0.004$, effect size ES = 1.17), PP ($t = -4.310$, $P = 0.001$, ES = 0.94) at 60°/s, and PP ($t = -2.202$, $P = 0.043$, ES = 0.76) at 180°/s. However, in the lateral single-leg squat jump (LSJ) test, most variables exhibited significant left-side dominance, including relative vertical peak force (PF-V) ($t = 2.537$, $P = 0.025$, ES = 0.47), lateral peak force (PF-L) ($t = 4.863$, $P < 0.001$, ES = 1.32), lateral impulse (Imp-L) ($Z = -2.023$, $P = 0.043$, ES = 0.94), and take-off velocity (TV) ($Z = -3.296$, $P = 0.001$, ES = 0.83). Limb dominance (Kappa coefficients = −0.29–0.65) (Supplementary Tables S5–S8; Supplementary Figure S1) and asymmetry magnitude (0.92%–20.35%) (Figure 4; Supplementary Tables S9 and S10) exhibited variability across tests.

3.2 Relationship between body composition, strength performance and skating time

Table 1 shows that the absolute lower limb muscle mass has stronger correlations with 100 m and 500 m skating time ($r = -0.63$, $P = 0.007$; $r = -0.69$, $P = 0.002$) than the relative values ($r = -0.53$, $P = 0.024$; $r = -0.52$, $P = 0.026$), and the knee flexion PP at 180°/s is largely correlated with skating time ($r = -0.60$, $P = 0.012$; $r = -0.58$, $P = 0.015$). In terms of jumping performance (Table 2), the correlations between lateral jump-related variables and skating time ($r = -0.63$ to -0.77) were higher than those for horizontal direction ($r = -0.54$ to -0.60) in the SLSJ, with TV showing the highest correlation. Similarly, variables significantly correlated with performance in the SLDJ were mostly concentrated in lateral jump. However, in all three directions, vertical performance variables such as the jump height and PF-V were consistently correlated with skating time ($r = -0.50$ to -0.55), but decreased after time normalization.

3.3 Relationship between critical variables asymmetries and skating time

The relationship between the IA of critical variables and skating time was examined. The results indicate that the lower limb muscle mass and isokinetic knee strength asymmetries were not associated

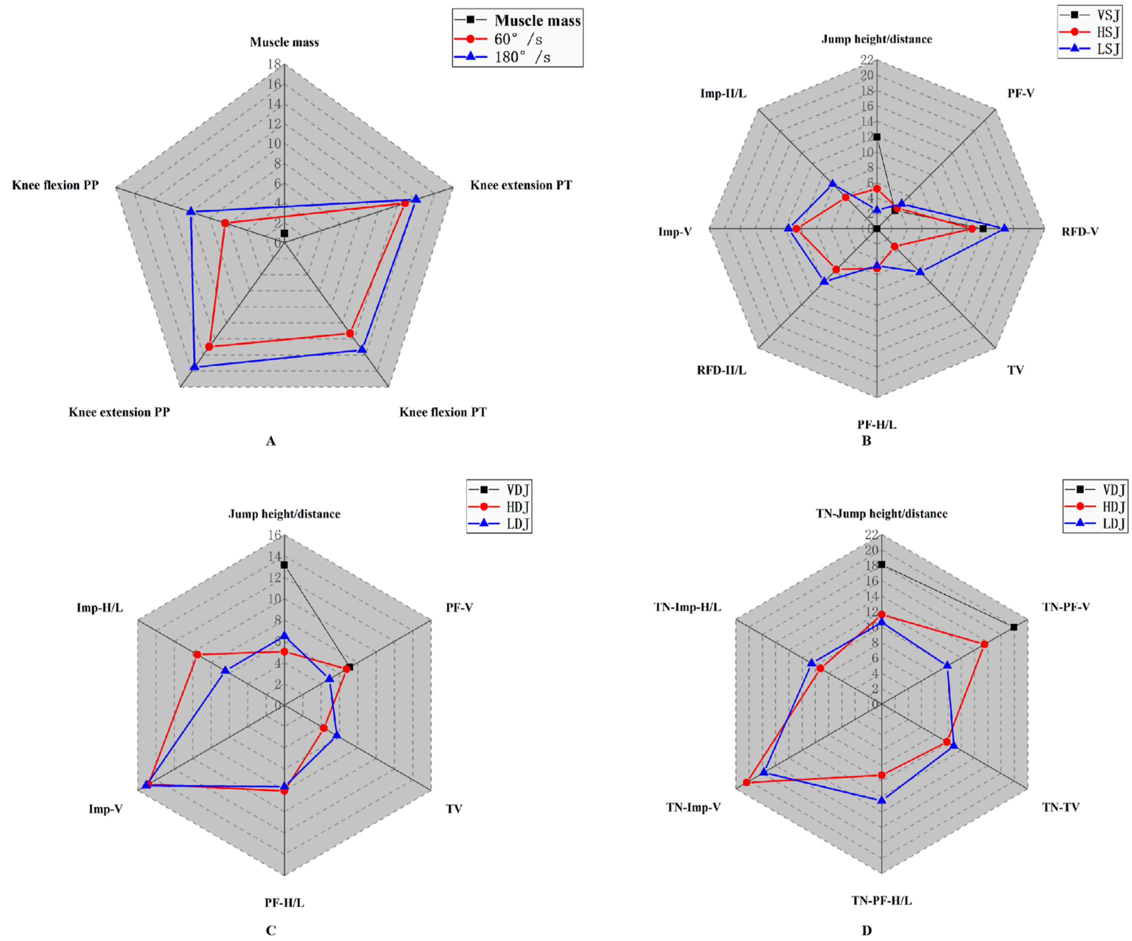

FIGURE 4
Radar chart depicting asymmetry in isokinetic knee strength and muscle mass **(A)**, SLSJ **(B)**, SLDJ **(C)**, TN-SLDJ **(D)**. V, vertical; H, horizontal; L, lateral; PP, peak power; PT, peak torque; Imp, impulse; PF, peak force; TV, take-off velocity; RFD, rate of force development; TN, time normalized.

with skating time. Furthermore, in the jumping tests (Table 3), regardless of SLSJ or SLDJ, only the lateral jump-related variables asymmetries and skating time exhibited a significant correlation (*r* = −0.54 to −0.57). To further investigate the correlation between the critical variables asymmetries and skating time, a quartile division was applied for critical variables asymmetries not significantly correlated with skating time, and the differences in skating time between the lowest quartile (Q1) and highest quartile (Q4) asymmetry groups were compared (Figure 5). Significant differences in skating time were observed between groups for the following variables: TV (100 m: t = −3.324, P = 0.029, ES = 2.71; 500 m: t = −6.476, P = 0.003, ES = 5.29), Imp-L in LSJ (500 m: t = −3.159, P = 0.034, ES = 2.58), jump height in VDJ (100 m: t = −3.071, P = 0.022, ES = 2.17), and PF-L in LDJ (100 m: t = −3.306, P = 0.016, ES = 2.34; 500 m: t = −3.258, P = 0.017, ES = 2.30).

4 Discussion

The purpose of this study was to evaluate the bilateral lower limb strength characteristics in adolescent speed skaters, and to investigate the relationship between critical variables asymmetries and skating time. The results partially support the hypothesis. Although there were differences in bilateral lower limb strength performance, only the TV in the HSJ and most LSJ related performance variables showed a significant left-side dominance. Limb dominance did not consistently favors the same side, and there were considerable differences in the asymmetry magnitude across tests. Furthermore, a positive relationship was observed between critical variables asymmetries and skating time.

The asymmetrical stroking technique in speed skating on corners can lead to increased blood flow restriction (BFR) in the right leg, with a significant decrease in oxygen saturation compared to the left leg (Born et al., 2014). BFR has been shown to promote muscle hypertrophy through increased secretion of growth hormone and activation of satellite cells (Hwang and Willoughby, 2019). However, no significant difference in bilateral lower limb muscle mass was observed in the subjects. Hettinga et al. (2016) showed that although speed skaters experience a significant decrease in oxygen saturation in the right leg during the corner phase, rapid re-oxygenation occurs during straight-line skating, thereby alleviating the BFR in the right leg. Consequently, the difference in muscle

TABLE 1 Correlation between body composition, isokinetic knee strength, and skating time.

Variables (n = 17)	100 m	500 m
Body composition		
Body fat	0.17	0.07
Absolute lower limb muscle mass	−0.63**	−0.69**
Relative lower limb muscle mass	−0.53*	−0.52*
Isokinetic test		
Relative knee extension PT at 60°/s	−0.01	−0.15
Relative knee flexion PT at 60°/s	−0.08	−0.19
Relative knee extension PT at 180°/s	−0.11	−0.12
Relative knee flexion PT at 180°/s	−0.09	−0.09
Relative knee extension PP at 60°/s	−0.01	−0.13
Relative knee flexion PP at 60°/s	−0.42	−0.47
Relative knee extension PP at 180°/s	−0.15	−0.14
Relative knee flexion PP at 180°/s	−0.60*	−0.58*

Abbreviations: PT, peak force; PP, peak power.

hypertrophy effects caused by BFR are diminished, leading to relatively balanced muscle mass in both legs (0.92% ± 0.64%), and the low degree of muscle mass asymmetry may also not be sufficient to effectively distinguish speed skaters of different competitive levels. It should be noted that the participants in this study were adolescent athletes, considering the typical asymmetric loading characteristics of speed skating, the lower limb muscle mass asymmetry may increase with training years, as well as the natural development (Luk et al., 2014). Future studies could evaluate adult athletes to further investigate the relationship between lower limb muscle mass asymmetry and speed skating performance. Furthermore, unlike most speed sports (Knechtle et al., 2010; Tsukahara et al., 2020), although increased relative muscle mass of the lower limb was associated with faster skating times (r = −0.52 to −0.53), its correlation was weaker compared to absolute values (r = −0.63 to −0.69), and no association was observed between body fat percentage and skating times. Mu and Xia (2013) reported the same result in adult speed skating athletes, which may be related to the speed skating specific technique that relies less on overcoming self-gravity (Konings et al., 2015).

Isokinetic strength testing revealed a laterality in the knee strength of speed skaters, the right leg exhibited higher relative knee extension PT, PP at 60°/s, and PP at 180°/s compared to the left leg ($P < 0.05$), consistent with the findings of Xia (2011). De Koning et al. (1991) demonstrated that speed skaters exhibit differences in the coordination patterns of bilateral lower limb during push-off, the net torque and average power at the right knee joint are significantly higher than those on the left side, with the push-off impetus primarily driven by knee extension in right stroke. Given that isokinetic knee extension strength testing primarily reflect the single-joint strength of the quadriceps, the corresponding right-side dominance may be attributed to this. Nonetheless, only the relative knee flexion PP at 180°/s was significantly correlated with skating time, while no correlation was found between the corresponding asymmetry and skating time. Indicating that due to the constraints of single-joint isolated movements, isokinetic knee strength testing may not effectively reflect the specific strength of speed skaters, consequently the corresponding asymmetry was not related to skating time. Nevertheless, considering the evidence of relationship between higher asymmetry in isokinetic knee strength and increased knee injury risk (Eagle et al., 2019), practitioners can still regularly monitor the corresponding asymmetry to prevent potential injuries.

In contrast to the right-side dominance in isokinetic knee extension strength, a significant left-side dominance in TV ($P < 0.05$) was observed in the LSJ and HSJ tests. According to the study by De Koning et al. (1991), the left leg exhibits higher muscle activation and approximately 30% greater output power compared to the right leg in corner stroke, the long-term repetition of the asymmetrical stroking movement pattern in corner may be the primary cause of the aforementioned phenomenon. Nevertheless, Zukowski et al. (2023a) did not report bilateral TV differences in HSJ and LSJ in speed skaters. In their study, participants were not restricted in arm swing, which may have affected the test outcomes by coordination strategies (Guo et al., 2020). When detecting the performance variables derived from force-time curves, significant left-side dominance was observed only in LSJ for variables such as PF-L and Imp-L. Nevertheless, the magnitude of impulse asymmetry is greater than that previously observed in ice hockey (Twible et al., 2024), another ice-based sport. This discrepancy may be associated with the consistent counterclockwise skating direction of speed skaters, which results in a constant asymmetric loading.

It is noteworthy that, despite most performance variables exhibited the left-side dominance in lateral jump tasks, still observed a significantly higher RFD in the right side during the LSJ task. This phenomenon may be related to the right leg reaching PP earlier in the curve skating (De Koning et al., 1991), and it also suggests that the asymmetry direction can vary among variables even within the same task. Therefore, when assessing the directional characteristics of IA, emphasis should be placed not only on the differences across different tasks, but also on the differences among different variables within the same task, giving different consideration to different variables even within the same task is of critical importance. For example, differently from other variables, RFD is the most sensitive variable to conditioning and deconditioning (Ruggiero and Gruber, 2024), which may result in a different asymmetry direction.

Furthermore, the aforementioned performance variables in LSJ were also significantly correlated with skating time, combined with the correlation between TV in LSJ ($r = -0.76$ to -0.77) and skating times was higher than that between TV in HSJ ($r = -0.54$ to -0.60) and skating times, indicating that the LSJ task may be more effective than the HSJ in detecting IA in speed skaters. Different to the terrestrial locomotion, where the propulsive force is primarily provided by the GRF in the same direction as movement, speed skating primarily relies on lateral pushing force to move forward, which act as the normal force in the direction of motion (Houdijk et al., 2002). Therefore, the LSJ may have higher fidelity

TABLE 2 Correlation between jump tests and skating time.

SLSJ (n = 14)	100 m	500 m	SLDJ (n = 17)	100 m	500 m	TN-SLDJ (n = 17)	100 m	500 m
Vertical			**Vertical**			**Vertical**		
Jump height	−0.52	−0.46	Jump height	−0.53*	−0.30	Jump height	−0.50*	−0.35
PF-V	0.08	0.06	PF-V	−0.28	−0.18	PF-V	0.16	0.18
RFD-V	−0.04	−0.12						
Horizontal			**Horizontal**			**Horizontal**		
Jump distance	−0.56*	−0.54*	Jump distance	−0.46	−0.31	Jump distance	−0.35	−0.34
TV	−0.60*	−0.54*	TV	−0.38	−0.22	TV	−0.42	−0.42
PF-V	0.24	0.18	PF-V	−0.55*	−0.54*	PF-V	−0.39	−0.42
RFD-V	−0.07	−0.14	PF-H	−0.25	−0.26	PF-H	−0.27	−0.31
PF-H	−0.42	−0.43	Imp-V	−0.44	−0.34	Imp-V	−0.39	−0.30
RFD-H	−0.34	−0.37	Imp-H	−0.34	−0.33	Imp-H	−0.32	−0.22
Imp-V	0.06	0.01						
Imp-H	−0.55*	−0.54*						
Lateral			**Lateral**			**Lateral**		
Jump distance	−0.41	−0.35	Jump distance	−0.38	−0.43	Jump distance	−0.37	−0.37
TV	−0.77**	−0.76**	TV	−0.56*	−0.48	TV	−0.39	−0.27
PF-V	−0.32	−0.45	PF-V	−0.53*	−0.50*	PF-V	−0.42	−0.40
RFD-V	−0.22	−0.28	PF-L	−0.55*	−0.54*	PF-L	−0.54*	−0.45
PF-L	−0.73**	−0.65*	Imp-V	−0.34	−0.34	Imp-V	−0.44	−0.30
RFD-L	−0.63*	−0.64*	Imp-L	−0.32	−0.33	Imp-L	−0.39	−0.22
Imp-V	−0.32	−0.30						
Imp-L	−0.63*	−0.65*						

Abbreviations: SLSJ, single-leg squat jump; SLDJ, single-leg drop jump; TN, time-normalized; PF, peak force; RFD, rate of force development; TV, take-off velocity; Imp, impulse.
*, $P < 0.05$;**, $P < 0.01$.

in simulating the skating push-off action compared to the HSJ. Just as Afonso et al. emphasized that due to the task-specific nature of IA, there are substantial differences in IA across different tasks. Therefore, when analyzing the relationship between IA and athletic performance, IA assessments should be based on tasks that are similar to the specialized technical neuromuscular control and coordination strategies (Afonso et al., 2022). It is recommended to prioritize the LSJ task when assessing IA in speed skaters with SLSJ tests.

In further comparing the associations between critical variables in SLSJ and skating time, only LSJ related performance variables such as RFD-L and Imp-L were significantly correlated with skating times (r = 0.54–0.57). Due to the minimal friction between the blades and the ice in the horizontal direction, speed skaters primarily rely on alternating lateral push-off to move forward, and the normal reaction force which is perpendicular to the gliding direction directly affects the effectiveness of push-off (Konings et al., 2015). Consequently, a high level of the RFD-L indicates that athletes can reach PF earlier and shorten the push-off time (Semmler, 2002), thereby increasing power output per unit time. And the Imp-L is the integral of the lateral force over the push-off time, an increase in the Imp-L can enhance the total push-off power output (Kozinc, 2022). Theoretically, reducing IA by enhancing the non-dominant side performance without compromising the dominant side performance, could increase the overall bilateral push-off power output. In addition, due to the alternating push-off with both legs, a larger asymmetry might cause a certain lateral deviation in the skating trajectory, potentially leading to

TABLE 3 Correlation between the critical variables asymmetries in jumping tests and skating time.

SLSJ (n = 14)	100 m	500 m	SLDJ (n = 17)	100 m	500 m	TN-SLDJ (n = 17)	100 m	500 m
Horizontal			**Vertical**			**Vertical**		
Jump distance	−0.01	0.23	Jump height	0.38		Jump height	0.25	
TV	−0.50	−0.32	**Horizontal**			**Lateral**		
Imp-H	−0.23	−0.05	PF-V	0.12	0.17	PF-L	0.56*	
Lateral			**Lateral**					
TV	0.50	0.47	TV	0.57*	0.55*			
PF-L	0.16	0.42	PF-V	0.20	0.31			
RFD-L	0.57*	0.54*	PF-L	0.44	0.43			
Imp-L	0.56*	−0.47						

Abbreviations: SLSJ, single-leg squat jump; SLDJ, single-leg drop jump; TN, time-normalized; PF, peak force; RFD, rate of force development; TV, take-off velocity; Imp, impulse.
*, P < 0.05.

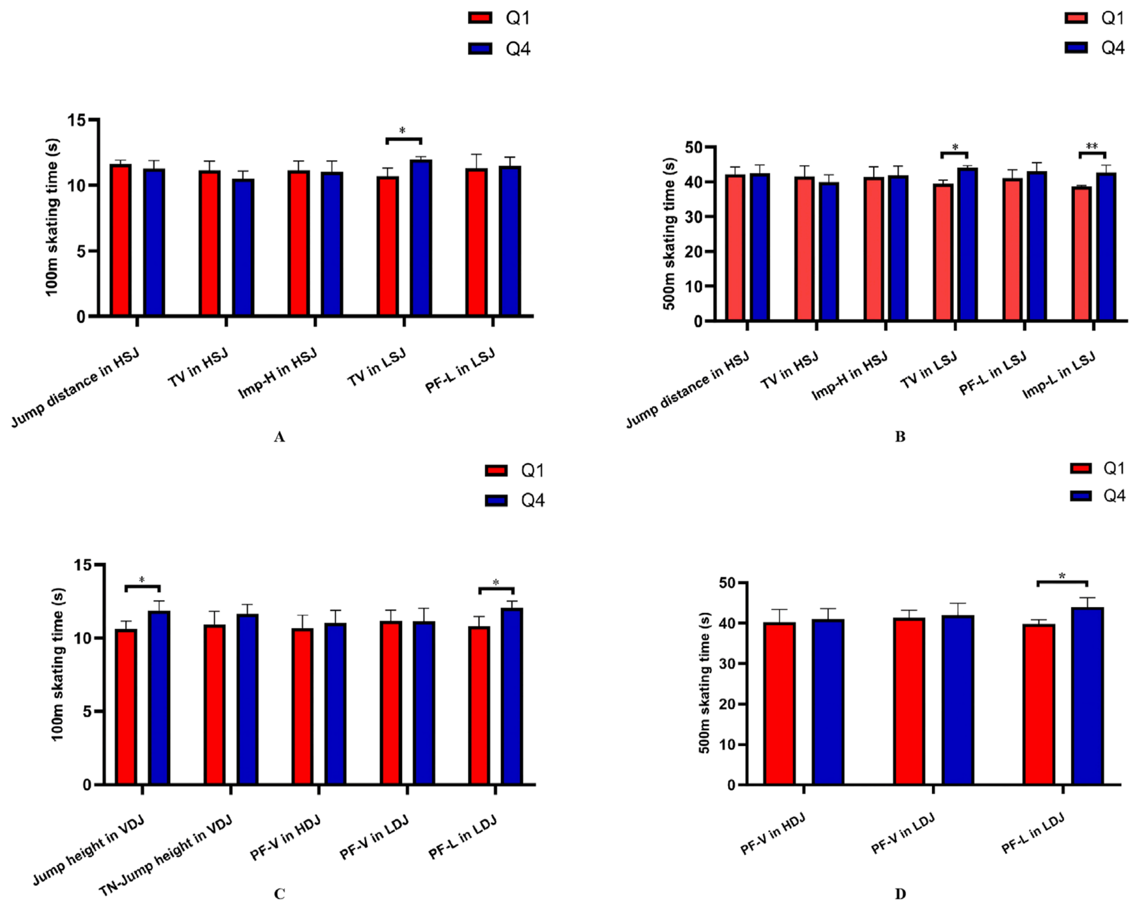

FIGURE 5
Comparison of 100 m **(A)**, 500 m **(B)** skating time between asymmetry groups (SLSJ). 100 m **(C)**, 500 m **(D)** skating time between asymmetry groups (SLDJ). Q1, lowest quartile group of asymmetry; Q4, highest quartile group of asymmetry; V, vertical; H, horizontal; L, lateral; HSJ, horizontal single-leg squat jump; LSJ, lateral single-leg squat jump; VDJ, vertical single-leg drop jump; HDJ, horizontal single-leg drop jump; LDJ, lateral single-leg drop jump; TV, take-off velocity; Imp, impulse; PF, peak force;*, P < 0.05;**, P < 0.01; ns, no significant difference.

an extended total skating distance (Kamst et al., 2012). Therefore, over-development of LSJ performance asymmetry might impair the skating performance. Notably, although PF-L asymmetry was not associated with skating time, impulse asymmetry can be better improved by increasing RFD on the non-dominant side along with enhancing PF. Furthermore, PF has been identified as a critical performance variable in similar roller skating events (Aedo-Muñoz et al., 2022), indicates that improvements in PF-L asymmetry may also benefit speed skaters. Furthermore, while no correlation was observed between the LSJ TV asymmetry and skating time, quartile statistical analyses demonstrated that athletes with lower TV asymmetry in LSJ had faster skating times, indicating that the LSJ TV asymmetry can still distinguish different levels of speed skating competitive ability to a certain extent. Nevertheless, aforementioned IA variables significantly correlated with skating time need to be obtained through the force platform, which may not be conducive to routine monitoring due to the ecological benefits. In theory, jump distance is primarily influenced by take-off angle and velocity, with the former varying within a relatively narrow range, making take-off velocity the main factor affecting jump distance (Graham-Smith and Lees, 2005). However, no significant correlation was observed between LSJ jump distance and its corresponding asymmetry with skating time, which may be related to the subjects landing on both feet sequentially, with lower limb flexibility affected the results (Cerrillo-Sanchis et al., 2024). Future studies may employ a simultaneous double-foot landing protocol to further investigate the impact of LSJ jump distance and corresponding asymmetry on skating performance, thereby improving potential practicality for routine monitoring.

Asymmetries in SLDJ performance variables were also found to be associated with skating time, the group with high VDJ jump height asymmetry demonstrated significantly longer 100 m skating time compared to the group with low asymmetry, consistent with the findings by Bishop et al. (2022) in soccer, where an increase in VDJ jump height asymmetry was associated with decreased 10 m sprinting performance. The speed skating starting technique shares similarities with on-land starting techniques, where both require rapid SSC contractions of the lower limbs and demand a high level of reactive strength (Song et al., 2017). Therefore, an increase in VDJ jump height asymmetry might have adverse effects on speed skating starting performance. Furthermore, although the present study showed that increased TV and PF-L asymmetries in LDJ were associated with prolonged skating time, the results should be interpreted with caution due to the relatively long ground contact time in LDJ. Considering prolonged take-off time may not effectively reflect corresponding reactive strength, the association between the LDJ performance asymmetry and skating time may be more related to the concentric contraction performance of relevant muscles (Möck et al., 2023). It is recommended to prioritize the VDJ as the testing task when assessing SLDJ performance asymmetry, and that other directional SLDJ can be replaced by the SLSJ. Finally, it should be noted that, although the asymmetry magnitude of several variables in this study exceeded established injury threshold standards (10% or 15%) (Barber et al., 1990), we cannot definitively conclude that the subjects will face a higher risk of injury. Bishop (2021) suggest that the previously established injury thresholds of 10% or 15% lack a certain objectivity, due to the task-specific nature of IA. The sensitivity of IA varies significantly across different tasks and variables, which might explain the inconsistencies in the findings regarding the predictive value of IA for injury risk. Therefore, injury thresholds should not be generalized but rather defined based on the characteristics of specific tasks and variables.

This study has certain limitations. This study only contained adolescent male speed skaters, the group specificity restricted the sample size, and the results may only be applicable to the same demographic. Future research may increase the sample diversity and size to compare the relationship between lower limb asymmetry and athletic performance across different genders and age groups in speed skaters. Additionally, this study only assessed the lower limb asymmetry of athletes at a specific time point. It remains unclear how the lower limb IA of adolescent speed skaters changes longitudinally throughout the season. Future research could include longitudinal studies regarding the adolescent speed skaters.

5 Conclusion

This study indicate that, influenced by the asymmetric loads during corner, adolescent speed skaters exhibit differences in bilateral lower limb strength performance, which are task-specific. Most LSJ performance related variables consistently show a left-side dominance, and increases in corresponding IA are correlated with prolonged skating time. Additionally, increased VDJ jump height asymmetry may also have adverse effects on sprinting skating performance. Furthermore, considering the relatively sensitive asymmetry identification of LSJ and VDJ among adolescent speed skaters, it is recommended to monitor and evaluate the lower limb asymmetry in speed skaters based on aforementioned tasks.

Data availability statement

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

Ethics statement

The studies involving humans were approved by Ethics Review Committee of Harbin Sport University. 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. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

ZJ: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Writing – original draft. YW: Data curation, Writing – original draft. BZ: Investigation, Resources, Writing – original draft. GB: Data curation, Investigation, Writing – review and editing. YD: Investigation, Software, Writing – review and editing. YZ: Data curation, Software, Writing – review and editing. LY: Conceptualization, Funding acquisition, Resources, Supervision, Writing – review and editing.

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Conflict of interest

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

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2025.1498911/full#supplementary-material

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Muscular strength and endurance adaptations to functional resistance training in young elite field hockey players

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Background: Functional strength training (FST) has gained considerable attention due to its potential in enhancing muscle strength, endurance, and body composition, especially among athletes. The purpose of this study was to assess the effects of a 12-week FST program on performance outcomes such as muscle strength, muscular endurance, and body composition in elite male field hockey players.

Methods: The study involved 28 male athletes from the Türkiye Hockey Federation Super League, with a mean age of 27.54 ± 1.34 years and an average athletic experience of 7.62 ± 0.48 years. The mean height of participants was 180.28 ± 4.54 cm, and their mean weight was 75.59 ± 3.08 kg. Participants were randomly divided into two groups: the experimental group (n = 14) and the control group (n = 14). Pre-intervention assessments were conducted to evaluate muscle strength (Leg Extension, Leg Curl, Bench Press, Pushdown), muscular endurance (30-s Sit-up and Push-up tests), and body composition [Body Mass Index (BMI) and Body Fat Percentage (BFP)]. The experimental group participated in the FST program three times per week for 12 weeks, while the control group maintained their usual training regimen. Post-test evaluations were performed using the same testing protocols. Statistical Analysis: Data were analyzed using two-way repeated measures ANOVA to assess the interaction effects of group and time (pre-test vs post-test). Partial eta squared (η^2) values were used to report effect sizes, and statistical significance was set at $p < 0.05$. Data analysis was carried out using SPSS 22.0 software. Normality was assessed through the Shapiro-Wilk test, and data distribution was further examined through skewness-kurtosis values, histograms, box plots, and Q-Q plots. Paired sample t-tests were performed for pairwise comparisons, with

Cohen's d used to determine the effect sizes. The classification for effect sizes followed Hopkins' (2002) guidelines: small (≥0.01), moderate (≥0.06), and large (≥0.14).

Results: Significant group × time interaction effects were found for all measured variables ($p < 0.05$). The experimental group showed greater improvements in body composition, muscle strength, and muscular endurance compared to the control group. Specifically, the experimental group experienced a significant reduction in BMI (pre-test: 21.17 ± 0.64 kg/m^2, post-test: 19.84 ± 0.85 kg/m^2, $p < 0.001$) and BFP (pre-test: 15.36% ± 0.62%, post-test: 12.13% ± 0.47%, $p < 0.001$), while the control group showed minimal changes in these variables. Muscle strength improvements in the experimental group were significant for Leg Extension (pre-test: 83.93 ± 4.87 kg, post-test: 66.07 ± 4.01 kg, $p = 0.003$), Leg Curl (pre-test: 99.29 ± 7.81 kg, post-test: 118.21 ± 5.04 kg, $p < 0.001$), and Bench Press (pre-test: 66.43 ± 6.91 kg, post-test: 87.14 ± 4.69 kg, $p < 0.001$). In contrast, the control group did not show significant improvements in these tests. Muscular endurance was also superior in the experimental group for both the 30-s Sit-up (pre-test: 19.21 ± 0.97, post-test: 23.36 ± 1.28, $p < 0.001$) and Push-up (pre-test: 24.66 ± 2.53, post-test: 27.04 ± 0.81, $p < 0.001$) tests. Effect sizes (Cohen's d) indicated moderate to large effects for all measured variables, with d values ranging from 0.46 to 1.14 for strength and endurance improvements.

Conclusion: The findings of this study demonstrate that a 12-week FST program significantly improves muscle strength, endurance, and body composition in elite male field hockey players. These results suggest that incorporating FST into athletic training regimens may optimize performance and enhance overall physical fitness in athletes.

KEYWORDS

physical muscular endurance, resistance training, strength development, fitness assessment, elite athletes, field hockey

Introduction

Recent advancements in sports science and training methodologies have enabled the development of more specific and effective sport-specific training models (Suchomel et al., 2020). Contemporary approaches emphasize the need to tailor training variables according to individual differences to optimize athlete performance and minimize the risk of injury (Branquinho et al., 2025).

While traditional strength training has long been regarded as a fundamental method for enhancing athletes' physical capacity, recent trends have shifted towards multi-joint, dynamic approaches that improve neuromuscular coordination (Suchomel et al., 2020; Branquinho et al., 2025; Santana, 2015). In this context, functional strength training (FST), which focuses on proprioceptive control and neuromuscular adaptations, enhances motor skills and supports performance improvements (Cook, 2010; Wan et al., 2025). Functional strength training provides a framework for improving athletic performance by activating various adaptation mechanisms through different methodological approaches. These approaches are referred to in the literature as High-Intensity Functional Training (HIFT), Integrated Neuromuscular Training (INT), French Contrast Training (FCT), and Santana's functional training model.

Research indicates that functional strength training significantly improves motor skills such as speed, agility, flexibility, cardiorespiratory capacity, endurance, coordination, maximal strength, and explosive power (Wan et al., 2025; Wang et al., 2025). Studies conducted in team sports such as soccer and basketball have reported that FST leads to significant improvements in muscle strength and endurance, sprinting, change of direction, and jumping ability (Hovsepian et al., 2021; Keiner et al., 2022; Khazaei et al., 2023). Similarly, noted that FST significantly enhanced explosive power, speed, and functional movement parameters in athletes across various sports, including soccer, basketball, sprinting, long jump, rugby, volleyball, and mixed martial arts (MMA) (Bashir et al., 2024; Bashir et al., 2022). Additionally, the acceleration of neuromuscular adaptations has been shown to trigger excess post-exercise oxygen consumption (EPOC) mechanisms and reduce injury risk; however, training load dosage and recovery periods must be carefully managed (Feito et al., 2018; Lloyd et al., 2015). Moreover, plyometric training has been reported to contribute to the development of change-of-direction ability, sprint speed, and explosive strength, reinforcing these adaptations when combined with strength training in functional training models (Gaamouri et al., 2023; Oliver et al., 2024).

These complex training methodologies are considered effective and applicable for field hockey, a sport that demands repeated sprints, rapid changes of direction, explosive power, and endurance (McGuinness et al., 2022; Jakeman et al., 2016). Field hockey players cover an average distance of 8–12 km per match, with a significant portion consisting of high-speed running and sprints, highlighting the critical importance of sprint performance for these athletes (Noblett et al., 2023). Supporting this view, demonstrated that hill sprint training based on a high-intensity interval training (HIIT) model effectively enhances maximal sprint speed (Jakeman et al., 2016). Emphasized that sprint, strength, and agility training contributes to increased lower and upper limb strength and anaerobic capacity in field hockey players, with combined methods playing a key role in the development of sport-specific skills (Sharma and Kailashiya, 2018).

Analyses of the physical demands of field hockey players based on their positions indicate that players reach higher speeds during high-effort situations compared to the overall game tempo (Lin et al., 2023). Forwards cover greater sprint distances, while defenders exhibit lower sprint rates (Noblett et al., 2023). Midfielders, on the other hand, require a high volume of running (Kuhlman et al., 2025). Additionally, reported that short rest intervals (2 min) in field hockey increase cognitive error rates, whereas longer rest intervals (5.5 min) do not provide additional physical performance advantages (Spooner et al., 2023). These findings highlight the critical importance of substitution timing for maintaining optimal performance.

Although numerous studies have examined the effects of functional strength training approaches across various sports, research specifically focused on field hockey remains limited. Given the complex motor skills required in field hockey, further experimental studies are needed to better understand position-specific physical demands and adaptations to modern training models.

This study aims to contribute significantly to the limited body of literature by investigating the effects of a 12-week FST program on field hockey players. The findings may assist coaches in developing more effective training programs for field hockey athletes and provide new insights into sport-specific training protocols. Furthermore, improving fundamental motor skills such as muscular strength and endurance may enhance key performance factors in field hockey, including speed, change of direction, balance, and technical proficiency, ultimately contributing to overall athletic capacity.

Methods

Participants and sample characteristics

This study involved 28 male elite field hockey players, all active participants in the Türkiye Hockey Federation Super Field Hockey League. The participants were selected based on strict inclusion criteria, which required a minimum of 5 years of competitive training experience in field hockey. This criterion ensured that the athletes had achieved the necessary physical conditioning and technical proficiency for high-level competition. The players demonstrated elite athleticism and engaged in national and international competitions, which reflects their advanced physical and technical capabilities. The participants' ages ranged from 18 to 25 years, a period during which athletes typically reach peak performance levels. All players underwent regular physical assessments as part of their involvement with their respective clubs, with evaluations focusing on enhancing strength, endurance, agility, and speed. In terms of health, none of the participants reported any history of cardiopulmonary diseases or chronic conditions that might interfere with high-intensity training, nor were they taking prescription medications that could affect performance or recovery. Each player passed the standard medical examination required by their field hockey clubs, confirming their suitability for professional, elite-level play.

The sample size for this study was determined using data from previous research (Dube et al., 2015), which helped estimate the expected effect size. Based on a medium effect size of 0.75, an alpha level of 0.05 (two-tailed), and a desired statistical power of 0.80, a power analysis conducted using G*Power 3.1 software indicated that at least 20 participants per group would be required to detect significant differences between the experimental and control groups. This sample size was chosen to ensure the robustness of the findings while accounting for potential attrition or non-compliance. The study included 28 male elite field hockey players from the Türkiye Hockey Federation Super League, with a mean age of 27.54 ± 1.34 years. Participants had an average height of 180.32 ± 4.52 cm, body mass of 75.59 ± 3.08 kg, and a body mass index (BMI) of 21.55 ± 0.71 kg/m^2. Their average body fat percentage was 15.54% ± 0.8%, and they had an average of 7.62 ± 0.48 years of training experience.

Participants were randomly assigned into two groups: a control group (n = 14) and an experimental group (n = 14). The control group had an average age of 27.36 ± 1.51 years, height of 181.00 ± 5.46 cm, and weight of 75.46 ± 2.61 kg, while the experimental group had an average age of 27.71 ± 1.54 years, height of 179.5 ± 3.44 cm, and weight of 75.73 ± 3.59 kg. Both groups were matched for key anthropometric variables to ensure that observed effects could be attributed to the intervention rather than baseline differences. After obtaining informed and written voluntary consent from all participants, block randomization was used to assign participants into study groups. The randomization process was based on age and skill level stratification to ensure balanced distribution across groups. Accordingly, after identifying and selecting a total of 28 eligible male field hockey players, participants were grouped into two blocks based on their skill level. Within each block, participants were randomly assigned to one of the two study groups—the experimental group (functional strength training) or the control group (regular training regimen) — using a computer-generated random sequence. To ensure allocation concealment and prevent potential selection bias, the randomization list was prepared in advance by a researcher who was not involved in the recruitment or assessment processes. Each participant's group assignment was placed in a sealed, opaque, and consecutively numbered envelope. These envelopes were opened only after the participant's baseline assessments were completed, ensuring that group allocation remained concealed until the assignment was implemented. This procedure ensured that both the participants and the researchers conducting the recruitment and initial assessments were blinded to group allocation at the time of participant enrollment, thereby enhancing the methodological rigor of the study and reducing selection bias. In summary, structuring the randomization and allocation process in this manner aimed to ensure initial homogeneity between the groups, minimize potential sources of systematic error, and enhance the internal validity of the study.

The key distinction between the groups was their additional training regimens. While both groups continued regular field hockey training, the experimental group incorporated a structured functional strength training program. This program, designed to enhance muscular strength, endurance, and overall athletic performance specific to the demands of field hockey, complemented their field hockey skills by targeting relevant muscle groups and movement patterns. Eligibility criteria were strictly defined to ensure participant safety and study relevance. All participants were required to be free of cardiopulmonary diseases and to have no history of recent or current medication use that could affect performance. Furthermore, to control for potential confounding effects, participants had not participated in any resistance or functional strength training programs in the 6 months prior to the study. Eligibility was verified using a comprehensive "Participant Information and Measurement Form," which included demographic details and baseline health information.

Ethical considerations were central to the study design and execution. Before the study began, all participants were informed about the research objectives, potential risks, and procedures. Each participant provided written informed consent, acknowledging their understanding of the study's aims, methods, and the voluntary nature of their participation. The study adhered to ethical standards, and approval was obtained from the relevant institutional review board. By including highly trained athletes from a competitive league, this study sought to assess the impact of functional strength training on athletic performance, contributing valuable insights into its application for elite field hockey players.

Ethical approval

The Ethical approval was obtained from the Health Sciences Ethics Committee of Çankırı Karatekin University, with the application submitted under meeting number 12 on 19 March 2024 (https://etikkurul.karatekin.edu.tr/dogrulama/4f769c2e2482475c). Participants provided informed consent, which included comprehensive details about the research, associated risks, potential benefits, confidentiality measures, and participant rights. The study strictly adhered to the ethical principles outlined in the Declaration of Helsinki, ensuring the protection of participants' rights and wellbeing throughout the design, procedures, and confidentiality measures. All stages of this study complied with the Helsinki guidelines for human research and met the current ethical standards in Sport and Exercise Science.

Measurement procedures

To control for potential confounding factors and ensure the reliability of the collected data, participants were instructed to rest for a minimum of 24 h before each testing session. This rest period was necessary to mitigate the effects of fatigue and prevent prior physical activity from influencing the test outcomes. Participants were also asked to maintain their usual dietary habits during the 24-h period leading up to the tests. Such dietary control was crucial, as nutritional status can significantly affect physical performance, particularly in strength and endurance tests (Smith and Doe, 2018). In addition, participants were required to refrain from consuming any stimulants or caffeine prior to the test to avoid interference with their physiological responses (Thomas and Ross, 2017). To standardize the testing conditions further, all participants wore identical field hockey boots with rubber studs during each assessment session. This ensured that no differences in footwear contributed to variability in performance, particularly in tests involving sprints or dynamic movements, where the type of footwear can impact traction and stability (Williams and Jones, 2019). The order of the tests (body composition, leg curl, leg extension, bench press, assisted pull-up, sit-up, and push-up for 30 s) was randomized to prevent any order effects, such as performance degradation due to fatigue during subsequent tests. This randomized order ensures that no particular assessment systematically benefits from being performed first or last, thus controlling for any biases associated with test order (Harrison and Gaffney, 2001).

Test session

Prior to each testing session, all participants underwent a standardized warm-up protocol designed to minimize the risk of injury and optimize performance during the tests. This protocol began with 5 min of light jogging to elevate the participants' heart rate and stimulate cardiovascular efficiency. Following this, participants performed 5 min of joint mobility exercises aimed at increasing flexibility and ensuring optimal range of motion, particularly in the major muscle groups that would be engaged during the tests, such as the quadriceps, hamstrings, and shoulders. The warm-up concluded with three progressive 30-m sprints, designed to activate the neuromuscular system and mimic the explosive, high-intensity movements typical in field hockey (Taylor and Jakeman, 2022). The warm-up was designed based on established protocols for athletic testing and was consistently followed across all testing sessions to ensure uniformity. The warm-up was performed under controlled environmental conditions, with ambient temperatures maintained between 22°C and 25°C to minimize the effects of extreme weather conditions on performance (Baker, 2017).

Testing sessions were conducted on a natural grass field at the athletes' respective club facilities. The use of a natural grass surface reflected the actual playing conditions of field hockey, ensuring that performance data collected during the tests were more relevant to the players' real-world experiences (Singh and Deswal, 2020). The choice of testing time during both morning and afternoon hours was intentional, as previous research has demonstrated that physical performance can vary across the day due to circadian rhythms, and this study aimed to account for any potential time-of-day effects (Roberts and Stevens, 2019). Participants wore form-fitting athletic attire, which allowed for freedom of movement and reduced the risk of discomfort or restriction during performance tests (Keiner et al., 2022). For footwear, athletes wore their regular indoor hockey shoes, which they were accustomed to using during training and competitive matches. This choice aimed to minimize the potential for performance differences due to unfamiliar or non-optimal footwear (Harris et al., 2018).

The testing procedure involved several assessments aimed at evaluating both muscle strength and muscular endurance. These

TABLE 1 Experimental test timeline.

Monday: All tests' practical demonstration
Tuesday
10:00 - Body composition measurements
15:00 – Leg Curl, Leg Ext., Bench Press
Thursday
09:00 – Assist. Pull up, Sit up and Push up
Functional Training Programs/12 Weeks (Total)
Study Conclusion and Analysis Evaluation

included body composition measurements, as well as strength tests (leg curl, leg extension, bench press) and endurance tests (assisted pull-up, sit-up, and 30-s push-up tests). These assessments were conducted on the same day in randomized order, with the participants performing each test in pairs to ensure efficiency and maintain testing consistency (Green and Lee, 2014). The use of paired testing, where two participants performed the same tests simultaneously, helped maintain a controlled environment and prevented delays during data collection. This approach has been shown to improve the efficiency of testing protocols, especially when working with a large group of participants (Nguyen and Brown, 2016; Palmer and Gray, 2018). To enhance the accuracy of the results, all measurements were taken using calibrated instruments, and each participant's performance was recorded and double-checked for consistency. This system of checks and balances helped ensure the integrity of the data collected during each testing session (Table 1).

Body height measurements

Body height was measured using a wall-mounted stadiometer (Holtain Ltd., England), following a standardized procedure to ensure accuracy. Participants were instructed to stand in the anatomical position, with bare feet together, heels touching, and breath held. The head was aligned in the frontal plane, ensuring the top of the head touched the vertex point of the headrest. This technique, which is widely used in anthropometric studies, follows the methodology described by Gordon et al. (Gordon et al., 2023), who emphasized the importance of consistent body alignment to minimize measurement errors. Similar protocols were applied by Johnson et al. (2022), demonstrating their reliability in various populations, including athletes.

Body Composition Examination

Body composition, including body weight (BW), body fat percentage (BFP), and body mass index (BMI), was assessed using the InBody 270 (Hologic QDR Series, Delphi A model, Bedford, MA, United States) in combination with Hologic APEX software (Version 13.3:3). Testing was conducted under controlled conditions: participants were in a rested, fasted, and hydrated state, and instructed to avoid vigorous physical activity for at least 24 h prior to testing (Mustafakaratas et al., 2020). Participants were asked to remove any metal objects or jewelry to prevent interference with the measurements. Daily calibration of the InBody 270 was performed using phantoms, following the manufacturer's guidelines, ensuring measurement accuracy. Measurements were taken with participants lying supine on the scanning table, feet slightly apart and arms at their sides, in line with procedures recommended by previous studies (Suarez et al., 2021). To control for circadian variations in body composition, testing time was standardized to 10:00 a.m., as suggested by several studies in the field (Hovsepian et al., 2021; Keiner et al., 2022; Khazaei et al., 2023).

One repetition maximum (1-RM) strength assessment

Muscle strength was assessed using the one-repetition maximum (1-RM) test for various exercises, including bench press, leg extension, leg curl, and assisted pull-up. Prior to testing, participants warmed up by performing 5–10 repetitions at approximately 50% of their estimated 1-RM. After a 1-min rest, participants performed a single repetition at approximately 80% of their estimated 1-RM. The weight was progressively increased after each successful attempt until failure was reached. The 1-RM was typically established within five attempts, as recommended in the sports science literature as a reliable measure of maximal strength (Seo et al., 2018). The testing protocol closely followed methods outlined by Seo et al. (Seo et al., 2018) and Jones et al. (Jones et al., 2021).

Bench press exercise for upper body strength-endurance

The bench press exercise involved participants lying supine on a bench, lowering the barbell to chest height, and then pressing it back upwards. This exercise primarily targets the pectoralis major, triceps, and anterior deltoid muscles. Bench press performance is widely regarded as an essential indicator of upper body strength-endurance, with multiple studies supporting its use in athletic strength testing (McGuire et al., 2020).

Assisted pull-up for upper body strength-endurance

The assisted pull-up machine was used to assess upper body strength-endurance. Participants performed repetitions by pulling themselves up on a bar positioned at 190 cm, using an overhand grip. Successful repetitions were recorded when participants pulled their chin above the bar. This exercise is effective in measuring strength in the latissimus dorsi, biceps, and trapezius muscles, contributing valuable data for assessing strength in athletes (Pekel, 2007a; Pekel, 2007b).

Leg extension for lower body strength-endurance

Leg extension exercises were performed using a machine designed to target the quadriceps muscle group, including the vastus lateralis, vastus medialis, and rectus femoris. This exercise is an effective method for evaluating lower body strength and endurance and has been widely used in both clinical and athletic settings to assess leg muscle performance (Mustafakaratas et al., 2020; Fitzgerald et al., 2018).

Leg curl for lower body strength-endurance

Leg curl exercises were performed using a machine that isolates the hamstrings by requiring participants to lie prone while lifting the weighted pads with their legs. This movement specifically targets the hamstring muscles in the posterior thigh and serves as a crucial measure of lower body strength. Proper technique is vital to prevent injury and ensure accurate muscle performance assessment (Oğuz et al., 2021).

30-Second Push-Up Test for Trunk Strength-Endurance

The 30-s push-up test was utilized to measure upper body muscular endurance, particularly for the trunk and arms. Participants began in a plank position and performed push-ups while ensuring their body remained in a straight line and their knees did not touch the ground. The number of push-ups completed within the 30-s interval was recorded. This test is widely used to assess muscular endurance, especially for the pectorals, triceps, and deltoids, and has been extensively validated in both athletic and clinical populations (McGuire et al., 2019; Milson et al., 2020; Milson et al., 2019).

30-Second Sit-Up Test for Trunk Strength-Endurance

The 30-s sit-up test was employed to assess abdominal endurance. Participants were instructed to lift their upper body towards their knees while maintaining proper form. The number of sit-ups completed within 30 s was recorded. This test is commonly used to evaluate core strength and endurance, particularly in the rectus abdominis and oblique muscles. It is widely recognized in fitness assessments and has proven to be an effective measure of trunk muscular endurance (McGowan et al., 2022).

Training interventions

This study utilized a pre-test-post-test experimental design, which was meticulously planned, implemented, and executed over a 14-week period, from early July to the end of September. The primary aim was to assess the effects of a structured physical functional strength exercise program on various physical and physiological parameters. A detailed outline of the program is provided in Table 1, which specifies the frequency, intensity, and type of exercises incorporated, as well as the progression of training throughout the duration of the study.

The participants in this study were athletes selected based on specific inclusion and exclusion criteria to ensure homogeneity in the sample and minimize confounding variables. Prior to the commencement of the exercise intervention, baseline assessments were carried out. These pre-test evaluations, which were conducted within 24 h before the program's initiation, included a series of standardized tests designed to measure key fitness variables such as body composition, muscular strength, endurance, and cardiovascular fitness. Post-test evaluations were conducted within 48 h following the conclusion of the 14-week intervention period, allowing for a window of time to ensure that any immediate effects of the training were captured. The same testing procedures were used to assess changes in physical and physiological parameters, ensuring consistency and reliability of the measurements. Key variables, including changes in body composition, muscle mass, strength endurance, and aerobic capacity, were tracked throughout the study.bIn addition to assessing physical fitness parameters, the study also aimed to investigate the impact of the intervention on specific markers of body composition, such as body fat percentage and lean mass. These measures were integral to understanding how the physical functional strength exercise program contributed to both functional performance and overall physical health over the 14-week period (Table 2).

Load control and exercise intensity management and equalization of training volume and workload

This study was conducted over a 12-week period, focusing on the effects of a functional strength training program on elite athletes. In managing load control, special attention was paid to ensuring that both the control and experimental groups experienced similar total training volumes, providing a fair comparison of the intervention's effects. The following methodological strategies were employed to equalize the volume and workload across both groups: To ensure consistency across the control and experimental groups, the total volume of training (frequency and duration) was standardized. Both groups followed a training schedule that involved the same frequency of sessions and comparable session lengths, with slight adjustments made for the experimental group to incorporate the additional functional strength exercises. This approach ensured that the experimental group was not subject to an excessive overall training load, which could confound the results. Specifically, while the experimental group performed extra functional strength exercises, the volume in these exercises was balanced with the existing training routines of both groups, avoiding an overload.

Free-weight exercise intensity control

The intensity of exercises performed with free weights was strictly controlled using the percentage of 1-RM (one-repetition maximum) method. This approach ensured that each participant's strength training was tailored to their individual capacity. At the beginning of the study, each participant underwent a 1-RM testing session to determine their maximum strength for key exercises (such as squats, bench press, and deadlifts). Based on the 1-RM values, the intensity of the free-weight exercises was prescribed as a percentage of their maximum strength. Over the 12 weeks, the intensity progressively increased in accordance with the participants' improvements in strength and endurance. The progression was individualized and followed a structured plan, with intensity levels adjusted every 2 weeks. The goal was to challenge participants' muscles at optimal loads for maximum adaptation without causing overtraining. As participants became stronger, the load was gradually increased, typically by 5%–10% of their 1-RM, ensuring that the intensity remained high enough to elicit physiological adaptations while avoiding injury.

TABLE 2 Detailed design of the Functional Strength training programs.

Week	Warm-up	Exercises	Volume & intensity	Focus
Week 1	10 min jogging, 10 min stretching	20 Squats, 20 Cross Crunches, 20 Climbers, 20 Lunges, 10 Box Jumps, 5 Assisted Pull-Ups, 30 m Sprint	2 sets each, 1 min rest, focus on technique and basic endurance	Develop movement mechanics, aerobic fitness, basic strength
Week 2	10 min jogging, 10 min stretching	20 Squats, 20 Cross Crunches, 20 Climbers, 20 Lunges, 10 Box Jumps, 5 Assisted Pull-Ups, 30 m Sprint	2 sets each, 1 min rest, maintain focus on technique	Improve endurance and muscle activation
Week 3	10 min jogging, 10 min stretching	20 Squats, 20 Cross Crunches, 20 Climbers, 20 Lunges, 10 Box Jumps, 5 Assisted Pull-Ups, 30 m Sprint	2 sets each, 1 min rest	Continue building strength and endurance
Week 4	10 min jogging, 10 min stretching	20 Squats, 20 Cross Crunches, 20 Climbers, 20 Lunges, 10 Box Jumps, 5 Assisted Pull-Ups, 30 m Sprint	2 sets each, 1 min rest	Improve endurance and neuromuscular coordination
Week 5	10 min jogging, 10 min stretching	20 Squats, 20 Cross Crunches, 20 Climbers, 20 Lunges, 10 Box Jumps, 5 Assisted Pull-Ups, 30 m Sprint	2 sets each, 1 min rest	Increase intensity while maintaining form
Week 6	10 min jogging, 10 min stretching	50 m Sprints (3 sets), 20 Squats (3 sets), 30 Jumping Jacks, 20 Climbers (2 sets), 10 TRX Rows (3 sets), 10 Kettlebell Swings (3 sets)	3 sets, moderate intensity, focus on power and conditioning	Increase volume and intensity, improve explosive strength
Week 7	10 min jogging, 10 min stretching	50 m Sprints (3 sets), 20 Squats (3 sets), 30 Jumping Jacks, 20 Climbers (2 sets), 10 TRX Rows (3 sets), 10 Kettlebell Swings (3 sets)	3 sets, moderate intensity, focus on endurance and muscular endurance	Emphasize muscular endurance and cardiovascular fitness
Week 8	10 min jogging, 10 min stretching	50 m Sprints (3 sets), 20 Squats (3 sets), 30 Jumping Jacks, 20 Climbers (2 sets), 10 TRX Rows (3 sets), 10 Kettlebell Swings (3 sets)	3 sets, moderate intensity	Continue endurance training and power development
Week 9	10 min jogging, 10 min stretching	40 Squats, 20 Box Jumps, 20 V-ups, 20 Bosu Balance, 40 Burpees, 20 Ball Slams (3 sets), 15 Kettlebell Press (3 sets)	3 sets, moderate intensity, increase volume	Focus on strength endurance and overall conditioning
Week 10	10 min jogging, 10 min stretching	40 Squats, 20 Box Jumps, 20 V-ups, 20 Bosu Balance, 40 Burpees, 20 Ball Slams (3 sets), 15 Kettlebell Press (3 sets)	3 sets, moderate intensity	Continue endurance and strength development
Week 11	10 min jogging, 10 min stretching	40 Squats, 2 Push-ups, 20 Box Jumps, 20 V-ups, 20 Bosu Balance, 20 Ball Slams (3 sets), 15 Kettlebell Press (3 sets), 3 Assisted Pull-Ups	3 sets, moderate intensity	Maintain strength and power, increase volume
Week 12	10 min jogging, 10 min stretching	40 Squats, 2 Push-ups, 20 Box Jumps, 20 V-ups, 20 Bosu Balance, 20 Ball Slams (3 sets), 15 Kettlebell Press (3 sets), 3 Assisted Pull-Ups	3 sets, moderate intensity	Final week of progressive training, focus on endurance and maximal effort

Monitoring rest and recovery and progressive overload strategy

Rest periods were carefully controlled to promote adequate recovery while maintaining intensity. For free-weight exercises, rest periods between sets were standardized at 90 s, allowing participants to recover sufficiently before performing subsequent sets at high intensity. This controlled rest period ensured that participants experienced appropriate muscle fatigue, contributing to strength and hypertrophy gains without compromising overall training volume. A progressive overload strategy was employed to ensure continued adaptation. The program included specific adjustments to the load based on regular 1-RM re-testing, performed every 4 weeks to assess the participants' progress. Following the re-assessment, the intensity of the exercises was adjusted, ensuring that the participants were consistently working within the optimal range for muscle growth and strength improvement. This method of periodization helped to balance training intensity and recovery, ensuring that the athletes were neither undertraining nor overtraining during the intervention period. In this study, participants underwent pre-test and post-test evaluations to measure changes in physical and physiological parameters. These included body composition, muscular strength, endurance, and cardiovascular fitness. During the 12-week training period, the experimental group engaged in functional strength exercises that supplemented their regular field hockey training, while the control group followed their usual training routine. Both groups completed the same pre-test and post-test assessments, which included standardized tests for muscular strength (e.g., squat, bench press), endurance (e.g., 30-s push-up test), and aerobic capacity. By ensuring that training volumes, intensities, and recovery periods were closely managed and matched across both groups, the study aimed to isolate the effects of the functional strength training program, providing clear insights into its impact on athletic performance.

Statistical Analysis

The data were analyzed using the SPSS 22 statistical software. Normality tests were conducted using the Shapiro-Wilk test, one of the statistical tests for normality. Additionally, skewness-kurtosis values, histograms, box plots, and Q-Q plots were examined to assess data distribution. Since the data followed a normal distribution, they were presented as mean ± standard deviation (±SD). Paired sample t-tests were employed for pairwise comparisons. To demonstrate the practical significance of the differences between pre-test and post-test results, effect sizes were reported. Cohen's d test was used to determine the effect size. The classification of effect sizes was based on the table proposed by Hopkins in 2002 (Ulupınar and İnce, 2021; Seo et al., 2021). A two-way repeated measures ANOVA test was applied to determine the interaction effect (group x time). The eta squared (η^2) value was used to express the effect size. According to the classification, an effect size of ≥0.01 was considered small, ≥0.06 moderate, and ≥0.14 large (Seo et al., 2021). In this study, a 95% confidence level and a significance level of $p = 0.05$ were adopted for interpretation.

Results

The findings obtained within the scope of the study are presented below.

As presented in Table 3, the mean age of the field hockey athletes participating in the study was 27.54 ± 1.34 years, with an average athletic experience of 7.62 ± 0.48 years. The athletes' mean height was 180.28 ± 4.54 cm, and their mean weight was 75.59 ± 3.08 kg. The mean body mass index (BMI) was calculated to be 21.55 ± 0.71, and the mean body fat percentage was 15.54 ± 0.58. The participants were randomly assigned to two groups: the control group, consisting of 14 athletes (age: 27.36 ± 1.51 years; height: 181.00 ± 5.46 cm; weight: 75.46 ± 2.61 kg), and the experimental group, also comprising 14 athletes (age: 27.71 ± 1.54 years; height: 179.5 ± 3.44 cm; weight: 75.73 ± 3.59 kg).

Table 4 presents the findings regarding the effects on physiological characteristics between the groups. According to the Cohen's d coefficient calculated to determine the effect sizes of the differences, the intervention's impact on body weight (kg) was found to be very large for the Experimental (FST) group (d = 2.06) and large for the Control group (d = 1.54). Regarding BMI (kg/m^2), the effect was near-perfect for the Experimental group (d = 4.79) and large for the Control group (d = 1.77). For body fat percentage (%), the effect was identified as near-perfect for the Experimental group (d = 5.87) and very large for the Control group (d = 3.74).

Table 5 presents the findings regarding the effects on Maximum Strength Measurements and Muscular Endurance parameters between the groups. According to the Cohen's d coefficient calculated to determine the effect sizes of the differences, the intervention's impact on leg extension (kg) was found to be very large for the Experimental group (d = 2.72) and large for the Control group (d = 1.20). For leg curl (kg), the effect was very large for both the Experimental group (d = 2.88) and the Control group (d = 2.25). Regarding bench press (kg), the effect was very large for the Experimental group (d = 3.51) and also very large for the Control group (d = 2.43). The intervention's impact on assisted pull-up (kg) was very large for both the Experimental group (d = 2.77) and the Control group (d = 3.03). For the 30-s push-up test, the effect was large for the Experimental group (d = 1.27) and large for the Control group (d = 1.45). Lastly, in the 30-s sit-up test, the effect was very large for the Experimental group (d = 3.65) and large for the Control group (d = 1.46).

Table 6 presents the findings from the repeated measures two-way ANOVA test comparing the effects of the intervention on body composition over time between the Experimental and Control groups. According to the results, statistically significant differences were observed between the groups over time in all physiological characteristics except for body weight (kg) ($p < 0.05$).

Table 7 presents the findings from the repeated measures two-way ANOVA test comparing the effects on Maximum Strength Measurements and Muscular Endurance performance parameters over time between the Experimental and Control groups. According to the results, statistically significant differences between the groups over time were observed in leg extension (kg), bench press (kg), assisted pull-up (kg), and sit-up (30 s) performance ($p < 0.05$).

Discussion

The findings of this study indicate that a 12-week Functional Strength Training (FST) program led to significant improvements in muscle strength, muscular endurance, and body composition in elite male field hockey players. The findings demonstrated significant improvements across several parameters, particularly in the experimental group. The findings from the current study provide compelling evidence regarding the significant impact of the intervention on both physiological characteristics and muscular performance in the Experimental and Control groups. As outlined in Table 4, the intervention produced very large effects on body weight (kg) for the Experimental group (d = 2.06) and large effects for the Control group (d = 1.54). Additionally, body mass index (BMI) was significantly impacted, with near-perfect effects observed for

TABLE 3 Distribution of participants' body composition parameters.

Variables	n	Mean	Std. Deviation	Min	Max
Age (years)	28	27.54	1.34	25	30
Athlete Age (years)		7.62	0.48	7.1	8.5
Height (cm)		180.32	4.52	174.25	189.00
Weight (kg)		75.59	3.08	70.00	80.00
Body Mass Index (kg/m^2)		21.55	0.71	20.00	22.9
Body Fat Percentage (%)		15.54	0.58	14.52	16.30

TABLE 4 Comparison of pre-test and post-test values for participants' body composition variables.

Parameters	Group	Pre test $\bar{X} \pm$ SS	Post test $\bar{X} \pm$ SS	Cohen d
Body Weight (kg)	Experimental Group	75.46 ± 2.61	70.07 ± 2.63	2.06
	Control Group	75.73 ± 3.59	70.77 ± 2.81	1.54
Body Mass İndex (kg/m2)	Experimental Group	21.94 ± 0.58	19.14 ± 0.59	4.79
	Control Group	21.17 ± 0.64	19.84 ± 0.85	1.77
Body Fat Percentage (%)	Experimental Group	15.36 ± 0.62	12.13 ± 0.47	5.87
	Control Group	15.73 ± 0.51	13.20 ± 0.81	3.74

*p < 0.05; Effect Size (Cohen d): Insignificant <0.2; Small = 0.2–0.59; Moderate = 0.60–1.19; Large = 1.20–1.99; Very Large = 2.0–3.99; Close to Perfect >4.0.

TABLE 5 Comparison of pre-test and post-test values for within-group maximum strength measurements and muscular endurance.

Parameters	Group	Pre test $\bar{X} \pm$ SS	Post test $\bar{X} \pm$ SS	Cohen d
Leg Extension (kg)	Experimental Group	83.93 ± 4.87	96.07 ± 4.01	2.72
	Control Group	85.71 ± 4.75	91.43 ± 4.82	1.20
Leg Curl (kg)	Experimental Group	99.29 ± 7.81	118.21 ± 5.04	2.88
	Control Group	81.43 ± 6.02	95.36 ± 6.34	2.25
Bench Press (kg)	Experimental Group	66.43 ± 6.91	87.14 ± 4.69	3.51
	Control Group	76.79 ± 3.17	83.57 ± 2.34	2.43
Assist. Pull Up (kg)	Experimental Group	53.93 ± 5.25	68.21 ± 5.04	2.77
	Control Group	53.57 ± 3.06	62.14 ± 2.57	3.03
Push Up (30 s)	Experimental Group	24.66 ± 2.53	27.04 ± 0.81	1.27
	Control Group	22.67 ± 1.16	24.13 ± 0.83	1.45
Sit Up (30 s)	Experimental Group	19.21 ± 0.97	23.36 ± 1.28	3.65
	Control Group	19.71 ± 1.68	21.86 ± 1.23	1.46

*p < 0.05; Effect Size (Cohen d): Insignificant <0.2; Small = 0.2–0.59; Moderate = 0.60–1.19; Large = 1.20–1.99; Very Large = 2.0–3.99; Close to Perfect >4.0.

TABLE 6 Comparison of physiological characteristic differences over time between groups.

Parameters	Group	Pre test $\bar{X} \pm$ SS	Post test $\bar{X} \pm$ SS	Group x time interaction		
				F	p	η^2
Body Weight (kg)	Experimental Group	75.46 ± 2.61	70.07 ± 2.63	0.181	0.674	0.007
	Control Group	75.73 ± 3.59	70.77 ± 2.81			
Body Mass İndex (kg/m2)	Experimental Group	21.94 ± 0.58	19.14 ± 0.59	**26.000**	**0.001***	**0.526**
	Control Group	21.17 ± 0.64	19.84 ± 0.85			
Body Fat Percentage (%)	Experimental Group	15.36 ± 0.62	12.13 ± 0.47	**4.495**	**0.044***	**0.147**
	Control Group	15.73 ± 0.51	13.20 ± 0.81			

*$p < 0.05$; η2: small >0.01, medium ≥0.06, large ≥0.14.

TABLE 7 Comparison of differences in maximum strength measurements and muscular endurance parameters over time between groups.

Parameters	Group	Pre test $\bar{X} \pm$ SS	Post test $\bar{X} \pm$ SS	Group × time interaction		
				F	p	η^2
Leg Extension (kg)	Experimental Group	83.93 ± 4.87	96.07 ± 4.01	**40.798**	**0.001***	**0.611**
	Control Group	85.71 ± 4.75	91.43 ± 4.82			
Leg Curl (kg)	Experimental Group	99.29 ± 7.81	118.21 ± 5.04	3.209	0.085	0.110
	Control Group	81.43 ± 6.02	95.36 ± 6.34			
Bench Press (kg)	Experimental Group	66.43 ± 6.91	87.14 ± 4.69	**42.892**	**0.001***	**0.623**
	Control Group	76.79 ± 3.17	83.57 ± 2.34			
Assist. Pull Up (kg)	Experimental Group	53.93 ± 5.25	68.21 ± 5.04	**8.320**	**0.008***	**0.242**
	Control Group	53.57 ± 3.06	62.14 ± 2.57			
Push Up (30 s)	Experimental Group	24.66 ± 2.53	27.04 ± 0.81	1.825	0.188	0.066
	Control Group	22.67 ± 1.16	24.13 ± 0.83			
Sit Up (30 s)	Experimental Group	19.21 ± 0.97	23.36 ± 1.28	**11.851**	**0.002***	**0.313**
	Control Group	19.71 ± 1.68	21.86 ± 1.23			

*$p < 0.05$; η2: small >0.01, medium ≥0.06, large ≥0.1.

the Experimental group (d = 4.79) and large effects for the Control group (d = 1.77). The intervention's effect on body fat percentage was particularly striking, with near-perfect improvements for the Experimental group (d = 5.87) and very large effects for the Control group (d = 3.74). In terms of muscular strength and endurance, as presented in Table 5, both groups experienced substantial gains. The Experimental group saw very large effects in leg extension (d = 2.72), bench press (d = 3.51), and assisted pull-up (d = 2.77) performance, while the Control group showed large to very large effects across the same parameters (d = 1.20 for leg extension, d = 2.43 for bench press, and d = 3.03 for assisted pull-up). Notably, the 30-s sit-up test also revealed a very large effect for the Experimental group (d = 3.65) and large effects for the Control group (d = 1.46), further confirming the intervention's positive impact on muscular endurance. Table 6 presents the results from the repeated measures two-way ANOVA test, which showed statistically significant differences between the groups over time in all physiological characteristics, with the exception of body weight ($p < 0.05$). Similarly, Table 7 shows that significant differences were observed over time in maximum strength measurements and muscular endurance performance, specifically in leg extension, bench press, assisted pull-up, and sit-up performance ($p < 0.05$). These findings collectively suggest that the intervention had a robust and sustained impact on both body composition and muscular performance, with particularly notable improvements in the Experimental group across all measured parameters.

These results suggest that FST can lead to positive changes, especially in strength improvements in both the lower and upper extremities, muscular endurance, and body composition in elite field hockey players. These findings are consistent with previous studies that report positive effects of functional training on overall motor skill performance (Bashir et al., 2024; Feito et al., 2018).

Biomechanical and neuromuscular adaptations affecting muscle strength

From the perspective of exercise physiology, the strength gains reflecting adaptive responses of the neuromuscular system to applied resistance must be considered within the framework of resistance training-specific adaptation mechanisms. The effects of resistance training on strength gains are explained by increases in motor unit activation, muscle fiber hypertrophy, and neuromuscular efficiency (Aagaard et al., 2002).

It is known that in the early stages of training, strength gains are primarily associated with neural adaptations, while muscle fiber hypertrophy contributes to the process over a longer period (Enoka and Duchateau, 2015; Schoenfeld, 2010). In this process, the increase in synaptic activity at supraspinal centers, strengthening of corticospinal pathways, and improvements in motor unit synchronization are part of the neural adaptation mechanisms of resistance training (Behm et al., 2015). Furthermore, mechanical tension created by high-intensity loads not only leads to increases in maximal and explosive strength (Balshaw et al., 2022; Maden-Wilkinson et al., 2021) but also activates the mTOR pathway to stimulate muscle protein synthesis, particularly leading to hypertrophy in type II muscle fibers (Robinson et al., 2024; Haff and Triplett, 2016; Markovic and Mikulic, 2010; Zemková and Zapletalová, 2022; Gonzalo-Skok et al., 2022; Zhang et al., 2023; Carvalho et al., 2014; Hoffman, 2019; Nagahara et al., 2024; Andersen and Aagaard, 2010; Fry, 2004; Tortu et al., 2024; West et al., 2013; Montgomery, 2006; Santos et al., 2014; Schoenfeld, 2013). In this context, FST may accelerate neuromuscular adaptations by placing more mechanical load on the musculoskeletal system through dynamic, multi-joint movements, thereby contributing to increased strength production (Haff and Triplett, 2016; Markovic and Mikulic, 2010). FST has been shown to trigger a broader spectrum of neuromuscular adaptations by supporting motor unit activation and intramuscular coordination mechanisms (Haff and Triplett, 2016). The findings of the present study also indicate that FST positively impacts strength gains by improving muscle activation dynamics, which is consistent with previous studies in the literature (Xiao et al., 2025; Hovsepian et al., 2021).

The application of strength gains to functional performance is as crucial as the development of strength itself. According to the Joint-by-Joint Model, strengthening core muscles can improve force transfer between the lower and upper extremities by enhancing postural stability (Zemková and Zapletalová, 2022). This process can lead to optimal performance gains by mobilizing the produced force more efficiently. Unilateral exercises, which activate stabilizing muscles to a greater extent, may play an important role in force transfer (Gonzalo-Skok et al., 2022; Zhang et al., 2023). Although core stabilization and motor unit activation were not directly measured in this study, the significant strength increases observed in both extremities suggest that unilateral exercises may contribute to functional force transfer. Furthermore, given the literature indicating that FST supports acceleration, sprinting, and reactive force development (Carvalho et al., 2014; Hoffman, 2019), the strength increases identified in this study may support potential improvements in speed and explosive strength skills. However, since sprinting and explosive strength were not directly measured in this study, future research should include measurements such as sprint duration, reactive force (RFD), and vertical jump to clarify their effects on sprint performance and agility. This highlights the need for comprehensive studies to enhance explosive strength skills in field hockey players, who frequently reach high speeds (Andersen and Aagaard, 2010).

Muscle fiber type transformation and endurance performance

Fast-twitch muscle fibers (Type II, particularly MyHC IIX) have a high force production capacity but are limited in endurance (Fry, 2004; Tortu et al., 2024). However, Type IIA fibers optimize both strength and endurance capacities, contributing to versatile performance (Fry, 2004; Tortu et al., 2024; West et al., 2013). High-intensity methods with short rest intervals, such as FST, can trigger the transformation of MyHC IIX to MyHC IIA, thereby enhancing muscles' ability to generate quick force and sustain endurance (Hoffman, 2019). This adaptation can provide an advantage in sports like field hockey, which involves variable tempo. However, since muscle fiber types were not directly measured in this study, further research is needed to verify the effects of this transformation process.

Explosive force production and its sustainability are supported by the ATP-PC and anaerobic glycolysis systems (West et al., 2013). FST may stimulate metabolic power, muscle mass, and anaerobic capacity development (Montgomery, 2006).

In field hockey, considering the high-volume running demands of midfield players (Hoffman, 2019; Nagahara et al., 2024), these adaptations can enhance both explosive strength and endurance (Andersen and Aagaard, 2010). The significant increase in muscular endurance observed in the 30-s push-up and 30-s sit-up tests is consistent with findings in the literature. Although the physiological process described could explain the results of this study, it requires further investigation through aerobic endurance and sprint performance field tests for a more comprehensive evaluation.

Body composition

Studies on body composition show that modern athletes have higher body mass indices than their predecessors, a change associated with genetic proficiency, improvements in training methodologies, nutritional approaches, and the evolution of sports dynamics (Santos et al., 2014). This change, reflecting an increase in muscle mass and a decrease in body fat percentage, is emphasized as advantageous in many sports (Schoenfeld, 2013). Research indicates that high body fat percentage negatively correlates with VO_2max and endurance and may lead to lower scores in tests such as the

30 m sprint and vertical jump (Sharma et al., 2023). While low body fat percentage provides an advantage for overall performance, high muscle mass increases Peak Power (PP) and Mean Power (MP) values, but excessive lean mass and muscle mass may negatively affect endurance due to increased oxygen consumption (Stanforth et al., 2014). According to the body composition results of this study, FST has a substantial impact on reducing body fat percentage and improving BMI in elite field hockey players. Similar results reported in studies with field hockey players (Stewart and Sutton, 2012; Suchomel et al., 2016) show that FST-based training programs promote fat loss alongside increased lean body mass (LBM), leading to improvements in balance, coordination, speed, and agility. Our findings emphasize the positive correlation between body composition and athletic performance, which is supported by the literature. However, further laboratory-based physiological measurements are needed to confirm the reliability of these results.

Conclusion

This study provides a significant contribution to the literature, as it is one of the few that investigates the effects of FST on the physical performance of elite field hockey players. The results demonstrate the positive effects of FST on muscle strength, muscular endurance, and body composition in these athletes. The findings suggest that FST could be an effective method for enhancing physical performance in field hockey. However, additional field-based research including specific tests on speed, acceleration, and agility is needed to determine its effect on these performance metrics. Coaches and sports scientists may consider FST as a means to regulate metabolic processes through aerobic and anaerobic loading techniques, thus contributing to fundamental motor skills and aligning these gains with sport-specific demands.

Practical applications

FST requires movement control and stabilization in both unison and bilateral movements. Therefore, it is highly recommended for the development of strength in the lower and upper extremities. Based on the findings of this study, FST is a practical approach for improving fitness, strength, endurance, and body composition. It can be incorporated into field hockey training programs to optimize the effects of strength development and improve overall physical performance, particularly in strength training exercises. Moreover, given its adaptability to different fitness levels, FST can be customized to meet individual training requirements and be used in daily training for elite athletes. Future research should examine FST's effects on other performance metrics such as sprint time, vertical jump, and agility, and its implementation in long-term training plans.

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 Ethical approval was obtained from the Health Sciences Ethics Committee of Çankırı Karatekin University, with the application submitted under meeting number 12/ on March 19, 2024 (Decide:12). Participants provided informed consent, which included comprehensive details about the research, associated risks, potential benefits, confidentiality measures, and participant rights. The study strictly adhered to the ethical principles outlined in the Declaration of Helsinki, ensuring the protection of participants' rights and well-being throughout the design, procedures, and confidentiality measures. All stages of this study complied with the Helsinki guidelines for human research and met the current ethical standards in Sport and Exercise Science.

Author contributions

ACG: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. ME: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. SA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. TA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. MT: Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing, Conceptualization. MS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. MM: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review and editing. MuS: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review and editing. BK: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review and editing. İÖA: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review and editing. HK: Conceptualization, Formal Analysis, Funding acquisition, Methodology, Resources, Software, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2025.1536885/full#supplementary-material

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Additional jump interval training as a form of warm-up on enhancing aerobic capacity, muscular strength, and power in female dancers: a cohort study

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Objectives: This study aimed to compare the effects of jump interval training (JIT) as a supplement to a warm-up with a control group that continued their regular warm-up routine, on the development of aerobic capacity, maximal isometric strength, and vertical jump power in female dancers over a 6-month period.

Methods: Fifty-five female sport dancers (aged 16.2 ± 0.9 years) were monitored throughout the 6 months, with evaluations conducted at baseline, 3 months, and 6 months. Aerobic capacity was assessed using the multistage fitness test (MFT), while muscular assessments included squat jump (SJ), countermovement jump (CMJ), and isometric mid-thigh pull test (IMTP) measured on force platforms. The participants were analyzed into two cohorts: one group adhered to the JIT warm-up, which involved three sets of 30-s bilateral squat jumps during the potentiation phase, while the control group (TWU) performed ballistic dance movements emphasizing explosive techniques, such as rapid leaps and forceful limb movements, in the same phase.

Results: After 6-months, significant differences were observed between groups in IMTP ($F = 8.702$; $p = 0.005$; $d = 0.796$, moderate effect size), SJ ($F = 5.454$; $p = 0.023$; $d = 0.637$, moderate effect size), CMJ ($F = 5.921$; $p = 0.018$; $d = 0.659$, moderate effect size), and MFT ($F = 52.370$; $p < 0.001$; $d = 1.950$, large effect size).

Conclusion: The study concludes that incorporating JIT exercises into warm-up routines significantly enhances aerobic capacity and muscular performance over 6 months, with early improvements in aerobic capacity and noticeable benefits in muscular performance such as SJ peak force, CMJ peak power, and IMTP peak force after three and 6 months. This study contributes to the field as one of the few that demonstrates the relevance and practicality of integrating microdosing (i.e., small but intensive JIT sessions throughout the week) into dance warm-up routines.

KEYWORDS

physical exercise, physical fitness, high-intensity interval training, microdosing, youth

Introduction

Female dancers face physical demands that require exceptional cardiovascular and muscular capabilities. The complex and intense choreography and dynamic movements of dance routines require high levels of aerobic capacity, enabling sustained performance without compromising technique or expression (Liiv et al., 2014). Studies suggests that dancers with enhanced aerobic capacities exhibit superior endurance and recovery, crucial for maintaining peak performance throughout rehearsals and performances (Smol and Fredyk, 2012; Angioi et al., 2009). Additionally, high-intensity interval training is recommended for dancers seeking to improve their aerobic capacity to meet these demands (Rodrigues-Krause et al., 2015). Alongside cardiovascular endurance, muscular strength and power are also essential for dance performance. These attributes are critical for executing explosive movements and achieving the agility required in dance (Uzunovic et al., 2010). Dancers with well-developed muscular strength and power demonstrate improved balance, and stability, which are indispensable for mastering dance movements (Long et al., 2021).

As part of dance training routines, incorporating warm-up exercises is of particular importance. For example, a study examining the effects of different stretching warm-up strategies in dancers found that combined stretching significantly improved balance, vertical jump height, and both pre-stretch and post-stretch range of motion (Morrin and Redding, 2013). When comparing stretching to dynamic warm-ups, a study conducted on dancers revealed that both types of warm-up routines led to similar improvements in range of motion (ROM) and motor abilities; however, it was noted that dynamic warm-ups slightly enhanced motor abilities more than stretching (Zaggelidou et al., 2023). In addition to performance benefits, neuromuscular warm-ups have been found to potentially offer protection against overuse injuries in dancers, according to findings from a 2-year prospective cohort study (Kaufmann et al., 2022).

Warm-up strategies can be optimized by incorporating microdosing of specific training interventions that can impact long-term physical fitness adaptations. For example, in physical education classes, incorporating additional core stability exercises into warm-ups enhanced muscular endurance, movement capability, flexibility, and balance (Chang et al., 2020). In wrestlers, it was observed that incorporating a dynamic stretching warm-up intervention over a 4-week period led to positive long-term adaptations in power, strength, muscular endurance, anaerobic capacity, and agility performance (Herman and Smith, 2008).

While warm-up strategies vary, it is widely accepted that the warm-up can be structured into four phases, following the RAMP strategy (Raise, Activate, Mobilize, Potentiate) (Jeffreys, 2017). The RAMP strategy consists of four phases: Raise—gradually increasing heart rate and body temperature through light aerobic activity; Activate—engaging specific muscles with dynamic movements to prepare them for the demands of the activity; Mobilize—improving joint range of motion through dynamic stretching; and Potentiate—performing sport-specific, high-intensity drills to optimize performance before the main activity (Jeffreys, 2017). During the Potentiate phase, the goal is to increase physiological and neuromuscular stress (McGowan et al., 2015), which can be leveraged to introduce microdosing of a training intervention. This approach may not only impact the immediate response to the session but also lead to long-term adaptations, similar to those seen with ballistic movements, for instance (Johnson et al., 2019).

Considering that dancers may benefit from enhancing aerobic capacity and muscular adaptations, strategies that target both aspects can be particularly promising for long-term improvements in their performance. One potentially beneficial approach is jumping interval training (JIT) (Kramer et al., 2019; Ache-Dias et al., 2016), which involves short bursts of high-intensity jumping exercises interspersed with brief periods of rest or lower-intensity activity. This training modality utilizes jumps as a primary exercise component and follows to the principles of high-intensity interval training, aiming to effectively engage muscles through dynamic and intense movements (Kramer et al., 2019; Ache-Dias et al., 2016). Scientific evidence supports that JIT can enhance cardiovascular fitness due to its high-intensity heart rate stimulus and the increased physiological demands that promote cardiovascular adaptations (Ma et al., 2024). Additionally, JIT not only improves aerobic capacity but also stimulates neuromuscular adaptations crucial for enhancing muscular strength and power (Ma et al., 2024). This is likely due to the repeated bouts of multiple jumps, which require reactive strength and contribute to improved muscular endurance.

Despite the importance of enhancing aerobic capacity and muscular strength and power, such as maximal strength or vertical jump, research investigating the impact of training on these characteristics in dancers is limited (Sanders et al., 2020; Roussel et al., 2014). Furthermore, there is a lack of research on how warm-up protocols, specifically incorporating small yet consistent doses of interventions like JIT, could be relevant for dancers. This type of analysis could identify approaches that minimize intervention time and optimize strategies to enhance physical fitness without disrupting the core content of dance sessions, which typically focus more on technical elements and choreography. Despite its potential, no study to date has tested JIT as a complementary approach for dancers, specifically as a supplement to warm-up routines, creating a gap that can be addressed.

Considering the significance and innovative approach of this study, the aim was to compare the effects of JIT as a supplement to a warm-up with a control group of dancers who continued their regular warm-up routine, on the development of aerobic capacity (measured by the multistage fitness test, MFT), muscular strength (assessed by the isometric mid-thigh pull test, IMTP), and power (measured by squat jump, SJ, and countermovement jump, CMJ) in female dancers over a 6-month period.

Methods

Study design

This study consisted in a prospective cohort design to monitor dancers' development of aerobic capacity, muscular strength, and power over a period of 6 months, with assessments conducted three times (baseline, 3-month and 6-month). The participants were classified into two cohorts: one group (JIT) incorporated a JIT micro-intervention within their warm-up protocol, while the other group (TWU) continued with their regular warm-up routines. Participants were enrolled based on their willingness to participate, with those expressing interest in the warm-up supplemented with JIT included in that group, while those who did not opt for JIT continued with their regular routines. The study followed the STROBE guidelines for reporting cohort studies (Cuschieri, 2019).

Setting

The study lasted 6 months, with evaluations consistently conducted under the same conditions (i.e., during the first training session of the week, in the afternoon, and following the same sequence). Assessments took place in three dance academies, with evaluations at baseline, 3 months, and 6 months all performed at the same location to ensure replicability of the conditions. The dance classes offered included ballet, folk dance, and hip hop. All participants were recreational dancers with an intermediate skill level. The recruitment process took place over 3 weeks prior to the baseline assessment. It involved reaching out to the dance academy directors and inviting participants and their parents to join the study.

Participants

The inclusion criteria for participants were as follows: (i) being female; (ii) aged between 15 and 18 years; (iii) not having injuries or severe illnesses that could compromise adherence to training sessions or cause them to miss evaluation periods; (iv) participating in at least 85% of the total training sessions scheduled by their academies; (v) not participating in any other training programs besides dance at their academies; and (vi) having more than 2 years of dancing experience. Exclusion criteria included: (i) participants who changed their cohort participation (e.g., switched from JIT to control or *vice versa*); (ii) missing any of the evaluations (i.e., instances where participants did not complete one or more of the scheduled assessments due to personal reasons, scheduling conflicts, or other unforeseen circumstances); (iii) declaring participation in additional training programs outside the regular sessions conducted by the academies; (iv) missing more than 15% of the overall training sessions scheduled during the observational study period.

After recruiting participants by directly contacting dance academies and reaching out to volunteers and their legal guardians through public announcements, we found a total of 62 participants. Based on the eligibility criteria, 5 participants were excluded before the baseline assessment: 3 were <14 years old and 2 had lower limb injuries. No participants were excluded due to attendance criteria or missing evaluations. During the follow-up, two additional participants were excluded due to leaving the dance academy for personal reasons. Consequently, 55 participants were successfully monitored from the baseline to the final evaluation (6-month mark). Among these participants, 26 voluntarily adhered to the JIT warm-up and continued with this option throughout the observation period, while the remaining 29 continued their traditional warm-up routines.

Overall (n = 55), the participants had average measurements of 16.2 ± 0.9 years, 1.59 ± 0.03 m in height, 50.3 ± 2.3 kg in body mass, and 19.8 ± 0.6 kg/m^2 in body mass index. Dancers adhering to JIT (n = 26) had average measurements of 16.2 ± 0.9 years, 1.60 ± 0.03 m, 50.7 ± 2.0 kg, and 19.9 ± 0.7 kg/m^2. Dancers in TWU (n = 29) had average measurements of 16.1 ± 0.8 years, 1.59 ± 0.03 m, 49.9 ± 2.5 kg, and 19.8 ± 0.5 kg/m^2. All sport dancers trained two to three times per week, with each session lasting between 80 and 110 min. They were classified as sport dancers based on the Participants Classification Framework (McKay et al., 2022), which defines them as trained/developmental dancers who attend classes three times a week and occasionally participate in competitions. The participants were at an intermediate level, having some prior dance experience but still in the process of refining their skills. Specifically, all participants had a minimum of 2 years of practice and had been introduced to the core techniques of the dance style. However, most were not competitive dancers and had not yet reached a level of proficiency free from technical errors. As such, all participants were still actively developing their technical skills in classes focused on improvement.

The Ethical Evaluation of Human Experiment of Guangzhou Sport University granted approval for this study (2024LCLL-92). Participants and their legal guardians received information regarding the study's procedures, potential benefits, risks, and the voluntary nature of their involvement. Informed consent was obtained from the legal guardians of participants under 18 years old, with each guardian signing a consent form to confirm voluntary participation. For participants aged 18 and over, they themselves signed the informed consent form. The research adhered to the ethical standards set forth in the Declaration of Helsinki.

Variables

The participants were classified into two cohorts: those who adhered to JIT warm-up and those who maintained TWU. This classification served as the independent variable in the study. As background, dance academy instructors had proposed a new warm-up routine (including JIT) to replace the traditional phase of ballistic technical elements that typically followed mobilization exercises. Under this new approach, the warm-up consisted of three phases in RAMP, with identical structure across all participants, except for the potentiation phase (fourth phase), which varied (JIT vs. control).

Although the warm-up content could vary over time, it was standardized across all participants except for the final phase. In the potentiation phase, participants adhering to JIT performed three sets of 30-s bilateral repeated squat jumps at a pace of 1.0 jump per second, interspersed with 30 s of rest. This routine was performed during all dance sessions (approximately 2–3 times per week). Conversely, participants in the TWU group maintained a potentiation phase involving ballistic dance movements (e.g., leaping Jump; saut de basque; Popping; fan dance leaps) emphasizing explosive techniques, such as rapid leaps and forceful limb movements. Slight variances were observed across the different academies, and to ensure consistency, an observational record was kept, showing similar trends in the selected movements.

The dependent variables in this study included peak vertical force in the isometric mid-thigh pull test (IMTP), peak force in the squat jump test (SJ), peak power in the countermovement jump test (CMJ), and total distance covered in the multistage fitness test (MFT). The relevance of studying these variables lies in their ability to assess key components of physical performance that are critical for dancers. The IMTP and SJ measure strength, which is fundamental for stability, control, and power in dance movements (Angioi et al., 2009). The CMJ reflects explosive movement ability, essential for jumps and rapid directional changes in dance (Blanco et al., 2021). Finally, the MFT provides insight into aerobic capacity, crucial for endurance during extended dance sessions (Redding and Wyon, 2003).

Procedures of assessment

The female dancer underwent three assessments: baseline, after three and 6 months. The evaluations were conducted under consistent conditions, specifically during the first training session of the week, following 48 h of rest. The same assessors evaluated all the athletes across all dance academies and time points, ensuring consistent evaluation conditions. The anthropometric measurements (height and body mass, collected only at baseline to characterize the participants) and muscular assessments took place in the afternoons within a room maintained at 22°C with a relative humidity of 50%. The aerobic capacity test was conducted into an indoor facility.

On evaluation day, participants first provided demographic information (age, years of experience, type of dance) and underwent anthropometric measurements (height and body mass). They then followed a standardized warm-up protocol, which included 5 min of moderate intensity jogging into the indoor facility, followed by dynamic stretching exercises for the upper limbs (7 min) and lower limbs (7 min). After dynamic stretching, participants performed reactive jumps and landing movements to prepare for the evaluations.

After 3 min of completing the warm-up, all participants followed the same sequence of evaluations: (i) isometric mid-thigh pull test (IMTP), (ii) squat jump test (SJT), (iii) countermovement jump test (CMJ), and (iv) multistage fitness test (MFT). Each muscular test included two trials interspaced by 3 min of rest. Before the recorded trials, participants completed a familiarization trial to ensure they understood the correct movements for each test. A 5-minute rest period was provided between each test.

Isometric mid-thigh pull test

For the IMTP assessment, athletes adopted a standardized power-pulling stance as recommended in previous studies, with knee angles set between 130° and 140° and hip angles at 145° (Comfort et al., 2015). The bar height was adjusted to half the distance between the greater trochanter and the lateral epicondyle of the knee, using a goniometer for precise alignment within acceptable ranges (Merrigan et al., 2020). The bar was secured firmly in place to eliminate any slack. Wrist straps were used to secure the athletes' hands to the bar, standardizing grip force and ensuring consistency in the measurements (Merrigan et al., 2020). Participants were instructed to apply maximum force on the bar for 3 seconds, focusing on explosive upward movement. The tests were conducted on a force platform (Quattro Jump, Kistler, Winterthur, Switzerland), with the average peak vertical force calculated from two trials used for subsequent data analysis.

Squat jump test

Participants performed an unloaded squat jump, selecting their preferred foot position. This position was measured and standardized to ensure consistency across all tests, in accordance with previous protocols (Sheppard and Doyle, 2008). Starting from a squat position at a self-determined comfortable depth with hands on their hips, they were instructed to jump with maximal effort. They aimed to extend their knees powerfully and land smoothly on the force platform with both feet simultaneously. Peak force (N) was recorded for each trial, and the average was used for subsequent data analysis.

Countermovement jump test procedures

Participants performed the traditional CMJ test, beginning from a standing position on the force platform, in accordance with previous protocols (Owen et al., 2014). Following instructions, they initiated the jump by swiftly descending into a comfortable partial squat through hip and knee flexion. This was immediately followed by an explosive extension of the hips, knees, and ankles to achieve maximum vertical height, with hands kept on the hips throughout the movement. Participants were instructed to keep their knees extended while in the air and to land smoothly on both feet simultaneously. Peak power (W/kg) were recorded for each trial, and the averages were used for subsequent data analysis.

Multistage fitness test

The MFT, also known as the 20 m shuttle run test, was implemented based on Leger's original work (Léger et al., 1988). The test comprised 23 levels, with each level lasting approximately 1 minute. The starting speed was 8.5 km/h and increased by 0.5 km/h at each subsequent level. During the test, a single beep indicated the end of each shuttle, while three simultaneous beeps indicated the start of the next level. If an athlete failed to reach the opposite "turn-around" line before the beep, they were issued one failed attempt. If they failed two consecutive attempts, they were withdrawn from the test, and their score was recorded as final. However, if the individual reached the line before the second consecutive beep, their failed attempts were reset. The total distance completed (m) before participants gave up or were excluded was considered the main outcome of the test.

Study size

Before starting the research, the sample size was calculated using G*Power software. To achieve a power of 0.85 and an effect size (f) of 0.2 for two groups measured at three different time points, a total of 48 participants was recommended for the repeated measures ANOVA.

Statistical methods

To compare the two cohorts (JIT and TWU) across three time points, a mixed ANOVA was employed, allowing for the examination of interactions between groups and evaluation moments. The assumptions of normality and homogeneity were verified using the Kolmogorov-Smirnov test ($p > 0.05$) and Levene's test ($p > 0.05$), respectively. Post hoc analyses were performed using the Bonferroni test to compare pairs of time points (baseline, 3 months, and 6 months), with partial eta squared employed to measure the effect size. Moreover, the standardized effect size (Cohen's d) was used for pairwise comparisons, following the thresholds (Hopkins et al., 2009): 0.0–0.2 for trivial ES, 0.2–0.6 for small ES, 0.6–1.2 for moderate ES, and >1.2 for large ES. All statistical analyses were performed with IBM SPSS Statistics (Version 27.0, IBM Corp., Armonk, NY), with significance set at $p < 0.05$.

Results

Table 1 presents the descriptive statistics for muscular performance outcomes and aerobic capacity across the groups. Figure 1 illustrates the variations in physical fitness outcomes between the two groups.

Significant interactions were found between groups and the time in regards the IMTP ($F = 27.750$; $p < 0.001$; partial eta squared = 0.344), SJ ($F = 15.777$; $p < 0.001$; partial eta squared = 0.229), and MFT ($F = 42.184$; $p < 0.001$; partial eta squared = 0.443).

The within-JIT analysis revealed significantly higher IMTP values after 6 months compared to baseline (mean difference: 93.2 N; $p < 0.001$) and after 3 months (mean difference: 88.7 N; $p < 0.001$). Similarly, within-TWU, higher IMTP values were observed after 6 months compared to the 3-month evaluation (mean difference: 31.7 N; $p < 0.001$).

Regarding the SJ, significantly greater values were observed after 6 months compared to baseline (mean difference: 25.7 N; $p < 0.001$) and after 3 months (mean difference: 19.9 N; $p < 0.001$) in the JIT group. Additionally, in the TWU group, the 3-month evaluation showed significantly lower SJ values compared to baseline (mean difference: 13.3 N; $p = 0.004$) and after 6 months (mean difference: 11.2 N; $p < 0.001$).

The within-JIT analysis revealed significantly higher CMJ values after 6 months compared to baseline (mean difference: 2.7 W/kg; $p < 0.001$) and after 3 months (mean difference: 2.2 W/kg; $p < 0.001$). Similarly, within the TWU group, higher CMJ values were observed after 6 months compared to the 3-month evaluation (mean difference: 1.8 W/kg; $p < 0.001$), and baseline values were also significantly higher than those at the 3-month assessment point (mean difference: 1.4 W/kg; $p < 0.001$).

Regarding the MFT, significantly greater values were observed after 6 months compared to baseline (mean difference: 153.8 m; $p < 0.001$) and after 3 months (mean difference: 33.8 m; $p < 0.001$) in the JIT group. Additionally, in the TWU group, the baseline evaluation showed significantly lower MFT values compared to after 3 months (mean difference: 46.9 m; $p < 0.001$) and after 6 months (mean difference: 75.2 m; $p < 0.001$), and after 6 months values were also significantly higher than those at the 3-month assessment point (mean difference: 28.3 m; $p < 0.001$).

In the baseline, no significant differences were observed between groups in IMTP ($F = 1.485$; $p = 0.228$), SJ ($F = 0.984$; $p = 0.326$), CMJ ($F = 17.930$; $p < 0.001$), CMJ ($F = 0.110$; $p = 0.741$), and MFT ($F = 0.122$; $p = 0.728$).

In the 3-month evaluation significant differences were found between groups in SJ ($F = 4.236$; $p = 0.044$), CMJ ($F = 4.371$; $p = 0.041$), and MFT ($F = 52.390$; $p < 0.001$), although no significant differences were observed between groups in IMTP ($F = 3.243$; $p = 0.077$).

After 6-months, significant differences were observed between groups in IMTP ($F = 8.702$; $p = 0.005$), SJ ($F = 5.454$; $p = 0.023$), CMJ ($F = 5.921$; $p = 0.018$), and MFT ($F = 52.370$; $p < 0.001$).

Discussion

Our cohort study found that, after the third month, the increases in aerobic capacity, SJ peak force, and CMJ peak power were significantly greater in the JIT cohort compared to the TWU cohort. Additionally, at the 6-month evaluation, the JIT cohort exhibited significantly greater maximal strength in the IMTP compared to the TWU cohort. The significant differences in the other outcomes observed at the third month persisted similarly through the 6-month period.

It was observed that JIT significantly contributed to enhancing aerobic capacity, resulting in consistent improvements that became significantly different from TWU after the 3-month evaluation. Our results align with a previous study which found that 3 weekly sessions over 6 weeks of JIT significantly enhanced absolute maximal aerobic capacity, though not the relative measure (Venegas-Carro et al., 2023). Additionally, our findings are consistent with a study conducted on gymnasts, which revealed significant improvements in MFT after 8 weeks in the JIT group (Ma et al., 2024).

As a form of high-intensity interval training that uses jumping as the modality, this type of exercise can induce cardiovascular improvements, including increased stroke volume and cardiac output (Engel et al., 2018). The repetitive and intense nature of jumping interval training (JIT), which often involves spending a significant amount of time above 90% of maximal oxygen uptake (Kramer et al., 2019), likely stimulates greater capillary density within skeletal muscles, enhancing oxygen delivery (Jacobs et al., 2013). It is also hypothesized that, similar to other high-intensity interval training methods, small dose JIT may promote mitochondrial biogenesis (Little et al., 2010), enhancing mitochondrial density and efficiency and improving oxidative phosphorylation. The use of jumping is particularly relevant, as it aligns with the types of movements promoted by the dance styles analyzed, thereby increasing the specificity of the training while providing an effective and time-efficient aerobic stimulus.

Our study also found that after a 3-month evaluation, the cohorts showed significant differences in squat jump (SJ) peak force and countermovement jump (CMJ) peak power. These results align with previous studies, such as one that used JIT three times a week over 4 weeks in recreational runners, which

TABLE 1 Descriptive statistics (mean ± standard deviation) of the muscular performance outcomes and aerobic capacity between groups.

	JIT (n = 26)	TWU (n = 29)	JIT vs. TWU Mean difference	JIT vs. TWU *p*-value	JIT vs. TWU Effect size (d)
IMTP (N)					
Baseline	1887.4 ± 166.8$^{£}$	1830.2 ± 179.9	57.2	$p = 0.228$	0.330
3-month	1891.8 ± 176.9$^{£}$	1807.6 ± 169.8$^{£}$	84.2	$p = 0.077$	0.486
6-month	1980.5 ± 181.8$^{\#,\$}$	1839.3 ± 173.1$^{\$}$	141.2	$^{*}p = 0.005$	0.796
6-month vs. baseline (d)	0.534, small ES	0.052, trivial ES			
SJ (N)					
Baseline	464.7 ± 64.7$^{£}$	443.7 ± 89.0$^{\$}$	21.0	$p = 0.326$	0.273
3-month	470.5 ± 64.3$^{£}$	430.4 ± 78.7$^{\#}$	40.2*	$^{*}p = 0.044$	0.561
6-month	490.4 ± 68.8$^{\#,\$}$	441.6 ± 84.3	48.8*	$^{*}p = 0.023$	0.637
6-month vs. baseline (d)	0.385, small ES	0.024, trivial ES			
CMJ (W/kg)					
Baseline	34.6 ± 4.0$^{£}$	34.2 ± 4.4$^{\$}$	0.38	$p = 0.741$	0.095
3-month	35.1 ± 4.5$^{£}$	32.8 ± 3.9$^{\#}$	2.36*	$^{*}p = 0.041$	0.548
6-month	37.3 ± 4.6$^{\#,\$}$	34.6 ± 3.6	2.71*	$^{*}p = 0.018$	0.659
6-month – baseline (d)	0.628, moderate ES	0.100, trivial ES			
MFT (m)					
Baseline	1,265.4 ± 43.7$^{\$,£}$	1,261.4 ± 41.4$^{\$,£}$	4.0	$p = 0.728$	0.094
3-month	1,385.4 ± 34.2$^{\#,£}$	1,308.3 ± 43.6$^{\#,£}$	77.1*	$^{*}p < 0.001$	1.982
6-month	1,419.2 ± 42.9$^{\#,\$}$	1,336.6 ± 41.8$^{\#,\$}$	82.7*	$^{*}p < 0.001$	1.950
6-month vs. baseline (d)	3.552, large ES	1.808, large ES			

JIT, jump interval training; TWU, standard warm-up; IMTP, isometric mid-thigh pull test; SJ, squat jump; CMJ, countermovement jump; MTF, multistage fitness test; ES, effect size;*significantly different between groups ($p < 0.05$); $^{\#}$: significantly different from baseline evaluation ($p < 0.05$); $^{\$}$: significantly different from 3-month evaluation ($p < 0.05$); $^{£}$: significantly different from 6-month evaluation ($p < 0.05$).

found increases in jump height and power output of the CMJ (Ache-Dias et al., 2016). Similar improvements in CMJ height were observed after 8 weeks of JIT training in female gymnasts (Ma et al., 2024).

The powerful nature of jumping exercises may stimulate a higher degree of motor unit recruitment and synchronization (Chimera et al., 2004). The repetitive, high-intensity jumps likely enhance neuromuscular efficiency by facilitating more rapid and efficient motor unit firing patterns, which are crucial for generating peak force and power (Behrens et al., 2016). Additionally, JIT may promote adaptations in the muscle-tendon unit due to the repetitive jumps and landings, increasing tendon stiffness (Fouré et al., 2010), which allows for more effective storage and release of elastic energy during dynamic movements. Enhanced intramuscular coordination and the activation of fast-twitch muscle fibers could also explain the greater force production and power output (Komi, 2003). These adaptations may be less prominent in technical ballistic dance movements, which often involve more submaximal, less explosive muscle contractions and do not stimulate the same level of neuromuscular adaptation necessary for maximal power and force production in jumps.

Interestingly, after 6 months, evaluations revealed that the cohorts also became significantly different in terms of IMTP peak force, with those adhering to JIT showing greater force. These results align with previous studies, such as one that used JIT three times a week over 4 weeks in recreational runners, which found increases in knee extensor strength during isometric contraction (Ache-Dias et al., 2016). Another study observed significant improvements in lower limb strength after a 6-week JIT intervention (Venegas-Carro et al., 2023).

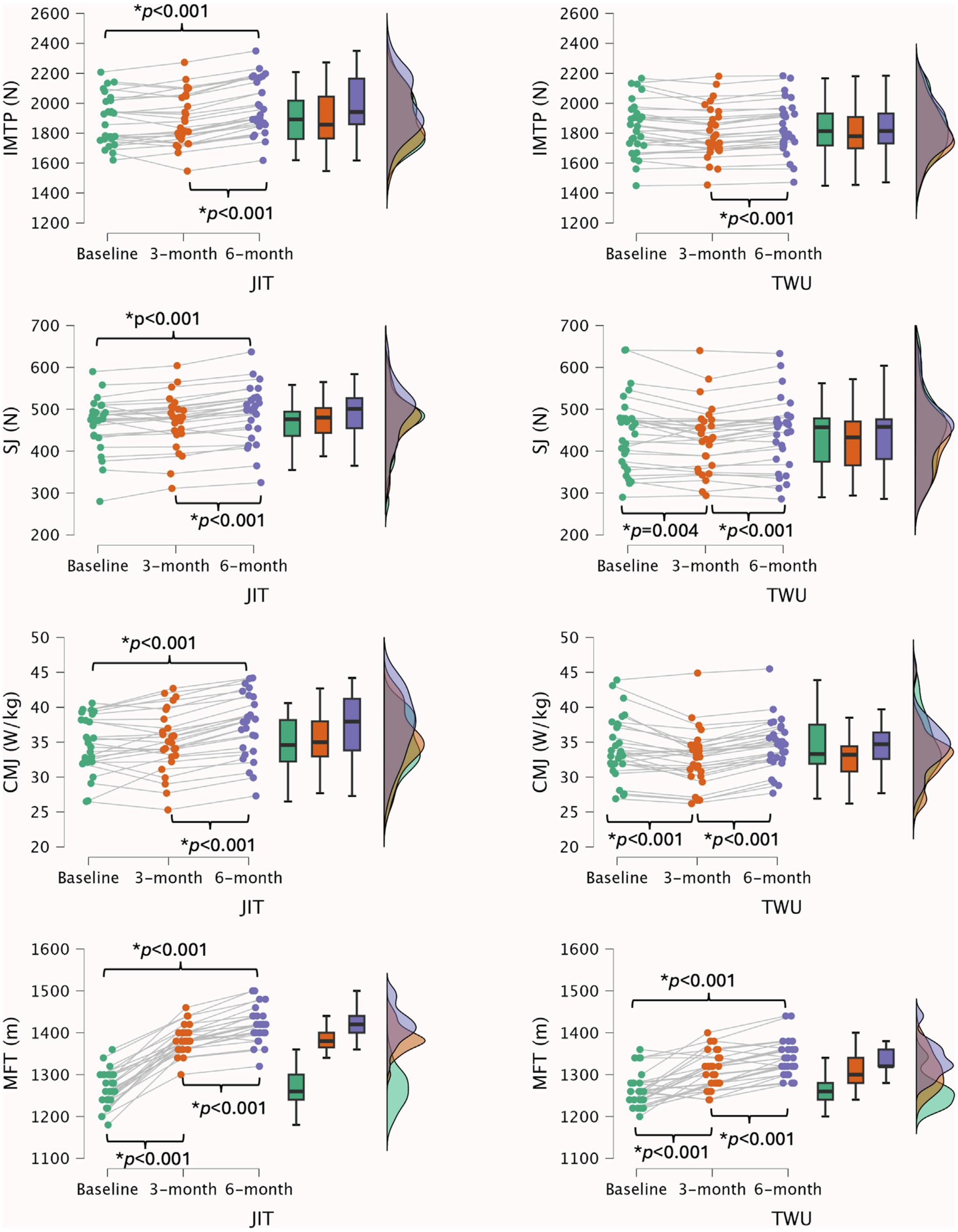

FIGURE 1
Variations in physical fitness outcomes for both groups. JIT, jump interval training; TWU, standard warm-up; IMTP, isometric mid-thigh pull test; SJ, squat jump; CMJ, countermovement jump; MTF, multistage fitness test.*: significantly different (p < 0.05).

The potentially increased firing rates of motor units and enhanced recruitment of fast-twitch muscle fibers (Komi, 2003) following JIT may explain the ability to generate high force outputs in isometric contractions like the IMTP. JIT possibly stimulated adaptations in the central nervous system, improving the capacity to generate force rapidly and efficiently (Davies et al., 2015). These adaptations may include heightened motor cortex excitability and enhanced motor unit synchronization (Ramirez-Campillo et al., 2021), crucial for maximizing peak force production during isometric contractions. In contrast, technical ballistic dance movements typically entail lower-force, rhythmic muscle actions that do not induce the same degree of neuromuscular adaptation required for high-force isometric contractions.

While our study shows interesting findings regarding the benefits of JIT integrated in warm-up on aerobic capacity and muscular performance, some limitations warrant consideration. Firstly, our cohort study design limits causal inference due to the absence of randomization, potentially introducing selection bias. Moreover, integrating different dance styles may have influenced the results, as each style imposes a different workload due to its unique routines and movements. Additionally, the study duration of 6 months may not capture longer-term effects or potential fluctuations in adherence to the exercise protocols. Moreover, we only analyzed female participants, which may limit the generalizability of the findings to males. Finally, confounding factors such as diet, sleep quality, recovery strategies, and general physical activity were not analyzed, all of which may concurrently contribute to the level of adaptations observed. Future research could employ randomized controlled trials with larger sample sizes to enhance generalizability and confirm causality. Moreover, investigating the underlying mechanisms behind JIT-induced improvements, such as mitochondrial biogenesis and muscle fiber adaptations, would provide valuable insights into its physiological effects. Longitudinal studies examining the sustainability of these adaptations beyond 6 months could further elucidate the durability of JIT's benefits.

For dance professors and coaches, our study's findings on JIT present practical implications for enhancing warm-up routines and improving performance outcomes among dancers. Integrating brief sessions of JIT into warm-ups has the potential to enhance aerobic capacity and muscular strength in medium term, which are essential for dance movements that demand explosive power. By incorporating JIT, instructors can target improvements in dancers' aerobic fitness, and overall muscular performance—qualities that are important for executing dynamic and powerful dance routines. For example, coaches can supplement their regular warm-ups (2–3 times a week) with a brief session of three sets of 30-s bilateral squat jumps at a pace of 1.0 jump per second, with 30 s of rest in between. This approach, totaling just 3 min, can promote meaningful adaptations, particularly in recreational dancers, though it may have less impact on those with higher fitness levels.

Conclusion

In conclusion, our cohort study demonstrates that incorporating JIT into warm-up routines significantly enhances aerobic capacity, peak force, and power output compared to TWU, with significant differences emerging after 3 months of training. The JIT cohort showed sustained improvements in squat jump peak force, countermovement jump peak power, and maximal strength, particularly after 6 months. Although the study's design limits causal inferences, the findings suggest that integrating JIT into warm-up routines can effectively enhance both aerobic fitness and muscular performance, providing valuable practical strategies for dancers.

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 Ethical Evaluation of Human Experiment of Guangzhou Sport University, with the assigned code number 2024LCLL-92. 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

QS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing. MW: Investigation, Methodology, Resources, Writing–original draft, Writing–review and editing. YN: Investigation, Methodology, 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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