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Comparison of Plyometric Repeated Sprint and Plyometric Aerobic Training on Physical Performance in Youth Soccer Players

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Abstract

High-intensity interval training (HIIT) and repeated-sprint sets (RSS) are established conditioning methods in soccer, yet their integration with plyometric training among highly trained youth soccer players remains underexplored. This study investigated the effects of an 8-week program combining plyometric training with either RSS (PLYO-RSS) or HIIT (PLYO-HIIT) on physical fitness in young soccer players. Twenty-nine male players (14–15 years) were randomly assigned to PLYO-RSS (n=14) or PLYO-HIIT (n=15). Both interventions lasted 20 minutes per session and replaced part of regular soccer training. Physical fitness assessments included countermovement jump (CMJ), 15-s repeated vertical jumps (15''RJ), five-jump test (5JT), 10 m and 30 m sprint, maximal aerobic speed (MAS), VO₂max, and repeated sprint performance (total sprint time, best sprint, fatigue index). Physiological markers (lactate, rating of perceived exertion, and HRmax) were also monitored. Significant improvements over time were observed in muscle power, sprint speed, aerobic capacity, and repeated-sprint ability ($p \leq 0.001$; $\eta^2 p = 0.339$ – 0.489). However, no main effects or group $\times$ time interaction effects were observed, indicating no evidence of differential responses between the two training modes. In conclusion, integrating plyometric training with either RSS or HIIT effectively enhances

physical fitness in highly trained youth soccer players, offering flexible options for training prescription.

Keywords: High intensity, combination modality, football, elite, young, muscle power

Introduction

Soccer is a physically demanding sport characterized by frequent high-intensity actions, including approximately 15 tackles, 10 headers, repeated 2–4 sprints every ~90 s, and frequent explosive kicks per match [1,2]. Although sprinting comprises only ~3% of match duration, it disproportionately influences decisive game moments and contributes 1–11% of total distance covered [3]. Effective performance in these actions requires integrating muscular power, repeated-sprint ability (RSA), agility, and aerobic capacity, underscoring the need to develop multidimensional physical fitness in youth players.

Single-mode training interventions, such as plyometric exercises, repeated-sprint sets (RSS), and high-intensity interval training (HIIT), have been shown to enhance specific fitness components in youth athletes (Tvrđy et al.). [4] demonstrated the effectiveness of a 6-week training program aimed at developing RSA in U19 soccer players, highlighting the importance of RSA in improving high-intensity performance. Plyometric training improves jump height, sprinting, and change-of-direction performance through adaptations in neuromuscular coordination, motor unit recruitment, and stretch-shortening cycle (SSC) efficiency [5–8]. A systematic review and meta-analysis by Zheng et al. [9] reported that plyometric training significantly enhances jumping, sprinting, and change-of-direction abilities in adolescent soccer players, with moderate improvements in jumping and change-of-direction performance and minor enhancements in sprinting ability. RSS training primarily enhances repeated sprint ability, anaerobic capacity, and fatigue tolerance during high-intensity bouts by promoting phosphocreatine resynthesis, glycolytic enzyme upregulation, and lactate clearance [10,11]. HIIT simultaneously improves aerobic and anaerobic systems, increasing maximal aerobic speed and cardiovascular efficiency [10,11]. For example,

Aloui et al. [12] demonstrated that combining repeated sprints with jump training produced larger improvements in repeated sprint performance than repeated sprints alone in male highly trained youth soccer players ($d = 1.6$ vs. 0.67 ; $p < 0.05$).

Emerging evidence from combined training interventions supports the potential for synergistic adaptations. Liu et al. [13]. In a systematic review and meta-analysis of 13 RCTs, it was reported that plyometric plus sprint training significantly improved repeated sprint ability compared with single-mode training ($g = -0.46$) and regular training ($g = -1.39$), with benefits also evident in youth populations. These enhancements are likely mediated by neurophysiological mechanisms (enhanced motor unit recruitment, firing frequency, and intermuscular coordination), biomechanical adaptations (improved SSC function, tendon stiffness, and force transfer), and metabolic improvements (increased mitochondrial density, oxidative enzyme activity, and buffering capacity). Collectively, these adaptations facilitate greater force generation, rapid deceleration, and efficient transitions during high-intensity actions, which are essential in soccer match play.

Despite the strong rationale for combining plyometric exercises with high-intensity conditioning, no studies have directly compared plyometric training paired with RSS versus HIIT in highly trained youth soccer players. Understanding potential differences in training outcomes is critical for designing time-efficient, sport-specific conditioning programs.

Therefore, the primary aim of this study was to examine the effects of an 8-week training program integrating plyometric exercises with either RSS (PLYO-RSS) or HIIT (PLYO-HIIT) on muscle power, sprint performance, repeated sprint ability, and aerobic capacity in U14 male soccer players. Based on the relevant literature [2,8,14]. We hypothesized that both interventions would produce significant improvements in all performance measures, with potential differences in the magnitude of adaptation depending on the training modality.

Material and Methods

Experimental approach to the study

Participants were randomly assigned to the PLYO-RSS or PLYO-HIIT group using a computer-generated sequence. Randomization was performed using a computer-generated block randomization procedure with allocation concealment ensured by an independent researcher. No stratification was applied because the sample was homogeneous with respect to age (14–15 years) and pubertal status. Throughout the 8-week intervention period, all athletes engaged in two training sessions per week (Figure 1). Consistent with the approach in other studies [15,16], a passive control group was not included in this study because the primary objective was to compare two active, ecologically valid training interventions (plyometric + repeated sprint vs. plyometric + HIIT) that are both widely used in youth soccer practice. Including a passive control group would have been less relevant to the applied context and could have raised ethical concerns by withholding effective training from players during their competitive season. Muscle power (assessed through CMJ, 15''RJ, and 5JT), sprint performance (10m and 30m), Maximal Aerobic Speed (MAS and VO_{2max}), and repeated sprint sets (RSS) performance indicators (TST, BST, and FI) were evaluated before and after the training period. The athletes' body height and mass were measured during the orientation sessions. Primary outcomes were defined a priori as measures of muscle power (CMJ, 15''RJ, 5JT) and sprint performance (10 m and 30 m). Secondary outcomes included aerobic fitness (MAS, VO_{2max}), repeated sprint ability (TST, BST, FI), and physiological markers (lactate, RPE, HRmax). To control the family-wise Type I error rate, related performance variables were analyzed using repeated-measures ANOVA, and Bonferroni corrections were applied for multiple post hoc comparisons. Peak Height Velocity (PHV) was calculated using the age-at-peak-height-velocity prediction equation developed by Moore et al. [17] (Table 1). Consequently, all participants were classified as pubertal, highly trained youth soccer players.

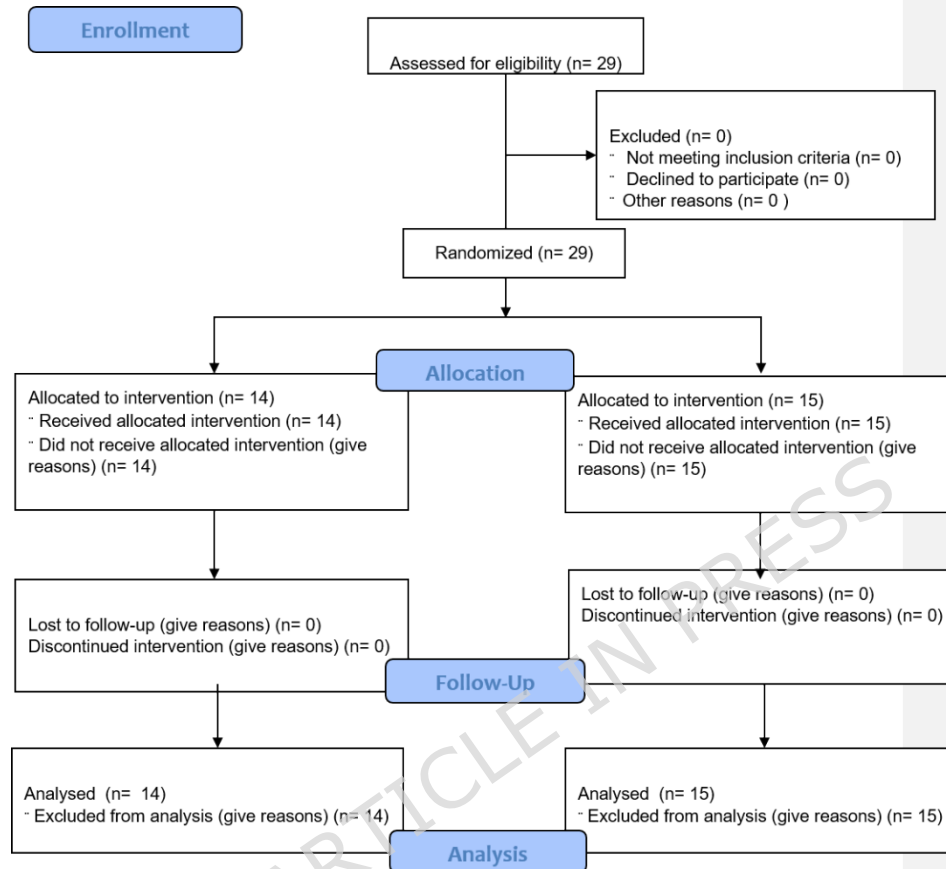


Figure 1: CONSORT Flow diagram of the study design.

Furthermore, all exercises in both groups were performed in a single session, twice a week. Moreover, the players in the PLYO-RSS group were asked to perform sets of plyometric exercises, followed by RSS exercises. Similarly, players in the PLYO-HIIT group executed the same sets/reps of plyometric and high-intensity exercises during the same session. All sessions were separated by a recovery period of 48 hours to avoid fatigue [18]. To minimize the effects of fatigue on explosive movements and injury risk [19] and based on previous strength/plyometric training studies in youth [18,20]. Rest intervals between sets were 3 minutes for each protocol to allow adequate recovery.

Table 1. Anthropometric characteristics of the study participants.

	PLYO-RSS (n=14)	PLYO-HIIT (n=15)	ANOVA p value
Age (yrs)	14.57 (0.26)	14.64 (0.26)	0.67
Height (cm)	167 (5.0)	171 (8.0)	0.58
BM (kg)	62.02 (7.45)	66.38 (5.34)	0.97
BF%	10.51 (1.22)	12.22 (2.35)	0.37
PHV	-0.40 (0.35)	-0.48 (0.27)	0.83

Notes: Values are means and standard deviations (SD); PLYO-RSS = combined plyometric and repeated sprint sets training group; PLYO-HIIT combined plyometric and high intensity training group; BM: body mass; BF%: body fat percent; PHV: peak height velocity.

Participants

In total, 29 male and highly trained U-14 soccer players from a national team of participated in this study (Table 1). The participants had undergone structured soccer training for the preceding four years, participating in four to five 90-minute training sessions per week and playing a competitive match each weekend. The average number of matches played was 19 ± 04 for the PLYO-RSS group and 18 ± 05 for the PLYO-HIIT group. The mean time spent during matches was 70.3 ± 1.2 minutes and 69.2 ± 1.5 minutes for the PLYO-RSS and PLYO-HIIT groups, respectively. It is important to note that all highly trained youth soccer players had regularly performed plyometric, HIIT, and RSS-specific exercises during their soccer training for at least 4 years prior to the start of the study.

According to et al. [21], the training and performance caliber of the participating soccer players can be classified as Tier 3. In other words, the participating players were highly trained and competed regularly at a regional or national level, typically within an organized club or academy structure.

The inclusion criteria included: (i) inclusion in the roster of the national youth team at the commencement of the calendar season, (ii) engagement in a minimum of 80% of matches [22], and (iii) not participating in an alternative training regimen during the study period. Conversely, the exclusion criteria encompassed: (i) players with extended injury periods (three months or longer), (ii) individuals joining the team late in the study season, and (iii)

goalkeepers, owing to the disparate physical demands inherent to outfield players [22].

The sample size for the present study was determined using G*Power (Statistical Power Analyses for Windows, Version 3.1.9.7; Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany). An a priori power analysis was conducted using F-tests appropriate for the study design, specifically a repeated-measures ANOVA with a within-between interaction (2×2 design). The study included two independent groups with measurements obtained at two time points. The significance level (α) was set at 0.05, the minimum effect size was assumed to be 0.35 [12], the correlation among repeated measures was fixed at 0.50, and the non-sphericity correction (ϵ) was set to 1. To achieve a statistical power ($1-\beta$) of 0.80, the minimum required total sample size was 20 participants, corresponding to an actual power of 84.0%. The software is freely available at: <https://www.gpower.hhu.de/>

All players were randomly assigned to a training group. No players were lost to the follow-up or excluded from the final analysis. Before the start of the study, all participants participated in 90-minute soccer-specific training sessions five times per week. None of the participants reported any current neuromuscular diseases or musculoskeletal injuries, and none were taking any dietary or performance-enhancing supplements that might have affected performance. Before the start of this study, all participants received a letter including written information about the study procedures. Parents or legal representatives and players provided written informed consent after a thorough explanation of the study's objectives, procedures, risks, and benefits. Ethical approval for the study was granted by the local ethics committee (National Centre for Medicine and Science of Sports of Tunis [CNMSS-LR09SEP01]), ensuring compliance with the latest version of the Declaration of Helsinki.

Procedures

Field tests were conducted on 3G synthetic soccer turf to ensure uniform testing conditions. The trials were conducted consistently between 5 p.m. and 7 p.m., with environmental variables maintained at specific levels: temperature (19–23°C), humidity (50–60%), and wind speed (≤ 2 m/s).

All participants were encouraged to perform at maximum effort throughout the tests. One week before the study began, two orientation sessions were held to familiarize participants with the general environment, equipment, and experimental procedures and to minimize subsequent learning effects. Evaluations included the muscle power (countermovement

(CMJ), 15-seconds repeated vertical jump (15''RJ), and five-jump test (5JT)), sprint (10m and 30m), aerobic power (Maximal Aerobic Speed (MAS) and $\text{VO}_{2\text{max}}$), and repeated sprint sets (RSS: total sprint time (TST), best sprint (BST), and fatigue index (FI)). Additionally, lactate, rating of perceived exertion (RPE), and maximum heart rate (HRmax) were assessed using the same standardized conditions. Instead, tests are generally carried out at the start and end of 8-week training programs to measure specific components of soccer-specific fitness [23]. Training and testing sessions were conducted on three separate dates. In this context, players performed sprint and power tests on the first day, an RSS test on the second day, and an aerobic test on the third day, with a 48-hour rest period between the second and third days. Thereafter, all participants performed a standardized 15-minute warm-up (submaximal running, dynamic stretching, low-intensity forward, lateral, and backward running, several acceleration runs, and jumping at progressively higher intensities). The participants followed the same test order during the pre- and the post-test. Testing took place on three separate days with 48 hours of rest between days.

Data Collection Tools

Anthropometric measurements

Anthropometric measurements, such as body height and body mass, were obtained using a wall-mounted stadiometer (Florham Park, NJ) and an electronic scale (Baty International, West Sussex, England), respectively. Skinfold thickness was assessed using Harpenden skinfold calipers, and body fat percentage was estimated using the Deurenberg et al. equation [24], chosen for its reported consistent prediction errors across adults and adolescents:

$$(\text{Body fat percentage} = 222.23 + 26.56 * \log (\text{Biceps, triceps, subscapular, and suprailiac}))$$

Biological maturity was noninvasively assessed using chronological age and body height in a regression equation. This equation, developed by Moore et al., predicted biological age from peak height velocity (PHV) [17]. Although the PHV prediction equation is widely used to estimate somatic maturation, it is essential to recognize its limitations. Prediction accuracy can vary at the individual level, and error margins are inherent when applied to heterogeneous samples. Despite these limitations, PHV was selected as the maturational covariate in the present study because it is a non-invasive,

practical, and validated tool for use in youth athletes, and is particularly relevant for identifying maturational timing during adolescence when rapid changes in growth and performance occur [25,26]. In addition, peak height velocity (PHV) was estimated using the Moore et al. [17] prediction equation. All participants were classified as pubertal. Baseline PHV values were comparable between the PLYO-RSS and PLYO-HIIT groups ($p > 0.05$), although randomization did not specifically match participants based on PHV.

Fitness tests

Primary outcomes

Countermovement jumps

Subsequent to the prescribed warm-up regimen, the countermovement jump (CMJ) test, executed without the inclusion of arm swing, was administered. Participants were well acquainted with the intricacies of the jumping protocols, having regularly performed jumps as part of routine club assessments and having undergone numerous practice testing sessions. To mitigate external variations in surface conditions that could affect results, all jump tests were conducted indoors. To ensure consistency, the exact verbal instructions and demonstrations were provided to all participants, and trained assessors monitored execution and corrected technique when the countermovement depth was excessively shallow or deep. Trials with inconsistent execution were repeated. To standardize jump testing, participants were instructed to adhere to the protocols conducted with highly trained youth soccer players [15]. For the CMJ, participants were asked to stand upright with feet shoulder-width apart, perform a rapid downward countermovement to a self-selected comfortable depth (avoiding excessive knee flexion), and then jump as high as possible while keeping hands on the hips [27]. Each participant performed three attempts for each jump test, and the highest recorded value in centimeters was recorded for subsequent analysis. A 2-minute recovery interval was observed between consecutive jumps to ensure optimal performance. The Ergojump® system (Ergojump® apparatus, Globus Italia, Codogno, Italy), a validated apparatus for measuring jump height, was used to conduct the test [28]. Participants executed the testing protocols while wearing conventional athletic footwear within an indoor facility with a non-slip, level surface. The ambient room temperature was maintained at a controlled range of 18-20°C. In highly trained pubertal youth soccer players, the countermovement jump (CMJ) demonstrates excellent reliability, with an ICC of 0.93 and an estimated SEM of ~0.7% of mean performance [29].

Five jump tests

The 15''RJ was utilized to assess the horizontal performance of the lower limbs in soccer players [30]. The prescribed testing protocol requires the participant to perform five consecutive jumps with feet initially joined, with the feet touching at both the initiation and termination of each jump. A fixed point serves as the designated starting position [30]. It is imperative to note that, once initiated, the participant is prohibited from executing a backward step with either foot. If the player falls forward or backward upon completing the final jump, the test is repeated. For 15''RJ and 5JT, participants were instructed to jump as quickly and explosively as possible, maintaining proper landing mechanics and minimal ground contact. All participants completed three familiarization trials prior to testing.

Jumping performance is quantified in centimeters, using a tape measure extending from the front edge of the player's feet at the starting position to the rear edge of the feet at the concluding position. The specialist overseeing the assessment focuses on the final jump to assess foot placement upon landing, ensuring stability and fixity. Previous reliability tests conducted with elite youth soccer players indicated high reliability, with an intraclass correlation coefficient (ICC) of 0.91 and a standard error of measurement (SEM) of 0.30 [16].

Sprint performance

The assessment of maximal sprinting speed included 10m and 30m sprint tests, in which participants attained maximal velocity as previously described by Selmi et al. [31][32] in a study conducted with highly trained youth soccer players. The sprint initiation occurred from a stationary standing position situated 20cm behind the initial timing gate at the starting line, with a uniform start stance maintained for each participant. To commence the test, participants positioned one foot at the starting line in an upright stance and were instructed to accelerate as rapidly as possible through each set of gates. Notably, a starting signal was deliberately omitted to eliminate the influence of reaction time. Time measurements were captured using photocell gates (Brower Timing Systems, Salt Lake City, Utah, USA, accuracy of 0.01s), positioned 0.4m above the ground. The protocol has demonstrated exceptional test-retest reliability (ICC = 0.99) and minimal variability [CV] < 3.0% in previous reports [32].

Repeated maximal jump test

The determination of maximal vertical jump height was executed through a 15-second rebound jump series (15''RJ), employing an Optojump Next system (Microgate, Bolzano, Italy) for precise measurement [30] in highly trained youth soccer players. The system has a sampling frequency of 1000 Hz. Before testing, the platform was calibrated according to the manufacturer's instructions. Previous studies have demonstrated the validity and reliability of the Optojump system for assessing jump height in youth athletes [33]. In this procedure, participants initiated from an upright position, evenly distributing their body weight over both feet, and positioning their arms freely at their sides. Following a voice cue, participants performed vertical jumps, aiming to achieve maximal height, and landed with both feet simultaneously. This jumping sequence was repeated for 15 seconds, with participants explicitly instructed to "jump as high as possible during 15 seconds, simulating header shots." The reliability (ICC of 0.90) of this test has been previously established in highly trained youth soccer players [34].

Secondary outcomes

Repeated sprint sets performance.

Participants executed the RSS following the specified protocol [31]. After each sprint, players concluded with a 10m deceleration followed by a 10m active jog recovery. To simulate customary team-sport conditions, the test transpired on artificial turf. Repeated sprint set (RSS) performance was assessed to evaluate anaerobic capacity and fatigue tolerance. Participants performed 6 × 20-m sprints with a 20-second passive recovery between sprints. Timing was recorded using photocell gates (Brower Timing Systems, USA) with an accuracy of ±0.01 s.

The measured variables were: Total Sprint Time (TST): The sum of all six sprint times; Best Sprint (BST): The fastest single sprint time within the set; and Fatigue Index (FI): Calculated to quantify performance decrement across repeated sprints using the formula by Fitzsimons et al. [35]:

$$FI = (Total\ Sprint\ Time / Best\ Sprint \times Number\ of\ Sprints) \times 100) - 100$$

In this formula, higher FI values indicate greater fatigue and worse fatigue resistance, whereas lower FI values reflect better fatigue tolerance during repeated sprint efforts.

This expresses the percentage decline in sprint performance over the RSS. Throughout all trials, participants received standardized verbal encouragement to ensure maximal effort in each sprint. The assessments were conducted in soccer shoes familiar to the players. For a single set of 5x20 m, the ICC and the CV values were previously reported in highly trained youth soccer players as 0.91, 2.0%; 0.91, 1.9%; and 0.45, 55.1% for TST, BST, and FI, respectively [31].

20m Multistage test

The assessment of maximal aerobic speed (MAS) was conducted using the University of Montréal multistage aerobic track test [36]. Participants performed the 20 m multistage shuttle run on a 200 m outdoor track. The initial speed was set to 6 km·h⁻¹ and controlled by pre-recorded audio signals that dictated the running pace. Speed increments of 1 km·h⁻¹ every 2 minutes were applied, as indicated by the audio signals, ensuring a standardized progression across all participants. MAS was defined as the highest running velocity maintained for a complete 2-minute stage. VO_{2max} was estimated using the validated formula for youth athletes:

$$VO_{2max} \text{ (mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}) = 31.025 + 3.238 \times v - 3.248 \times \text{age} + 0.1536 \times v \times \text{age}$$

where v is the maximal running velocity in km·h⁻¹, and age is in years [37].

The participant's MAS, indicative of maximal aerobic power, corresponded to the most recently completed stage. Finger-tip capillary lactate concentrations ([Lac]) were measured both before and 3 minutes after the test, employing a hand-held Lactate Pro device (Arkray, KDK, Japan). Previous research has affirmed the reliability and validity of this test for estimating VO_{2max} in both trained and untrained young and middle-aged females and males ($r = 0.97$, 6.0 ± 1.2 , $Syx = 1.92$) [31]. Heart rate (HR) was continuously monitored throughout the three RSS sessions using a Polar Accurex Plus heart rate monitor (Kempele, Finland). Both mean and peak HR values obtained during the test were included in the statistical analyses. Notably, the HR_{max} recorded at the end surpassed the predicted HR_{max} (196 ± 0.2 bpm), calculated using the Tanaka et al. [38] equation ($208 - 0.7$

× age), and this difference was found to be statistically significant. In adolescents, the 20 m multistage fitness test shows excellent test-retest reliability ($ICC \approx 0.93$) [39], and in trained soccer players, the typical error is ~ 2.3 shuttles (~ 0.23 stages) [40], supporting its precision for monitoring change.

Training programs

The intervention was conducted during the pre-season period (August–October 2021), with five weekly sessions for both experimental groups. PLYO-RSS and PLYO-HIIT participants underwent an 8-week aerobic and speed-training program. The intervention sessions were conducted on the standard soccer pitch (see Table 2 for details). The training sessions were organized within a specific micro-cycle, each lasting 90 minutes. Consequently, participants engaged in PLYO-RSS and PLYO-HIIT sessions on two designated days (Tuesday and Friday) within the training week.

It is acknowledged that, in youth soccer players, physical fitness naturally improves across the competitive season, which may have contributed to the significant time effects observed in both groups and partly explains the lack of significant group × time interactions. Therefore, the improvements in sprint, jump, and aerobic performance likely reflect a combination of seasonal progression and the specific training interventions. To enhance reproducibility and clarify the plyometric stimulus, additional details are provided: the plyometric program included squat jumps, countermovement jumps, horizontal bounds, single-leg hops, and drop jumps. Intensity was progressively increased by increasing box height (20–40 cm), increasing movement complexity (bilateral to unilateral), and emphasizing rapid ground contact times, thereby providing a controlled and progressively challenging neuromuscular stimulus. This detailed description enables a more rigorous evaluation of the comparability of training load between groups and the adequacy of the plyometric component in contributing to performance adaptations.

The PLYO-HIIT training component consisted of a series of intermittent exercises performed at 105–110% of the MAS achieved at the culmination of the Multistage test. This was supplemented with 3–4 sets of 5–8 repetitions of plyometric exercises, with 60–90 seconds of rest between sets (Table 3)

Conversely, PLYO-RSS training involved maximal sprint exercises over a 20m distance, comprising 3 to 5 sets with a 25-second rest interval. Additionally, PLYO-RSS sessions included 3 to 4 sets of 5 to 8 repetitions of plyometric exercises (Table 4).

Notably, both training modalities required excluding specific soccer drills, such as passing, crossing, ball kicking, corner-kick drills, and penalty kicks, for a total of 20 minutes per session. The remaining 45 minutes were dedicated to soccer-specific training, with the standardized warm-up lasting 15 minutes and the cool-down lasting 10 minutes in both experimental groups. Notably, the overall training volume was consistent between the two groups.

To gauge the participants' perceived exertion, an RPE was recorded at the conclusion of each training session. Internal training load was monitored using the session-RPE method [41]. Players reported their perceived exertion 30 minutes after each training session using the Borg CR-10 scale (0 = “rest,” 10 = “maximal exertion”). Further details of the exercise program are provided in Tables 2, 3, and 4.

Table 2. Plyometric jump training program (2 sessions every week).

Week	Volume × (reps)	sets	sets	Ground contacts	
				Session 1	Session 2
1	3 reps)	sets	(5	15	15
2	4 reps)	sets	(5	20	20
3	5 reps)	sets	(6	30	30
4	5 reps)	sets	(8	40	40
5	3 reps)	sets	(5	15	15
6	4 reps)	sets	(6	24	24
7	5 reps)	sets	(8	40	40
8	5 reps)	sets	(8	40	40

Table 3. Description of the 8-week HIIT program of each session.

Week	Sessions	HIIT
1	1	2 x (6 min of 15''-15'' at 100 % of MAS)
2	2	
3	3	2 x (7 min of 15''-15'' at 105 % of MAS)
4	4	
5	5	2 x (8 min of 15''-15'' at 110 % of MAS)
6	6	
7	7	2 x (9 min of 15''-15'' at 110 % of MAS)
8	8	
9	9	2 x (6 min of 15''-15'' at 100 % of MAS)
10	10	
11	11	2 x (8 min of 15''-15'' at 105 % of MAS)
12	12	
13	13	2 x (9 min of 15''-15'' at 110 % of MAS)
14	14	
15	15	2 x (9 min of 15''-15'' at 110 % of MAS)

MAS: Maximal Aerobic Speed; HIIT: high-intensity interval training

Table 4. Repeated sprint training (2 sessions every week).

Week	Set	Repeated sprint - Intensity	Recovery between		Distance per session (m)	Weekly distance (m)
			Sprint	Sets		
1	2	5 x 20 m ; 100 %	15s	1min	200	400
2	3	5 x 25 m ; 100 %	15s	1min	250	500
3	4	5 x 20 m ; 100 %	15s	2min	300	600
4	4	5 x 20 m ; 100 %	15s	2min	400	800
5	2	5 x 20 m ; 100 %	15s	1min	200	400
6	3	5 x 20 m ; 100 %	15s	2min	300	600
7	4	5 x 20 m ; 100 %	15s	2min	400	800
8	4	5 x 20 m ; 100 %	15s	1min	200	400

Statistical Analysis

All statistical analyses were conducted utilizing SPSS 28.0 (SPSS, Inc., Chicago, IL, USA). The predetermined significance level was set at $p < 0.05$. Before analysis, the data were checked for normality using the Shapiro-Wilk test. Following confirmation of normality, a 2 (groups: PLYO-RSS vs PLYO-HIIT) $\times$ 2 (time: pre, post) repeated-measures analysis of variance (ANOVA) was conducted to examine the acute effects of the two conditions on measures of physical fitness. In cases where group $\times$ time interactions attained statistical significance, post-hoc tests specific to the groups (i.e., paired sample t-tests) were conducted to pinpoint the statistically significant comparisons. The effect size was quantified using partial η^2 for each factor (time, group, and time $\times$ group interaction) and interpreted using conventional thresholds (small: 0.01–0.059; medium: 0.06–0.14; large: ≥ 0.14). In addition, Cohen's d was used as a measure of pre-post comparisons and interpreted using conventional thresholds (small: 0.2; medium: 0.5; large: 0.8) to provide a more straightforward interpretation of the magnitude of training effects when differences were detected.

Results

Table 5 presents the outcomes of combined high-intensity and plyometric training compared with plyometric and repeated-sprint training on various physical fitness components.

Muscle Power Performance

CMJ

No significant main effect of group or time-by-group interaction (both $p > 0.05$) was observed. However, a significant main effect for time was evident ($p = 0.001$, $\eta^2p = 0.399$), indicating an overall increase in CMJ scores from pre-training (31.5cm) to post-training (33.5cm, mean difference = 1.98cm, $d = 0.31$).

15''RJ

As with CMJ, no significant main effect of group or a time-by-group interaction was observed (both $p > 0.05$). Nonetheless, a significant main effect for time was identified ($p = 0.001$, $\eta^2p = 0.453$), indicating higher 15''RJ scores post-training (29.9cm) than pre-training (27.4cm; mean difference = 2.54cm, $d = 0.36$).

5JT

No significant main effect for group or time-by-group interaction (both $p > 0.05$) was observed. A significant main effect for time ($p = 0.001$, $\eta^2p = 0.421$) revealed an increase in 5JT values from pre-training (11.3cm) to post-training (11.8cm, mean difference = 0.451cm, $d = 0.28$).

Sprint Performance

10m Sprint and 30m Sprint

No significant main effect for group or time-by-group interaction (all $p > .05$) was observed. However, significant main effects for time were identified for both 10m ($p = 0.001$, $\eta^2p = 0.339$) and 30m sprint times ($p = 0.001$, $\eta^2p = 0.489$). Faster sprint times were evident post-training for both 10m (1.71 s) and 30m (4.33 s), compared to pre-training (10m: 1.76 s, 30m: 4.35 s). Cohen's d for 10m and 30m sprint times was 0.15 and 0.04, respectively.

Aerobic Performance

MAS and VO_{2max}

No significant main effect for group or time-by-group interaction (all $p > 0.05$) was observed. However, a significant main effect of time was identified for MAS ($p = 0.001$, $\eta^2p = 0.801$) and VO_{2max} ($p = 0.001$, $\eta^2p = 0.489$), indicating higher post-training scores for MAS (17.39 km/h) and VO_{2max} , respectively ($d = 0.6$).

Additional Metrics

Blood Lactate, RPE, and HRmax

No significant main effects for group, time, or time-by-group interactions (all $p > 0.05$) were observed for blood lactate and RPE. For HRmax, no significant main effects for group or time (both $p > 0.05$) were observed, but a significant interaction between time and group ($p = 0.031$, $\eta^2p = 0.173$) was identified. Post hoc comparisons revealed a significant increase in HRmax for the PLYO-RSS group (198 bpm post-training, $p = 0.006$), while no significant difference was observed for the PLYO-HIIT group (198 bpm post-training). Notably, at baseline, HRmax was significantly lower in the PLYO-RSS group compared to the PLYO-HIIT group ($p = 0.01$).

Recognizing that the baseline HRmax for the PLYO-RSS group was lower than for PLYO-HIIT and that this might lead to regression to the mean, we reanalyzed the data using analysis of covariance (ANCOVA), controlling for baseline HRmax. This analysis did not alter the study's outcomes, which showed a significant time-by-group interaction ($p = 0.038$, $\eta^2p = 0.167$). Post hoc comparisons confirmed a significant increase in HRmax for the PLYO-RSS group (196.6 ± 3.6 bpm at pre to 198.3 ± 4.1 bpm at post, $p = 0.007$, $d = 0.22$), while no significant difference was observed for the PLYO-HIIT group (198.2 ± 6.5 bpm at pre to 198.2 ± 5.3 bpm at post, $p = 0.904$).

RSS Performance

TST, BST, and FI variables

No significant main effect for group or time-by-group interaction (both $p > 0.05$) was observed. However, a significant main effect for time was identified for TST ($p = 0.001$, $\eta^2p = 0.479$, $d = 0.22$), BST ($p = 0.001$, $\eta^2p = 0.421$, $d = 0.11$), and FI ($p = 0.001$, $\eta^2p = 0.463$, $d = 0.07$), indicating changes in performance over time of a small magnitude. Overall, these results highlight the impact of the different training conditions on various physical fitness components, with improvements observed in muscle power, sprint performance, and aerobic capacity.

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Table 5. Effects of combined aerobic and plyometric training versus plyometric and repeated sprint training on components of physical fitness in highly trained male pubertal soccer players.

Variable	Time	ANOVA					x
		PLYO-RSS	PLYO-HIIT	Group	Time	Group Time	
<i>Muscle power performance</i>							
CMJ height (cm)	Pre	31.4 (2.8)	31.6 (3.4)	>0.05	0.001	>0.05	
	Post	33.2 (2.8)	33.8 (3.5)				
15''RJ (cm)	Pre	26.9 (3.1)	27.9 (4.5)	>0.05	0.001	>0.05	
	Post	28.7 (2.6)	31.2 (4.4)				
5JT (m)	Pre	11.5 (0.9)	11.3 (0.7)	>0.05	0.001	>0.05	
	Post	11.8 (0.8)	11.7 (0.7)				
	Post	232.2 (10.1)	231.7 (13.1)				
<i>Sprint performance</i>							
10m (s)	Pre	1.74 (0.16)	1.79 (0.16)	>0.05	0.001	>0.05	

30m (s)	Post	1.68 (0.18)	1.75 (0.17)	>0.05	0.001	>0.05
	Pre	4.36 (0.21)	4.35 (0.19)			
	Post	4.34 (0.21)	4.31 (0.18)			
<i>Aerobic power performance</i>						
MAS (km/h)	Pre	15.50 (1.36)	15.77 (1.55)	>0.05	0.001	>0.05
	Post	17.39 (1.27)	17.50 (1.55)			
VO ₂ max (ml/min/h)	Pre	67.23 (6.72)	66.98 (7.18)	>0.05	0.001	>0.05
	Post	73.46 (7.0)	72.52 (8.61)			
Blood Lactate (mmol/l)	Pre	5.1 (1.2)	5.1 (1.1)	>0.05	>0.05	>0.05
	Post	5.6 (1.1)	5.8 (0.9)			
HRmax (bpm)	Pre	196.7 (3.6)	198.1 (6.5)	>0.05	>0.05	0.031
	Post	198.5 (4.1)	198.0 (5.3)			
RPE (AU)	Pre	8.8 (1.1)	8.5 (1.5)	>0.05	>0.05	>0.05
	Post	9.0 (0.8)	8.9 (0.8)			
<i>RSS performance</i>						
TST (s)	Pre	42.80 (1.78)	43.33 (1.64)	>0.05	0.001	>0.05
	Post	38.62 (0.65)	38.89 (1.13)			
BST (s)	Pre	4.05 (0.22)	4.02 (0.18)	>0.05	0.001	>0.05
	Post	3.68 (0.11)	3.69 (0.17)			
FI (%)	Pre	5.83 (1.56)	5.10 (1.49)	>0.05	0.001	>0.05
	Post	7.29 (2.79)	7.23 (1.61)			

MAS: Maximal Aerobic Speed; HIIT: high-intensity interval training; CMJ: Counter Movement Jump, FI: Fatigue Index, HRmax: Maximum Heart Rate, RSS: Repeated Sprint Sets, RPE: Rate of Perceived Exertion, 5JT: The five-jump test, TST: Total Sprint Time, BST: Best Sprint Time, FI: Fatigue Index

Discussion

The primary aim of this study was to examine the effects of combining plyometric training with either repeated sprint sets (RSS) or high-intensity interval training (HIIT) on muscle power, sprinting ability, aerobic power, and RSS performance in highly trained pubertal youth soccer players. The main finding was that both interventions produced comparable improvements across physical performance measures, indicating that either training combination can serve as an effective conditioning strategy for this population.

Both groups demonstrated significant improvements in RSS performance. Although no group $\times$ time interaction was detected, effect-size differences suggested subtle variation in the magnitude of improvement. The absence of differential effects between groups may be attributed to the relatively short intervention duration (eight weeks), the small sample size, and the participants' maturational stage, which can affect responsiveness to specific training stimuli—for example, as reported by Liu et al. [13] reported

that plyometric sprint and plyometric HIIT programs produced comparable improvements in repeated sprint performance ($g = -0.46$ vs. -0.42), supporting our observation that both combined interventions yield similar outcomes. Physiological adaptations likely underpin these gains, including enhanced oxygen delivery and utilization (e.g., greater mitochondrial content, capillarization, and aerobic enzyme activity), as well as anaerobic mechanisms such as improved phosphocreatine resynthesis, glycolytic enzyme activity, and buffering capacity [42–44]. For instance, Iaia et al. [42] reported reduced lactate accumulation and increased monocarboxylate transporter expression following intermittent-sprint training, highlighting metabolic adaptations consistent with our findings. Although most performance indicators improved, FI slightly increased from pre- to post-test. Given that higher FI values indicate reduced fatigue resistance, this suggests that while sprint and power measures improved, the players experienced a marginal decrease in fatigue tolerance.

Beyond metabolic factors, neurophysiological mechanisms provide a plausible explanation for the observed performance gains. Both interventions required frequent high-intensity accelerations, decelerations, and changes of direction, movements known to stimulate adaptations in motor unit recruitment, neural drive, and intramuscular coordination [45,46]. Enhanced motor unit synchronization and firing frequency likely improved force generation during short ground-contact phases, thereby facilitating faster sprints and greater tolerance to repeated effort. Moreover, the inclusion of plyometric drills directly targeted the stretch-shortening cycle (SSC), promoting more efficient storage and release of elastic energy, reducing electromechanical delay, and increasing tendon stiffness [47,48].

Psychophysiological factors may also contribute, particularly increased movement efficiency and technical proficiency in handling repeated high-intensity efforts [49,50]. The repetitive practice of soccer-specific actions (e.g., 180° changes of direction in the RSS test) likely enhanced anticipatory adjustments, resulting in faster, more coordinated execution. This could explain why both groups demonstrated notable RSS gains despite differences in training mode.

Improvements in CMJ, 15''RJ, 5JT, and 10–30 m sprints were also observed in both groups, corroborating evidence from previous RCTs in youth soccer players [6], which reported moderate-to-large gains in jump and sprint performance following plyometric-based interventions. The repeated sprint

component likely provided additional neuromuscular stimulus through rapid deceleration and re-acceleration, reinforcing stretch-shortening cycle utilization and motor unit recruitment, as observed in similar adolescent training studies [51,52]. Given the relatively short eight-week duration, these adaptations are likely driven by neuromuscular mechanisms rather than hypertrophic changes [53,54]. The rapid decelerations inherent in RSS training may have functioned as an additional plyometric stimulus by requiring effective braking and re-acceleration, thereby reinforcing SSC function and contributing to sprint and power gains even in the absence of explicit jump drills (Dos' Santos et al., 2019).

The development of power and sprinting ability is particularly critical in soccer, where actions often require force production within very short timeframes. Improved neural efficiency, SSC utilization, and coordination between eccentric-concentric transitions are therefore central adaptations that likely explain the performance gains in both interventions [56]. The intervention was conducted during the pre-season period (August–October 2021). It is acknowledged that youth soccer players may experience natural improvements in physical fitness throughout the competitive calendar through regular training and match exposure. Therefore, the significant time effects observed in both groups could reflect a combination of the experimental intervention and seasonal progression in physical fitness. This has been discussed as a potential confounding factor, and the absence of a passive control group is noted as a limitation when interpreting the intervention-specific effects.

Limitations of this study must be acknowledged. First, the absence of a plyometric-only or passive control group limits our ability to isolate the specific contribution of plyometric training or account for natural development. However, the choice of two active interventions was made to reflect ecologically valid training practices and maximize practical relevance. This absence should nevertheless be considered when interpreting the results. Furthermore, additional neuromuscular measures (e.g., rate of force development, reactive strength index, or force plate assessments of deceleration mechanics) would have provided more profound insight into the mechanisms underlying performance improvements. In addition, although participants were classified as pubertal, inter-individual differences in biological maturation may have influenced responsiveness to training. Future studies may consider matching or stratifying participants by PHV to further minimize potential confounding. Furthermore, another limitation of the

present study is that the trial was not preregistered in a publicly accessible registry (e.g., ClinicalTrials.gov or OSF). Pre-registration would have increased transparency and minimized potential selective reporting of outcomes. Future studies should consider pre-registering protocols to strengthen methodological rigor. Finally, the findings are restricted to highly trained male U14 players, and generalization to other populations should be made with caution.

In summary, combining plyometric training with either RSS or HIIT results in similar improvements in aerobic power, repeated-sprint ability, muscle power, and sprint performance in pubertal, highly trained youth soccer players. These benefits are likely mediated by an interplay of metabolic, neuromuscular, and psychophysiological mechanisms, including enhanced motor unit recruitment, neuromuscular coordination, and SSC efficiency [55]. Future studies incorporating direct neurophysiological and biomechanical assessments are warranted to better elucidate these adaptations.

Conclusions

This study demonstrates that an 8-week training program combining plyometric exercises with either repeated-sprint sets (PLYO-RSS) or high-intensity interval training (PLYO-HIIT) effectively improved repeated-sprint ability, aerobic power, linear sprinting, and muscle power in highly trained U-14 male soccer players. No significant differences were observed between the two interventions, indicating comparable effectiveness for enhancing multiple aspects of physical fitness. These findings suggest that coaches and strength and conditioning professionals can strategically select either PLYO-RSS or PLYO-HIIT based on the training phase, available time, and competition schedule. For instance, PLYO-HIIT may be prioritized during the pre-season to enhance maximal aerobic speed and VO_{2max} , whereas PLYO-RSS may be emphasized during the in-season to more closely replicate the repeated-sprint demands of match play. Future research, including single-mode training and passive control groups, is warranted to better isolate the specific contributions of repeated sprint, high-intensity interval, and plyometric training to physical performance adaptations in youth soccer players. Overall, the study provides evidence-based guidance for periodized training design, offering practitioners flexibility in selecting combined training modalities to optimize performance outcomes in highly trained pubertal soccer players. Future research, including single-mode training and

control groups, is warranted to better isolate the specific contributions of repeated sprint, high-intensity, and plyometric training to performance adaptations in this population.

Declarations

Ethics approval and consent to participate

The study was approved by the National Centre for Medicine and Science of Sports of Tunis [CNMSS-LR09SEP01] and conducted in accordance with the Declaration of Helsinki. Moreover, Parental Informed Consent forms were obtained from all participants for study participation.

Consent for publication

Not applicable

Availability of Data and Materials

The datasets used and/or analyzed during our study are available from the corresponding author upon reasonable request, provided the appropriate permits are obtained from the relevant authorities.

Conflicts of Interest

The authors declare no conflict of interest.

Author's Contributions

MAS, HİC, RH, and NLB conceived this study. MD, NLB, and HİC undertook the statistical analysis. HİC, RHS, NLB, and RM interpreted the data. MAS, RH, HİC, NLB, SB, and RM developed the manuscript. MAS, RH, HİC, MD, RHS, RM, SB, and NLB critically revised the manuscript and approved the final manuscript for publication. All authors read and approved the final manuscript.

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