



# Unilateral Plyometric Training is Superior to Volume-Matched Bilateral Training for Improving Strength, Speed and Power of Lower Limbs in Preadolescent Soccer Athletes

by

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*This study compared the effects of unilateral and bilateral plyometric training on strength, sprint performance and lower limb power. Sixty-eight preadolescent soccer athletes were randomly assigned to a unilateral plyometric training group (n=23), a bilateral plyometric training group (n=23) and a control group (n=22). Both plyometric training groups trained with equal volumes of unilateral or bilateral exercises for 15 minutes in each session, at which time the control group performed soccer-specific drills. Plyometric exercises were executed twice weekly for 10 weeks during the competitive season. The following tests were performed before and after the intervention: single-leg and double-leg countermovement jump, squat jump, horizontal jumps in different directions, maximal isometric strength of quadriceps and hamstrings, sprint performance, agility and balance. Unilateral plyometric training resulted in greater improvements compared to the control group in the following variables: hamstrings strength (ES: 0.91,  $p=0.037$ ), 5m sprint time (ES: 0.93,  $p=0.004$ ), single-leg countermovement jump (ES: 0.90,  $p=0.006$ ), single- and double-leg squat jump (ES: 0.87,  $p=0.030$  and ES: 0.73,  $p=0.067$ , respectively) and single-leg hop performance (ES: 1.01,  $p=0.004$ ). The only tests where there was an improvement of BPT compared with the CG were the single-leg and double leg SJ (ES: 0.76,  $p=0.026$ ; ES: 0.70,  $p=0.050$ ). Quadriceps strength, side hop test, double-leg horizontal jump test, flamingo balance test and modified agility T-test were equally improved in all three groups ( $p<0.001$ ). In conclusion, unilateral lower-limb plyometric training is more effective in increasing muscle strength and power in preadolescent soccer players when compared to bilateral training or soccer training alone.*

**Key words:** single-leg training, stretch-shortening cycle, performance, youth athletes.

## Introduction

Plyometric training is an integral component of training which many fitness specialists use for optimizing strength and power performance in several sports (Davies et al., 2015; Ramirez-Campillo et al., 2018; Bogdanis, Donti, et al., 2019). The main characteristic of lower-limb plyometric exercises, such as jumps and hops, is the use of the stretch-shortening cycle which allows muscles to store elastic energy during a rapid eccentric muscle contraction and then release it during the subsequent concentric muscle

contraction (Enoka, 2015). Plyometric training is increasingly used in sports settings and several studies have shown considerable improvements in jumping ability, maximal strength, speed, acceleration and agility (Fatouros et al., 2000; Thomas et al., 2009; Michailidis et al., 2013).

Plyometric exercises are commonly used in soccer training because they can be easily performed and combined with other sport-specific explosive activities, while they do not require a lot of space, time and equipment (Faigenbaum et al., 2007; Michailidis et al., 2013).

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Competitive soccer performance requires high levels of agility, power and efficient usage of the stretch-shortening cycle, during short-duration maximal efforts (Thomas et al., 2009; Ramirez-Campillo et al., 2018; Ribeiro et al., 2019). In high-level soccer, a research study showed that elite players selected for the national team, were superior in the above variables than the non-selected players (Ramirez-Campillo, Meylan, et al., 2015). Plyometric exercises improve these physical abilities and consequently could fit into soccer training organization to improve performance in movements such as changes of direction, accelerations and decelerations (Michailidis et al., 2013).

Jumping and hopping are fundamental skills in several children's sports and, therefore, plyometric training may be an appropriate training intervention for improving performance in preadolescent athletes (Johnson et al., 2011). It is recommended that young athletes should start plyometric training with their own body weight and avoid high impact plyometric exercises (depth jumps, because of the high injury risk for bones and tendons (Fatouros et al., 2000; Michailidis et al., 2013). In order to implement a complete plyometric training program for children, coaches should take into consideration athletes' age and the level of experience, as well as their injury records (Davies et al., 2015). In addition, the fundamental principle of progressiveness on sets and repetitions of strength training should always be followed in order to avoid training overload, especially in preadolescent athletes (Davies et al., 2015). A number of studies report plyometric training as an effective method for improving jumping ability, sprint performance and strength not only in adults (Faigenbaum et al., 2009; Meylan and Malatesta, 2009) but also in pubertal children (Johnson et al., 2011; Peitz et al., 2018). In contrast, plyometric training in preadolescents, and its effectiveness on power development has not been investigated to the same extent as in adults. In a relatively recent meta-analysis, plyometric training in preadolescents was reported to improve jumping performance, while its effects on agility were not as apparent (Asadi et al., 2017). A previous study in 10-year old boys employed a supplementary, to soccer drills, 12-week training program using single and double

leg plyometric exercises, and reported improvements in speed and jumping performances (Michailidis et al., 2013). Despite recent findings that plyometric training may improve various aspects of speed and power in young athletes, the evidence is scarce for preadolescent soccer players and there is still a need to optimize the characteristics of this type of training specifically for this group of athletes.

There is evidence that unilateral plyometric training may be more effective, compared with bilateral plyometric training in adults (Bogdanis, Dondi, et al., 2019). This type of plyometric training may confer greater improvements in performance, especially in sports which involve unilateral explosive muscle actions (sprinting, jumping and changes of direction) (Appleby et al., 2020). Furthermore, unilateral plyometric exercises enhance neuromuscular activation and consequently, may reduce side asymmetries in performance (Ramirez-Campillo et al., 2018). Despite its potential for conferring greater improvements in explosive performance, unilateral plyometric training has not been thoroughly examined in young athletes. The few studies in children have either used bilateral plyometric training alone or combined with resistance training (Faigenbaum et al., 2007; Meylan and Malatesta, 2009; Ribeiro et al., 2019). Only one study compared bilateral, unilateral and combined plyometric training in youth (11 years old) soccer players and reported that the combined unilateral and bilateral plyometric training was more effective in improving several muscle power and balance performance measures (Ramirez-Campillo, Burgos, et al., 2015). However, despite the useful information provided in that study, the plyometric training program was relatively high in volume (120-240 jumps per session), and due to its long duration (24 sets per session), it replaced part of the soccer training. Moreover, the length of the training intervention was only 6 weeks with the volume increasing linearly, and it would be interesting to investigate the effects of unilateral and bilateral training of lower limbs and periodized volume, over a longer period of time.

Thus, the aim of the present study was to evaluate the effects of 10 weeks of periodized unilateral and bilateral plyometric training on strength, sprint and jumping performance in

preadolescent soccer athletes. It was hypothesized that unilateral plyometric training would result in greater improvements of performance compared with bilateral training.

## Methods

### *Participants*

One hundred and five (105) preadolescent boys aged 8-13 years from the same soccer school of a Greek Superleague club were initially recruited (Flow diagram, **Figure 1**). Data collection took place in the middle of the competitive season. All athletes participated in three soccer training sessions (in groups of sixteen players of the same age-group) per week (60 min duration each) and played at least 25 minutes on a soccer match at the end of the week. All participants and their parents were informed about the process of the study and the parents gave written consent for their children's participation. The study was approved by the local Institutional Review Board (approval code 1525) and all procedures were in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). The medical history of the subjects was checked to ensure that all participants did not suffer from any health problems (chronic disease, recent injury or surgery). Volunteers were included in the study if they were training in an organized soccer academy for at least 12 months and had never participated in a plyometric training program. Goalkeepers (n=6) were not included in the study. Also, seventeen of the participants did not complete all testing sessions and were excluded from data analysis. In addition, after the 10-week intervention, fourteen athletes were excluded from the study because they hadn't participated in at least 70% of the training sessions. Thus, the data from sixty-eight boys were analysed and presented in this study (**Table 1**).

### *Design and Procedures*

A randomized controlled design was used to investigate the effects of unilateral and bilateral plyometric training on strength, sprint performance, agility and power of lower limbs in preadolescent soccer athletes. Participants were randomly assigned to three different training groups: a unilateral plyometric training (UPT) group, a bilateral plyometric training (BPT) group and a control group (CG) (**Table 1**). First, the

participants performed four familiarization sessions in a two-week period, containing both bilateral and unilateral plyometric exercises. Performance measurements were taken one week before and one week after the training intervention. On the first visit, anthropometric measurements, balance, CMJ, SJ performances and maximal isometric strength of quadriceps (MISQ) and hamstrings (MISH) were measured in a laboratory. On the following day horizontal jumps in different directions, as well as sprint and agility tests were performed on the soccer field. A 10-minute standardized warm-up preceded all testing sessions. All assessments were performed before 3:00 PM, in the same order and with the same recovery (2.5-3 min) between every trial for each participant.

After familiarization and baseline testing, the players participated in a 10-week plyometric training program with two plyometric training sessions per week (**Figure 2**). More specifically, a 15-min plyometric training session in two different variations (bilateral or unilateral leg support) was performed after a 10-minute standardized warm-up, including 3 min of easy running, dynamic stretching and soccer drills. While the two intervention groups (UPT - BPT) performed the plyometric exercises, athletes of the CG performed ball possession drills. In the main part of the soccer session, athletes of all groups participated in small or medium sided games (4 vs. 4, 5 vs. 5 or 6 vs. 6 for 20 min) and a larger game (7 vs. 7 or 8 vs. 8 for 10 min). Finally, in the last part of the training session, all athletes performed a 5-min cool-down with jogging and penalty shots. In the third session of the week, all athletes performed soccer specific drills and games. In total, soccer sessions had at least 48 hours rest between them and their duration was 60 minutes.

### *Familiarization sessions*

Before the start of the 10-week intervention program and the initial measurement, athletes performed four plyometric training sessions in two weeks (two bilateral plyometric sessions and two unilateral plyometric sessions). These training sessions had low volume (40 foot-contacts per training session) and their structure was based on the intervention sessions, with emphasis placed on the technical execution of the plyometric exercises. The target of these 2-

week familiarization training sessions was to familiarize the young athletes with the exercises used in the intervention, to ensure correct execution and jumping technique regarding the position and the stability of the pelvis, knees and feet during landing and to avoid muscle soreness during the main plyometric training sessions.

#### *Training intervention*

The participants in all groups trained for 10 consecutive weeks (**Figure 3**). During this 10-week program, the type of plyometric drills increased progressively, in terms of number of repetitions, as well as the level of difficulty. In the current study, four jump types, with increasing level of difficulty were used: basic jumps, side jumps, multiple jumps and box/step jumps. In addition, the volume of the plyometric training sessions increased progressively by 20 foot-contacts per week over three weeks, while on the fourth week there was a drop in training volume. The 5th week was defined as a “recovery-regeneration week”, with all athletes abstaining from plyometric training, while soccer training was maintained. This 5-week period was repeated, starting with an initial volume of 80 foot-contacts (**Figure 3**).

During all training sessions, a standardized warm-up was performed for all groups (3 min of easy running, dynamic stretching and soccer drills). Plyometric training volume for the UPT and BPT groups was equalized, with the BPT performing all jumps with support on both legs, while the UPT group performed 50% of the jumps on each leg separately. Each plyometric training session consisted of 3 drills performed with maximum effort for 3 to 5 sets of 6 to 10 repetitions each and a 1:5 to 1:10 recovery period (**Table 3**).

#### *Measurements*

##### *Anthropometric measurements*

Body height was measured using a stadiometer (Leicester Height Measure, UK), while body mass and body fat were measured using a bioimpedance scale (BC-1000, Tanita, Tokyo, Japan). The level of biological maturation was estimated by determining the age of Peak Height Velocity (PHV) using anthropometric data according to Mirwald et al. (2002).

##### *Balance flamingo test*

Single leg balance ability was evaluated with the flamingo balance test (De Miguel-Etayo

et al., 2014). The participants were asked to stand on one leg for one minute, while the other leg was kept flexed at the knee joint and gripped with the same side arm with the foot close to the buttocks. The final score was calculated as the average of the right and left leg performance, which was defined as the number of times the participant lost their balance within one minute of balancing (lower scores indicate better balance). Participants were given one familiarization trial before each test.

##### *Vertical and horizontal jumping ability tests*

Vertical jumping ability was evaluated by measuring flight time with a Chronojump platform (Boscosystem, Spain) during single and double-leg squat jump (SJ) and a countermovement jump (CMJ) tests. For all vertical tests 3 trials were performed, and the best jump was kept for analysis. For the unilateral tests, performance was calculated as the sum of the best right and left leg jumps.

Horizontal jumping ability was evaluated by the following tests: (a) Double-leg jump test (standing broad jump), (b) Single-leg hop test, (c) Jumping sideways test, (d) Single-leg side hop test (**Figure 4**) (Caffrey et al., 2009; Myers et al., 2014; Bardid et al., 2015; Lockie et al., 2015). In the double-leg jump and single-leg hop tests, the participants were required to jump as long as possible with free arms. In the jumping sideways and side hop tests the participants were asked to jump laterally, using one or both legs, over a 30 cm zone, as fast as possible for 10 consecutive repetitions (**Figure 4**). During these tests, the hands of the participants were kept on their hips. Participants performed 3 trials of each jump and the best was kept for analysis. For the horizontal single-leg tests, performance was calculated as the average time of the best effort of the right and left leg.

##### *Maximal isometric strength:*

Maximal isometric strength of the quadriceps and hamstrings was evaluated using a handheld dynamometer (MicroFet2, Hoggan Scientific, Salt Lake City, US) at a standardized knee angle, which was measured using a digital inclinometer (Gymna, GymnaUniphy NV, Belgium). The dynamometer was calibrated at the start of each testing day and recorded force in N. More specifically, quadriceps strength was evaluated in the sitting position with the knee

angle set to 60 degrees and the hip angle set at 90 degrees. Straps were used to keep the thigh and torso at the preset positions. Hamstrings strength was measured in the prone position on a physiotherapy bed, with the knee angle at 30 degrees, while the hips were held on the bed using straps. During both tests, the dynamometer was placed at a pre-marked position on the shank (posterior or anterior), close to the ankle (Mentiplay et al., 2015). Athletes were instructed to push maximally for 3 s and executed 3 trials for each leg and each test. The sum of the best unilateral trials (right + left leg) were kept for statistical analysis.

#### *Sprint and Agility performance:*

Sprint performance was evaluated with 5 m, 10 m and 20 m sprints, while agility was assessed with the modified T-test using photocells (Fitlight Sports Corp., Ontario, Canada). For the sprint test, athletes started 30 cm behind the first photocell and then ran at maximal speed through the other three photocells placed at 5 m, 10 m and 20 m. Players executed two sprints and the best performance was kept for analysis.

For the modified T-test, athletes started 30 cm behind the first photocell, and ran maximally in a "T-figure" route, finishing at the starting photocell. More specifically, the subjects sprinted forward for 10 m and then sprinted 5 m to the right or left (depending on the direction of the trial), sprinted again in the opposite direction for 10 m, sprinted 5 m back to the middle marker before turning and sprinting back to the starting line to finish as fast as possible (Lockie et al., 2015). Four trials were completed to check both directions (right and left) and the average of the best efforts from each side were kept for statistical analysis.

#### *Statistical analysis*

Statistical analysis was conducted by using the SPSS Statistics Ver. 23 (IBM Corporation, USA). Data are presented as means  $\pm$  standard deviation. The effects of two different plyometric training interventions on all dependent variables were examined using a 3  $\times$  2 mixed model two-way analysis of variance-ANOVA [3 groups (UPT, BPT, CG)  $\times$  2 time points (pre- and post-training)]. When statistically significant differences ( $p < 0.05$ ) were observed, the Tukey's test was used for post-hoc analysis. The effect sizes for main effects and interactions were

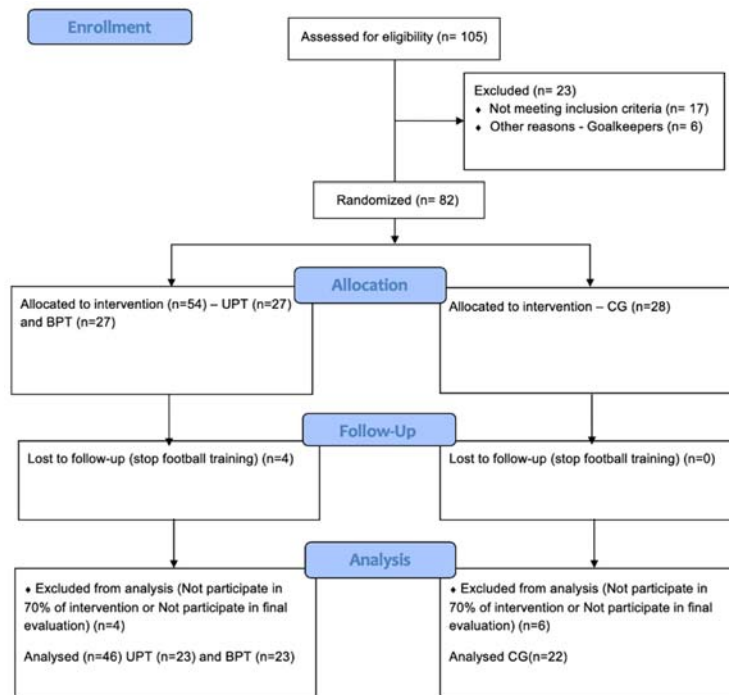
determined by Partial eta squared ( $\eta^2$ ) values (small: 0.01 to 0.059, moderate: 0.06 to 0.137, large:  $>0.138$ ). The effect size (ES) for pairwise comparisons was evaluated by Cohen's  $d$  (small:  $>0.2$ , moderate:  $>0.5$ , large:  $>0.8$ ). Statistical significance was set at  $p < 0.05$ .

## **Results**

The 2-way ANOVA showed significant group  $\times$  time interaction for hamstrings strength ( $p=0.009$ ,  $\eta^2=0.14$ ), quadriceps strength ( $p=0.046$ ,  $\eta^2=0.09$ ), 5 m sprint ( $p=0.005$ ,  $\eta^2=0.15$ ), jumping sideways test ( $p=0.047$ ,  $\eta^2=0.09$ ), double-leg SJ ( $p=0.013$ ,  $\eta^2=0.12$ ), single-leg SJ ( $p=0.022$ ,  $\eta^2=0.11$ ), single-leg CMJ ( $p=0.009$ ,  $\eta^2=0.14$ ) and single-leg hop ( $p=0.002$ ,  $\eta^2=0.17$ ).

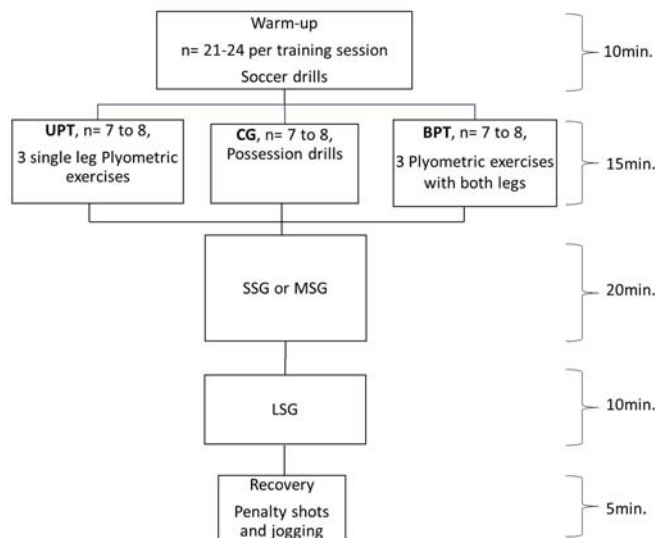
The post-hoc tests showed that changes in the above performance variables were significantly greater in the UPT than the CG and/or the BPT in four out of the eight tests. Specifically, the improvement of hamstrings strength in the UPT was greater than the improvement in the BPT (ES: 0.69,  $p=0.020$ ) and the improvement in the CG (ES: 0.91,  $p=0.037$ , Figure 5). Similarly, improvement in the single-leg hop was significantly greater in the UPT compared with the BPT (ES: 0.87,  $p=0.025$ ) and the CG (ES: 1.01,  $p=0.004$ , respectively) (Figure 7). The change in performance for the 5 m sprint was greater in the UPT than in the CG (ES: 0.93,  $p=0.004$ , Figure 6). Finally, the change in single-leg CMJ performance was greater in the UPT compared with the CG (ES: 0.90,  $p=0.006$ ) (Figure 7). In contrast, for all the above variables, none of the changes in performance of the BPT were significantly different from changes in the CG (Fig. 5-7).

The follow-up post-hoc tests also showed that the improvement in the double and single leg SJ tests were of equal magnitude in both the UPT (ES: 0.87,  $p=0.030$ ; ES: 0.90,  $p=0.026$ ) and the BPT group (ES: 0.76,  $p=0.026$ ; ES: 0.70,  $p=0.050$ ) compared with the CG (Figure 7). Notably, for the BPT the single-leg and double leg SJ were the only tests that were improved more than the CG (Figure 7).



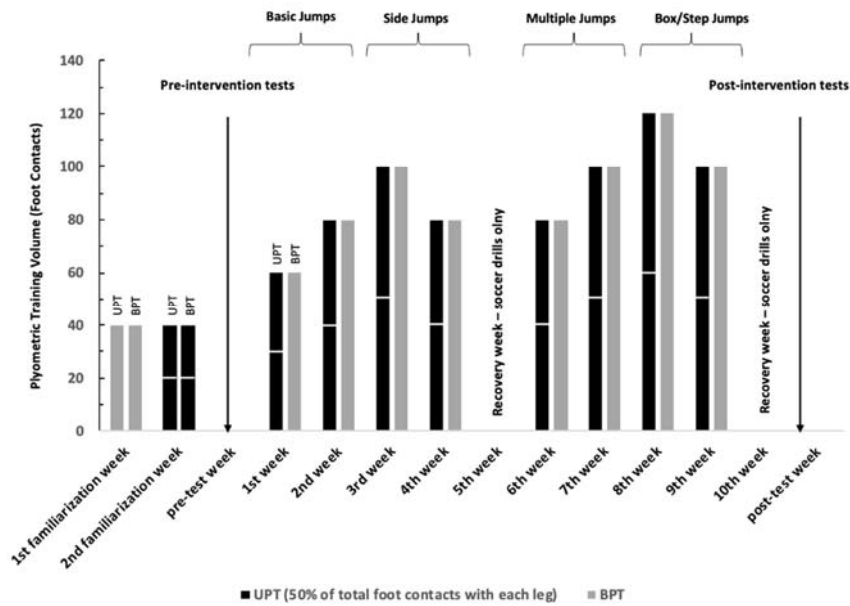
**Figure 1**

Flow diagram (Consort) for the randomized control trial study design. Unilateral Plyometric Training group (UPT), Bilateral Plyometric Training group (BPT) and Control Group (CG).



**Figure 2**

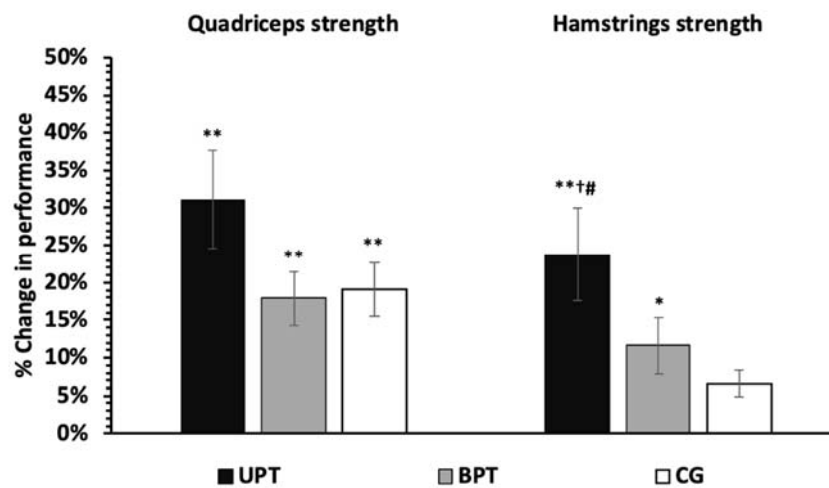
Schematic representation of a training session during the intervention, the total number of soccer athletes per training part and the duration of each training part. SSG: Small-Sided Games, MSG: Medium-Sided Games, LSG: Large-Sided Games, Unilateral Plyometric Training group (UPT), Bilateral Plyometric Training group (BPT) and Control Group (CG).



**Figure 3**  
*Schematic representation of the plyometric training volume during the familiarization, training and testing weeks. Four groups of plyometric exercises of increasing difficulty were used every two weeks, starting with less demanding exercises (basic jumps) and ending with higher load exercises (box/step jumps). Unilateral Plyometric Training group (UPT), Bilateral Plyometric Training group (BPT) and Control Group (CG).*



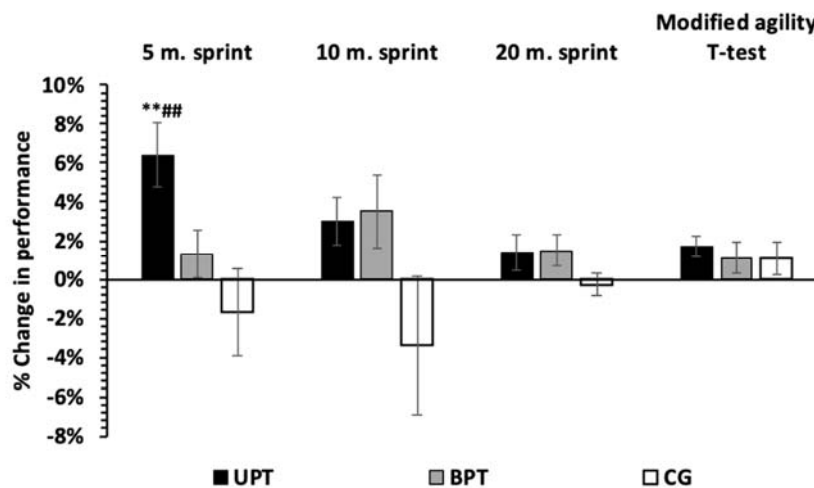
**Figure 4**  
*Horizontal jump performance tests of lower limbs: (a) Double-leg jump test (standing broad jumps), (b) Single-leg hop test, (c) Jumping sideways test, (d) Single-leg Side hop test.*



**Figure 5**

Changes in maximal isometric strength of quadriceps and hamstrings performance for the unilateral plyometric training group (UPT), the bilateral plyometric training group (BPT) and the control group (CG). Values are expressed as means  $\pm$  SE.

\*:  $p < 0.05$  and \*\*:  $p < 0.01$  from pre-training (baseline) values,  
 †:  $p < 0.05$  between UBT and BPT and #:  $p < 0.05$  between the UPT and CG.

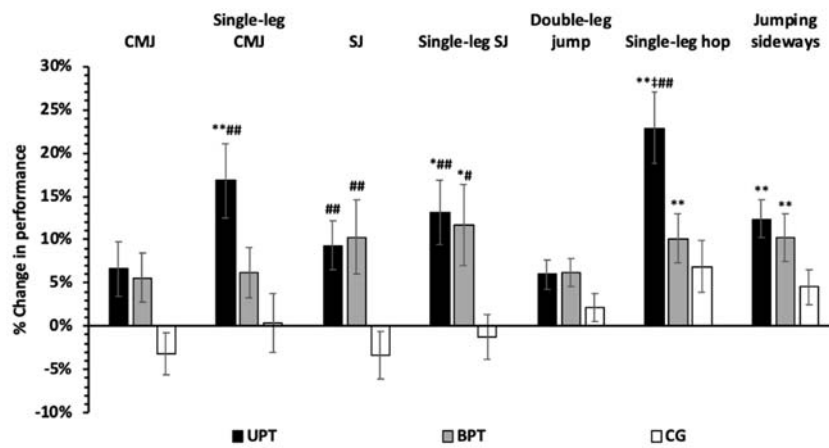


**Figure 6**

Changes in 5 m, 10 m and 20 m sprints and the modified agility T-test performance for the unilateral plyometric training group (UPT), the bilateral plyometric training group (BPT) and the control group (CG). Values are expressed as means  $\pm$  SE.

\*\*.:  $p < 0.01$  from pre-training (baseline) values and ##.:  $p < 0.01$  between the UPT and CG





**Figure 7**

Changes in single- and double-leg vertical and horizontal jump performance for the unilateral plyometric training group (UPT), the bilateral plyometric training group (BPT) and the control group (CG). Values are expressed as means  $\pm$  SE.

CMJ: Countermovement jump, SJ: Squat jump

\*:  $p < 0.05$  and \*\*:  $p < 0.01$  from pre-training (baseline) values,

‡:  $p < 0.01$  between UBT and BPT, #:  $p < 0.05$  and ##:  $p < 0.01$  between the UPT and CG.

**Table 1**

Participants characteristics in three different age groups and Unilateral Plyometric Training group (UPT), Bilateral Plyometric Training group (BPT) and Control Group (CG). Values are presented as mean  $\pm$  SD.

	UPT (n=23)	BPT (n=23)	CG (n=22)
Age (years)	9.9 $\pm$ 1.8	10.0 $\pm$ 0.5	10.2 $\pm$ 1.6
Height (cm)	142.2 $\pm$ 8.7	139.2 $\pm$ 7.0	141.6 $\pm$ 10.4
Body mass (kg)	39.3 $\pm$ 8.2	36.1 $\pm$ 7.8	38.5 $\pm$ 10.6
Body fat (%)	20.7 $\pm$ 5.7	20.1 $\pm$ 6.7	19.7 $\pm$ 6.7
Years from PHV	-2.9 $\pm$ 1.2	-3.2 $\pm$ 0.9	-2.9 $\pm$ 1.2
Training experience in a soccer academy (years)	4.3 $\pm$ 2.0	3.5 $\pm$ 1.5	3.7 $\pm$ 1.2

**Table 2**

*Plyometric drills and number of foot contacts for the unilateral plyometric training (UPT) and the bilateral plyometric training group (BPT) during the 10-week training intervention.*

Plyometric drills			UPT		BPT		Total Foot contacts
Weeks	Drills	Sets	Foot contacts	Sets	Foot contacts		
Basic jumps	1 <sup>st</sup>	Jumps in nine squares	3	3 per leg	3	6	60
		Jumps over hurdles (10 cm) in four directions	3	3 per leg	3	6	
		Jumps in four directions after light signal	2	6 per leg	4	6	
	2 <sup>nd</sup>	Jumps in four squares	3	4 per leg	3	8	80
		Jumps over hurdles (15 cm) in four directions	3	4 per leg	3	8	
		Random jumps in nine squares	4	4 per leg	4	8	
Side jumps	3 <sup>rd</sup>	Standing jumps between two cones	5	5 per leg	5	10	100
		Side jumps over a hurdle (10 cm)	4	4 per leg	4	8	
		Lateral jumps from a balance mat	3	3 per leg	3	6	
	4 <sup>th</sup>	Lateral jumps over a cone	3	4 per leg	3	8	80
		Lateral jumps over a hurdle (15 cm)	4	4 per leg	4	8	
		Standing jumps on a balance mat	3	4 per leg	3	8	
5 <sup>th</sup>	Recovery week: soccer drills only						
Multiple jumps	6 <sup>th</sup>	Jumps in ladder	3	4 per leg	3	8	80
		Jumps over hurdles (15 cm)	3	4 per leg	3	8	
		Jumps over cones	4	4 per leg	4	8	
	7 <sup>th</sup>	Lateral jumps in ladder	3	3 per leg	3	6	100
		Lateral jumps over low hurdles (15 cm)	5	5 per leg	5	10	
		Diagonal jumps over cones	4	4 per leg	4	8	
Box/Steps jumps	8 <sup>th</sup>	Jumps on a step (20 cm)	5	4 per leg	5	8	120
		Jumps on steps (20cm) in four directions	5	4 per leg	5	8	
		Jumps on four steps (20 cm)	5	4 per leg	5	8	
	9 <sup>th</sup>	Lateral jumps on step (20 cm)	5	5 per leg	5	10	100
		Diagonal jumps on steps (20 cm)	3	3 per leg	3	6	
		Jumps on steps with different height (10-30 cm)	4	4 per leg	4	8	
10 <sup>th</sup>	Recovery week: soccer drills only						

**Table 3**  
*Pre- and post- intervention test results in Unilateral Plyometric Training group (UPT), Bilateral Plyometric Training group (BPT) and Control Group (CG). Values are presented as mean  $\pm$  SD.*

Tests	UPT		BPT		CG	
	Pre	Post	Pre	Post	Pre	Post
Jumping sideways (s)	9.48 $\pm$ 1.90	8.15 $\pm$ 0.96**	9.73 $\pm$ 1.58	8.63 $\pm$ 1.30**	9.58 $\pm$ 1.01	9.13 $\pm$ 1.13
Side hop (s)	12.79 $\pm$ 4.20	9.80 $\pm$ 2.63++	14.13 $\pm$ 4.13	11.58 $\pm$ 4.18++	13.24 $\pm$ 3.30	11.47 $\pm$ 3.10++
Balance flamingo (drops/min)	20 $\pm$ 8	17 $\pm$ 5++	20 $\pm$ 8	17 $\pm$ 6++	20 $\pm$ 7	17 $\pm$ 5++
Double-leg jump (m)	1.41 $\pm$ 0.24	1.49 $\pm$ 0.28++	1.33 $\pm$ 0.16	1.41 $\pm$ 0.18++	1.41 $\pm$ 0.22	1.44 $\pm$ 0.25++
Single-leg hop (m)	1.05 $\pm$ 0.24	1.26 $\pm$ 0.23**	1.04 $\pm$ 0.21	1.13 $\pm$ 0.19**	1.06 $\pm$ 0.22	1.13 $\pm$ 0.26
Double-leg CMJ (cm)	21.3 $\pm$ 5.3	22.2 $\pm$ 4.6	19.7 $\pm$ 4.9	20.6 $\pm$ 5.1	21.6 $\pm$ 6.0	20.9 $\pm$ 6.4
Single-leg CMJ (cm)	22.2 $\pm$ 7.0	25.0 $\pm$ 5.7**	20.4 $\pm$ 5.4	21.7 $\pm$ 6.4	21.9 $\pm$ 7.3	21.9 $\pm$ 7.7
Double-leg SJ (cm)	20.4 $\pm$ 4.8	21.9 $\pm$ 4.4	18.3 $\pm$ 4.5	19.9 $\pm$ 4.8	20.1 $\pm$ 4.7	19.5 $\pm$ 5.8
Single-leg SJ (cm)	20.3 $\pm$ 6.2	22.4 $\pm$ 5.8*	18.3 $\pm$ 5.0	20.1 $\pm$ 5.4*	19.6 $\pm$ 6.1	19.3 $\pm$ 6.3
5 m. Sprint (sec)	1.34 $\pm$ 0.11	1.25 $\pm$ 0.09**	1.36 $\pm$ 0.11	1.34 $\pm$ 0.07	1.32 $\pm$ 0.16	1.34 $\pm$ 0.14
10 m. Sprint (sec)	2.26 $\pm$ 0.16	2.19 $\pm$ 0.14	2.33 $\pm$ 0.16	2.25 $\pm$ 0.24	2.24 $\pm$ 0.29	2.28 $\pm$ 0.21
20 m. Sprint (sec)	3.98 $\pm$ 0.29	3.91 $\pm$ 0.26	4.15 $\pm$ 0.26	4.08 $\pm$ 0.24	4.03 $\pm$ 0.34	4.04 $\pm$ 0.34
Modified Agility T-test (s)	10.19 $\pm$ 0.58	10.01 $\pm$ 0.54++	10.35 $\pm$ 0.53	10.23 $\pm$ 0.52++	10.34 $\pm$ 0.65	10.22 $\pm$ 0.61++
Quadriceps strength (N)	501 $\pm$ 153	627 $\pm$ 162**	433 $\pm$ 107	499 $\pm$ 104**	494 $\pm$ 176	580 $\pm$ 205**
Hamstrings strength (N)	357 $\pm$ 106	419 $\pm$ 98**	299 $\pm$ 66	326 $\pm$ 58*	342 $\pm$ 111	364 $\pm$ 122

\*:  $p < 0.05$  and \*\*:  $p < 0.01$  from pre-training values of each respective group. †:  $p < 0.05$  and ††:  $p < 0.01$  main effect of time (pre vs. post), irrespective of group.

The 2-way ANOVA showed no significant group  $\times$  time interaction, but only a main effect of time for the side hop test ( $p < 0.001$ ,  $\eta^2 = 0.38$ ), double-leg horizontal jump test ( $p < 0.001$ ,  $\eta^2 = 0.24$ ), flamingo balance test ( $p < 0.001$ ,  $\eta^2 = 0.22$ ) and the modified agility T-test ( $p = 0.003$ ,  $\eta^2 = 0.13$ ). For the double-leg CMJ, although there was a significant group  $\times$  time interaction ( $p = 0.047$ ,  $\eta^2 = 0.09$ ), the post-hoc tests did not show any significant differences. However, for the CMJ, the ES for the comparisons between UPT and CG and BPT and CG were 0.68 and 0.70, respectively.

For quadriceps strength, the post-hoc test showed that it was equally increased in all three groups ( $p < 0.001$ ), with the ES being 0.81, 0.65, 0.46 for the UPT, BPT and CG, respectively (Figure 5). Finally, there was no significant interaction or main effect of time ( $p > 0.05$ ) for 10 and 20 m sprint performance.

## Discussion

The main finding of the present study was that a periodized 10-week supplementary unilateral plyometric training program, performed twice weekly for 15 min each time, was more effective than an equal volume of bilateral training, in increasing various aspects of strength and power performance in preadolescent soccer players. More specifically, improvements were greater in the UPT than the BPT and CG for maximal isometric strength of hamstrings, 5-m sprint performance and single-leg vertical and horizontal jumping ability. Also, single and double leg SJ were equally improved in both UPT and BPT compared with the CG. Notably, this progressive and periodized plyometric training protocol, led to considerable improvements in performance and enabled players to reach high

plyometric training loads without any injuries.

To the authors' knowledge, this is one of the few studies in preadolescent athletes, which included a wide range of performance tests, including short sprint running performance (5, 10 and 20 m), horizontal and vertical one- and two-legged jump performance, as well as maximal strength. Previous studies employing plyometric training in children, did not include any direct measurements of maximal strength (Michailidis et al., 2013; Ramirez-Campillo et al., 2018). For example, Michailidis et al. (2013) and Ramirez-Campillo et al. (2018) used a submaximal 10-RM bilateral squatting and knee flexion/extension test, respectively and calculated 1 RM using general equations. However, the present study is the first to measure maximal isometric knee extension and flexion forces for each leg separately in preadolescent children. Maximal isometric strength of quadriceps improved in both plyometric training groups (UPT and BPT), as well as in the control group that performed only soccer training (Figure 5). Notably, there was a trend for greater improvement in quadriceps strength following unilateral PT compared to that observed in CG ( $ES = 0.47$ ;  $p = 0.068$ ). (Figure 5). In contrast, there was a clearly greater improvement of maximal isometric strength of the hamstrings for the UPT than for the BPT and CG (Figure 5). One possible explanation for the improvement of the hamstrings muscles, may be their role for the stabilization of the knee joint during single leg plyometric exercises (Hewett et al., 1996). Thus, a greater activation of the hamstrings muscles during single-leg plyometric training, due to both the greater stabilization work that they perform and the 2-fold greater load of supporting the whole body weight, may be the underlying mechanisms for the greater improvement seen in the UPT group.

The present study showed that unilateral plyometric training resulted in an improvement in sprint performance only for the distance of 5 m, while the 10 m and 20 m sprint performance remained unchanged (Figure 6). Similar findings have been recently reported in a study examining the effects of plyometric training frequency on 5 m, 10 m, 20 m and 30 m sprint performance in pre-pubertal soccer players (Bouguezzi et al., 2018). In that study, plyometric training was performed in one or two weekly sessions, and

training volume was increased linearly for 8 weeks. Interestingly, and in accordance with the findings of the present study, only the 5 m sprint time was improved following either one or two weekly training sessions; notably, the total volume of plyometric training was similar to that in the present study (Bouguezzi et al., 2018). One possible explanation for the improvement of sprint performance in the first part of a brief sprint, may be the association of maximum sprint velocity and acceleration with hamstrings strength (Ishøi et al., 2018). Thus, the greater improvement in hamstrings strength in UPT (Fig. 5), may be related with the improvement in 5 m sprint time in that group. Moreover, a possibly greater increase in lower limb extensors' muscle power, as evidenced by the greater improvement of single-leg CMJ and single-leg hop in the UPT (Fig. 7), would increase the propulsive forces exerted on the ground during the first, slower and forceful, foot contacts, and consequently acceleration and 5 m sprint time (Marques et al., 2011). Although some previous studies have shown improvements in sprint performance over distances ranging from 10 m to 30 m (Meylan and Malatesta, 2009; Michailidis et al., 2013), these may be related to the more advanced maturation level of the participants, as indicated by their anthropometric characteristics and age [e.g. 13 years old in the study of Meylan and Malatesta (2009)]. There is sound evidence that adaptations to plyometric and strength training are affected by maturation, with greater benefits in boys observed during or after peak height velocity (Asadi et al., 2017; Moran et al., 2017). The fact that the participants in the present study were around 3 years before the age at peak height velocity, may explain the relatively low (<2%) but statistically significant improvement in agility performance (T-test), in all groups (Figure 6). This is in accordance with the findings of a recent review, which concluded that the effect of plyometric training on agility is meaningfully greater in older youths than in 10-12 year old boys (Asadi et al., 2017).

In the present study, both vertical and horizontal single leg jumps (i.e. single-leg CMJ and single-leg hop) were improved more in the UPT than in the BPT and CG (Figure 7). Notably, these two jumps involve the stretch-shortening cycle, while the single leg SJ, which was equally

improved in the UPT and BPT does not (Figure 7). The greater improvement in horizontal and vertical jumping performance after UPT has been previously observed in adults (Bogdanis, Tsoukos, et al., 2019), and may be explained either by training specificity, since this group was trained solely with single-leg jumps, or by the greater load imposed on the leg extensor muscles during single-leg jumps supporting the whole body (Bobbert et al., 2006). This view is supported by a previous study showing that neuromuscular activation, as indicated by electromyographic (EMG) activity, is around 10-25% higher during unilateral compared with bilateral vertical jumps. Thus, although EMG data were not obtained in the present study, it may be argued that unilateral plyometric training may have resulted in greater muscle activation. Moreover, along with the likely greater improvement in intra-muscular coordination (changes in motor-unit synchronization and activation) with UPT, there may also be a greater improvement in inter-muscular coordination (better synergistic muscle recruitment strategies) compared with BPT (Markovic and Mikulic, 2010; Bouguezzi et al., 2018), supporting the possible impact of training specificity. Additionally, training with single-leg is characterized by slower muscle contractions, allowing generation of much higher forces compared with double-leg jumps (Bobbert et al., 2006). Based on the force-velocity curve, the slower muscle contraction would enable muscles to work closer to their optimum velocity and to generate greater power and impulse, which would lead to greater adaptations compared with the faster bilateral jumps (Van Soest et al., 1985; Wilson et al., 1993; McBride et al., 2002; Bobbert et al., 2006).

In contrast, all double leg jumps were similarly improved in both UPT and BPT groups (Fig. 7). This is also in accordance with previous studies in adults (Bogdanis, Tsoukos, et al., 2019) and children (Johnson et al., 2011; Michailidis et al., 2013; Bogdanis, Donti, et al., 2019; Tottori and Fujita, 2019). The improvement in double leg jumps was moderate in magnitude (Figure 7), which is a common finding in studies with children. For example, Meylan and Malatesta (2009) found an improvement in CMJ (+7.9%) in young soccer players following an 8-week plyometric training program during the

competitive season.

However, other studies have reported much greater improvements (15-20%) (Thomas et al., 2009; Michailidis et al., 2013; Bouguezzi et al., 2018). The discrepancy among studies regarding the magnitude of improvement in jumping performance, may be related to the pre-training fitness and most likely to the maturation status of the participants (Moran et al., 2017). An interesting study in 11.4 years old soccer players compared the effects of unilateral and bilateral plyometric exercises as well as their combination on measures of vertical and horizontal jumping performance, sprint ability and static balance (Ramírez-Campillo et al. 2015). Despite the short duration of the training intervention (only 6 weeks), all three training protocols improved to the same extent several performance measures that were examined. However, they noted that out of the 21 performance measures, the combined unilateral and bilateral training group showed greater improvement than the control group in 13 of them, while the unilateral and bilateral group in only 6 and 3, respectively (Ramírez-Campillo et al., 2015). Although this finding supports the notion of using combinations of unilateral and bilateral exercises in child soccer players, careful examination of the results of the study by Ramírez-Campillo et al., (2015) shows that the only performance measures which were better in the combined compared with the unilateral training, were three balance tests and the two-legged tests (CMJ, double-leg horizontal jump and DJ). In the remaining performance measures (single leg jumps, bounds, kicking and agility), both unilateral and combined training conferred the same results. Due to the much higher volume of training in that study, i.e. week 1: 120 jumps and week 6: 240 jumps per session, compared with the present study (60-120 jumps per session, see Table 2), their combined training group performed 80-160 unilateral jumps per session (Ramírez-Campillo et al., 2015). It is, thus, possible that this large volume of unilateral jumps was related with the enhanced performance in the unilateral tests. It is also unknown if this high volume used in that study can be tolerated without overload injuries for longer periods in pre-pubertal athletes. Therefore, it may be argued that unilateral is superior to bilateral plyometric training, and the present study showed that it

may be highly effective when integrated in relatively low volumes into soccer training of child players. This premise is based on the nature of soccer movements, which are in most cases unilateral (e.g. accelerations, kicks, changes of direction) and rarely bilateral (e.g. double leg jump for a header). In this respect, unilateral plyometric training may be more effective in the long term for optimizing neuromuscular performance of lower limbs, but this remains to be investigated.

The sideways jumping and side hop tests evaluate the functional ability (i.e. combination of jumping and coordination abilities) under time-pressure (Granacher et al., 2014). This assessment is a basic tool in a testing battery called Körperkoordinationstest für Kinder (KTK), which is commonly used to evaluate functional ability and coordination in children (Bardid et al., 2015). Also, exercise specialists often use the functional assessment tests to identify possible weaknesses in the functionality of one of the two limbs and decide whether an athlete is ready to return to sports activity after an injury (Bolgla and Keskula, 1997; Itoh et al., 1998). In the present study these tests were significantly improved by both types of plyometric training (Fig. 7) and thus it may be argued that these tests assess mainly agility and balance and less an improvement in leg muscle power.

The findings of the present study have important practical applications for preadolescent soccer athletes. We show that a periodized unilateral plyometric training program of short

duration performed twice weekly, is more effective for improving short sprint and jump performance during in-season training, as compared with an identical and volume-matched bilateral plyometric training program. Thus, youth soccer coaches may safely use unilateral plyometric exercises after the general warm-up and before the main part of the training session in order to enhance performance in preadolescent boys. A limitation of the present study is the lack of assessment measurements that would reveal possible mechanisms for the greater improvement of performance after unilateral training, such as EMG activity. Another limitation is the absence of measurements in the middle of the intervention, which could offer more information about the time-course of adaptations of unilateral and bilateral plyometric training.

In conclusion, the present study showed that a 10-15 min unilateral plyometric training performed twice per week for 10 weeks during in-season, enhances various measures of sprinting and jumping performance in preadolescent soccer athletes. This may be due to greater neuromuscular adaptations as a result of the greater load imposed on the leg extensors and/or the specificity of training during single leg exercise protocols. Due to the nature of soccer game, which involves explosive single-leg actions, unilateral plyometric training may be a highly effective and safe training modality for optimizing sprinting and jumping performance in preadolescent soccer players.

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