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Effects of plyometric exercise training with optimal drop heights on reactive strength, maximal strength, and vertical stiffness in junior basketball players: a randomised controlled trial

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ABSTRACT
This study examined the effects of 8 weeks of low-to-moderate intensity plyometric training with optimal drop heights on maximal isometric strength, vertical stiffness, and reactive strength in junior male basketball players. Participants were randomly divided into training ($n = 20$) and control ($n = 20$) groups from 3 teams with same division in the state league. Before and after 8 weeks of training, the drop jump (DJ) and isometric mid-thigh pull (IMTP) tests were performed to evaluate force-time measures. The optimal drop height was determined as the height that provided the highest reactive strength index (RSI). The ground contact phase during the DJ was divided into 2 subphases, braking and propulsion, for a detailed analysis of force-time curves. The analyses revealed that plyometric training significantly improved RSI ($p < 0.001$, Cohen's $d = 1.507$), ground contact ($p < 0.001$, $d = -1.255$), braking ($p = 0.001$, $d = -1.066$) and propulsion phase ($p < 0.001$, $d = -1.078$) time. Significant improvements were observed in the peak vertical ground reaction force ($p < 0.001$, $d = 1.715$), peak centre of mass displacement ($p = 0.005$, $d = -0.989$), vertical stiffness ($p = 0.004$, $d = 0.983$). However, there was no significant difference in the jump height ($p = 0.382$, $d = 0.267$) and maximal isometric strength ($p = 0.602$, $d = 0.147$). Plyometric training provided improvements in reactive strength, vertical stiffness, but did not improve maximal isometric strength.

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Introduction

Basketball is a team sport with intense physical demands that often involves running, jumping, and changing direction tasks. During a basketball game, these tasks occur in an intermittent and repetitive pattern (Abdelkrim et al., 2010) and are persistent elements of basketball movement. For example, the average number of jumping tasks in a basketball

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game has been reported to be 44 (Abdelkrim et al., 2007). In a more recent study, the average number of jumping tasks in a basketball game was reported to be 146, with 83% of these jumps being performed with bilateral take-off and 17% with the more demanding unilateral take-off (Talpey et al., 2021). These numbers indicate that players need to have good jumping skills to be successful in basketball (Ziv & Lidor, 2009). The performance of the aforementioned motor tasks depends on strength qualities (Cronin & Hansen, 2005; Ugarkovic et al., 2002), and to improve them, a training method known as plyometric training, which mainly consists of different jumps such as drop jumps (DJs), has long been used in basketball training (e.g., Brown et al., 1986).

Plyometric training utilises and enhances the stretch-shortening cycle (SSC), a natural form of muscle function, and has the potential to improve physical fitness attributes in basketball players, regardless of sex and age (Ramirez-Campillo et al., 2022). SSC occurs when a muscle-tendon unit (MTU) is eccentrically stretched and immediately concentrically contracted, resulting in muscle force potentiation (Komi, 2003). Athletes who can productively use SSC can produce more force and speed (Turner & Jeffreys, 2010). This increase is best explained by 2 proposed models: mechanical and neurophysiological, which rely on contributions from the parallel and series elastic elements of the MTU and stretch reflex, respectively (Komi & Gollhofer, 1997; Lloyd and Oliver, 2020). SSC or plyometric training programmes vary in intensity, duration, drop height, number of jumps per session and frequency of training sessions (Bobbert, 1990). Although a recent meta-analysis indicated that plyometric training generally improves fitness attributes in basketball players (Ramirez-Campillo et al., 2022), the extent to which a specifically designed plyometric exercise programme improves fitness attributes in junior basketball players varies from programme to programme. In addition, the magnitude of improvements in various strength and jumping measures was not at the same level, as evidenced by the variable effect sizes reported in Ramirez-Campillo et al. (2022). For instance, significant small-to-large effects (with exact values in parenthesis) were reported on vertical jump power (0.45), countermovement jump height (1.24) and drop jump height (0.53).

Lower-body plyometric exercises, including jumps in place, standing jumps, multiple hops, box jumps, and drop jumps, are characterised by different intensity levels, directional movements, and box heights. Classically, the intensity of plyometric exercises is divided into 3 categories: low, moderate, and high, based on the effort required to perform the exercise and the loading force (Chu & Myer, 2013). Specifically, in their seminal book, ‘Plyometrics’, Chu and Myer (2013) describe various plyometric exercises categorised by intensity: low (e.g., ankle hops and skipping), moderate (e.g., box jumps and split squat jumps), and moderate to high (e.g., drop jumps, depending on variant and drop height). The intensity of plyometric exercises should be prepared by considering the age of athletes, training history and experience with plyometrics (Chu & Myer, 2013). Although some studies have investigated the effects of high-intensity plyometric training based on a DJ training programme with fixed box heights on junior athletes, low and moderate intensities have also been suggested for junior athletes to minimise the risk of injury in late-maturing or inexperienced adolescents (e.g., Ramirez-Campillo et al., 2018b). On the other hand, fixing the height of the box in jumps would fix the external load for the whole cohort, and it is likely that this load would provide a low training stimulus for early maturing and experienced youths (Cronin & Radnor, 2019). One solution is to use individualised external loads using an optimal drop height (ODH) approach for jumps to optimise training adaptation (Ramirez-Campillo et al., 2018b). This approach has been tested in junior soccer players in a DJ specific training programme, and the results are promising (Ramirez-Campillo et al., 2018b); however, the current literature is limited to its application in junior basketball players and plyometric exercises that combine DJs with lower-intensity jumps.

Various tests and measures have been used to monitor the performance of athletes and evaluate the effectiveness of plyometric or SSC training. For this purpose, portable force plates are increasingly used in exercise and sports science, and a variety of strength qualities, jump measures, and tests can be applied using force plates (Cohen & Kennedy, 2022). One of these strength qualities is the reactive strength, which can be defined as the SSC ability to rapidly change from eccentric to concentric contraction (Young, 1995). Reactive strength is usually quantified using the reactive strength index (RSI) with a DJ protocol, and the DJ-RSI is calculated as the ratio of jump height (JH) to ground contact time (GCT) (Young, 1995) and depends on contributions from the parallel and series elastic elements of the MTU (Lloyd et al., 2011). Another strength property is the maximal strength, which is the ability to generate maximum external force (Haff, 2019). Among several tests and measures, the maximal strength of the leg musculature can be assessed using the absolute peak force (PF) achieved in the isometric mid-thigh pull (IMTP) test (Haff et al., 1997), and IMTP-PF has been shown to be related to many performance metrics. For instance, IMTP-PF has significant moderate to high linear correlations with countermovement jump height (correlation coefficient, $r = 0.82$), squat jump height ($r = 0.87$), and 20-m sprint time ($r = -0.69$) (Haff, 2019). Although a meta-analysis (Villarreal et al., 2010) suggested that plyometric training (without combined isometric strength training or electrostimulation) improves strength performance in general, improvements in outcome measures for maximal isometric strength are not unequivocal (Herrero et al., 2006; Wilson et al., 1993), and data for junior athletes are limited. With information on maximal isometric strength, it would be more objective to evaluate the sources and mechanisms of improvement in physical fitness attributes by plyometric training.

Another measure used to assess the effects of SSC training is vertical stiffness (Kvert) (Maloney & Fletcher, 2021), which is calculated as the ratio of the peak vertical ground reaction force (VGRF) to the peak vertical body centre of mass (BCOM) displacement (McMahon & Cheng, 1990) and relies on the stretch reflex properties of motor units (Komi & Gollhofer, 1997). To date, 2 studies have investigated the effects of plyometric training on Kvert, yet they were conducted with water- (Sporri et al., 2018) or ground-based plyometric training in adult athletes (Rojano Ortega et al., 2022); therefore, data for junior athletes are limited. In addition to Kvert, Pedley et al. (2022) recently proposed a new method to evaluate SSC performance during DJ. According to this method, the lower limb is modelled as a linear spring capable of storing elastic potential energy, and how well this model follows the mass spring model is determined by the spring-like correlation (SLC). The SLC is a unitless number between 0 and 1, and the closer it is to 1, the more successfully it is considered to follow the spring model. Classification of spring-like behaviour is done by evaluating at which part of the GCT period the impact peak occurs during the DJ and in combination with the SLC. Although the number of publications in this area is limited, no study has examined the effect of plyometric training on the spring-like behaviour model in junior athletes.

Despite extensive research on the effects of plyometric training, several important gaps remain, particularly concerning the use of optimal drop heights (ODHs) and their effects on junior athletes. First, most studies on plyometric training have used fixed drop heights, yet very few have been designed using individualised ODHs. Second, although reactive and maximal strength are often evaluated, there is limited research on how these respond specifically to plyometric exercise training with ODHs, particularly when maximal strength is assessed using the IMTP test in junior athletes. Third, while various metrics that define reactive strength quality have been examined, Kvert has not been studied extensively in the context of ODH, especially in conjunction with the novel method of spring-like behaviour for categorising SSC performance (Pedley et al., 2022). Given these limitations in the current literature, the aim of this study was to investigate the effects of low-to-moderate intensity plyometric exercise training with ODHs on Kvert, IMTP-PF, DJ-RSI, and accompanying DJ measures in junior basketball players during the in-season. It was hypothesised that an 8-week plyometric training programme would improve strength qualities, vertical stiffness and spring-like behaviour with varying effect sizes.

Materials and methods

Participants

A statistical power analysis was performed a priori for sample size estimation using G*Power 3.1.9.6 software (Faul et al., 2007). Based on the moderate effect size (dz = 0.45) of RSI reported by Ramirez-Campillo et al. (2023) in their meta-analysis, the minimum sample size required to meet the criteria of alpha = 0.05 and power = 0.80 was calculated to be 12 participants for strength measures for an 8-week plyometric training intervention, but to account for possible injury risks and inability to participate in the plyometric training intervention, groups of 20 participants were designed. A total of 40 participants were included in the study. A total of 20 junior male basketball players aged 15–17 years participated for each group in this study. The study was conducted in 2 groups as plyometric training group (TG, height: 186.9 ± 8.0 cm, weight: 80.7 ± 11.3 kg, age: 16.5 ± 0.8 years) and control group (CG, height: 191.5 ± 6.6 cm, weight: 83.3 ± 10.9 kg, age: 16.6 ± 1.2 years). Since the participants were junior athletes, their biological maturation status was also considered, and their biological maturity offset was calculated according to the Mirwald equations (Mirwald et al., 2002). The results of the anthropometric measurements are presented in Table 1. There were no statistically significant differences in anthropometric values between TG and CG before the study.

Table 1. The height, weight, age and maturation outcomes of the participants.

Variables	Plyometric training group	Control group
Height (cm)	186.9 ± 8.0	191.5 ± 6.6
Weight (kg)	80.7 ± 11.3	83.3 ± 10.9
Age (years)	16.5 ± 0.8	16.6 ± 1.2
Maturity offset (years)	2.9 ± 0.8	3.2 ± 0.9

All participants had been playing basketball at a competitive level for at least 3 years. Participants' weekly practice time ranged from 9 to 12 h. The athletes in the TG continued their regular basketball training and participated in plyometric training 2 days per week. The athletes in the CG participated only in regular basketball training. The participants did not have any neuromusculoskeletal problems that would affect their performance at the time of the pre-tests. All participants and their families gave informed consent to participate in the study. The experimental procedures were approved by local Human Research Ethics Committee (0593-ODTUİAEK-22).

Study design

We examined the effects of an 8-week low-to-moderate intensity plyometric exercise training with ODHs to improve physical fitness attributes of junior basketball players. Two groups were formed from junior male basketball players, one followed the regular basketball practice and plyometric programme, and the other followed the regular basketball practice and extra passing and shooting drills in similar durations as plyometric exercises. Before and after an 8-week period, all players performed DJ and IMTP tests. The study was designed as a randomised controlled trial. The assigned groups consisted of junior athletes who had trained together for at least 3 years and were randomly allocated.

Plyometric training procedures

Plyometric training intervention continued twice a week for a total of 8 weeks. Previous studies suggested that the most effective duration of plyometric training should be less than 10 weeks and approximately between 8 and 10 weeks (Bedoya et al., 2015; De Villarreal et al., 2009). The frequency of plyometric training varies according to the sport and the training history of the athletes. However, in general, plyometric training sessions are recommended only 2 or 3 times a week on non-consecutive days. Therefore, there was a 48-h rest period between the 2 training sessions (Chu & Myer, 2013). Participants did not take part in competition before the plyometric training sessions. While designing the study, it was taken into consideration that the participants were junior athletes and their adaptation to training was monitored. The number of repetitions to be performed in the study was determined according to the impact of the jumps. At the same time, the concept of ODH was used in the study (Ramirez-Campillo et al., 2018b). ODHs were calculated using the RSI. ODHs were calculated using an incremental DJ protocol (adapted from Byrne et al., 2017). When calculating the ODH, participants performed DJs starting from a 20 cm box. The drop height was increased by 5 cm increments to a maximum of 60 cm or until RSI showed 2 subsequent decreases (Flanagan & Comyns, 2008). The drop height at which the highest RSI value was recorded was identified as the ODH.

The ODH was calculated at the beginning of the study to establish individualised training loads for each athlete. Fixing the drop height across the cohort would mean that one fixed external load may be sufficient for some junior athletes, yet it may be excessive or insufficient for others (Acero et al., 2012). We repeated the incremental ODH calculation protocol at the 5th week to adjust the external load in plyometric exercises, accounting for performance gains achieved during the first 4 weeks of training. This approach ensured that junior athletes trained with optimal, personalised external loads throughout the 8 weeks. The ODHs and corresponding RSI values were provided as supplementary online material.

No injuries were observed during the training or within the study. Two participants were injured in competitions with direct contacts. Rest intervals were 1 min between sets and 2 min between exercises. The complete plyometric training plan with the number of jumps was given in Table 2.

Anthropometric measurements

The height of the participants was measured with a Holtain portable stadiometer. During measurements, the participants were in anatomical posture in a static position. The trunk length of the participants was measured while sitting on a 50 cm box on the stadiometer. The leg flexion angle was around 90 degrees. The leg length was calculated by subtracting the trunk length from the body height. The body mass was measured with a Tanita scale.

Vertical jump test

In the study, DJ was used to measure the effects of the plyometric training programme. DJ measurements were performed with a force plate. The drop height was fixed to 30 cm in the measurements. The participants performed DJs with their hands on their hips. Separation of the hands from the hips was considered as an error and the measurement was repeated. Participants were instructed to stay on the force plate minimum, then jump upward maximally. Each participant jumped 3 times and the best performance was used for further processing (Byrne et al., 2017).

During the DJs, the VGRF traces were recorded at 2000 Hz with a portable single force plate (Kistler 9260AA, Switzerland) for 10 s, and only 1 DJ was performed during the sampling period. The VGRF traces of DJs were analysed using a custom code written in MATLAB. The code calculates Kvert, DJ-RSI, and accompanying 14 DJ measures. The formulation of the measures was described in detail in Celik et al. (2024) and Pedley et al. (2022), and briefly below:

- *Jump Height* (JH in cm): The peak displacement attained by the body centre of mass (BCOM) during the flight phase calculated using the flight time in the air.

Table 2. Eight-week plyometric exercise training programme.

	Sets and repetitions							
Type of exercise	Week1	Week2	Week3	Week4	Week5	Week6	Week7	Week8
Ankle hops	2 × 10	3 × 10						
Squat jump	2 × 10	2 × 12	3 × 10	3 × 10	3 × 10			
Lunge jump	2 × 10	2 × 12	3 × 10	3 × 10	3 × 10			
Tuck jump	2 × 5	1 × 5	2 × 5	2 × 5	2 × 8	2 × 10		
Deep squat jump			1 × 5	1 × 5			2 × 10	2 × 10
Box jump				1 × 8	1 × 10	1 × 8	2 × 10	2 × 10
Split squat jump						2 × 10	2 × 10	
Drop jump					1 × 8	2 × 8	3 × 10	3 × 10
Total number of jumps	70	83	75	83	94	76	84	70

- *Reactive Strength Index* (RSI in m/s): RSI is calculated by dividing the jump height by the time on the ground. It is a frequently used measure for evaluating SSC performance.
- *Ground Contact Time* (GCT in ms): GCT covers the time from the moment of the first contact with the ground to the time when contact is broken. It is used to classify SSC (<250 ms fast, >250 ms slow, Schmidtbleicher, 1992).
- *Braking Phase Time* (BPT in ms): GCT was further divided into 2 sub-phases as braking and propulsion. BPT is the time from initial contact with the force platform to the instant of zero vertical velocity of the BCOM.
- *Propulsion Phase Time* (PPT in ms): PPT was from the instant where the BPT ends to the point where contact of the foot with the platform ends.
- *Peak Center of Mass Displacement* (PCOMD in cm): PCOMD is the peak vertical displacement during the jump from the moment of landing on the force plate until the end of the braking phase.
- *Peak Vertical Ground Reaction Force* (PGRF in body weight (BW)): PGRF is the global maximum value of the VGRF in the braking and propulsion phases.
- *Normalized Vertical Stiffness* (Kvert in N/m/kg): Kvert was calculated as the ratio of the PGRF during the contact phase of the jump to the displacement of the BCOM at the time of the PGRF. It was then normalised by the body mass.
- *Landing Peak Force* (LPF in BW): The peak VGRF applied to the BCOM during the braking phase.
- *Take-off Peak Force* (TPF in BW): The peak VGRF applied to the BCOM during the propulsion phase.
- *Average Power Eccentric Phase* (LPow W/kg): The mean mechanical power applied to the BCOM during the braking phase.
- *Average Power Concentric Phase* (Tpow in W/kg): The mean mechanical power applied to the BCOM during the propulsion phase.
- *Landing to Take-off Time Difference* (LTTD in %): Braking phase peak force timing to propulsion phase peak force timing difference.
- *Braking Impulse* (Braking Impulse in BW*s): The vertical impulse applied to the BCOM during the braking phase.
- *Propulsion Impulse* (Propulsion Impulse in BW*s): The vertical impulse applied to the BCOM during the propulsion phase.
- *Spring Like Correlation* (SLC in unitless): A Pearson product-moment correlation between the VGRF applied to the BCOM and the vertical displacement of the BCOM in the contact phase (Pedley et al., 2022).
- *Spring Like Behavior* (SLB in unitless): A classification that evaluates the function of the stretch-shortening cycle according to Pedley et al. (2022).

Isometric mid-thigh pull test

IMTP test was used to measure the maximal isometric strength of the participants (Haff, 2019). The participants performed the IMTP test with a non-moving apparatus on the same portable force plate used in the vertical jump test. Before the IMTP test, the height of the bar was adjusted according to the participant's second pull position. This position provides a knee extension angle of 120–135 degrees and as used in previous studies participants (Haff, 2019). In the tests, the position of the trunk should be upright and the position of the feet should be positioned under the bar, centred on the force platform, and in accordance with the participant's foot span roughly centred on the bar, and the knees should remain in slight contact with the bar (Comfort et al., 2019). During the test, the participants were asked to pull the stationary bar upwards as fast and as hard as possible while holding their position and pushing their feet into the force plate. Before pulling the bar, the participants were instructed not to perform a countermovement, and the measurement was invalidated in this case. Participants performed 3 trials, and the trial with the maximal VGRF value was considered as the participant's maximal isometric strength for further analysis.

Data collection and measurement protocol

All measurements in the study were performed as pre- and post-test measurements. One week after the pre-test measurements, an 8-week training programme was practiced. At the end of the training programme, the post-test measurements were performed 48 h after the last training session. All pre- and post-test measurements were performed using the same protocol. The measurements of all participants were completed within 2 days. The anthropometric measurements of the participants were completed on the first measurement day of the study and biological maturation outcomes were calculated. On the second measurement day of data collection, vertical jump and IMTP tests were performed. Before starting the measurements in the study, all participants were subjected to a standardised warm-up protocol. After jogging for 5 min at an average pace and at least 1 dynamic exercise for each major muscle group (Flanagan et al., 2008). Participants were given the opportunity to practice the test to create familiarisation before the measurements. It is assumed that all participants showed maximal effort in the tests. All measurements were performed at the same time in the evening (18:30–20:30).

Statistical analysis

Descriptive statistics (mean ± standard deviation) of all variables were calculated. Normality distribution of the variables was checked with Lilliefors test. Independent samples t-tests were used to determine the initial differences between TG and CG in height, weight, age, and maturity offset. A 2 × 2 mixed factorial (time (within-subjects) and group (between-subjects)) repeated measures ANOVA with Bonferroni post-hoc tests was performed to determine significant differences after the plyometric training programme for each force-time measure. Two-way ANOVA models were run with equal sample sizes in each group, and their assumptions were checked: sphericity (automatically satisfied as there were 2 levels for each factor), homogeneity of variance (using Levene's test), and normality of residuals (using Q-Q plots) (Navarro et al., 2025). In addition, Cohen's d (denoted as d) was used to estimate effect sizes in groups, and the effect sizes were categorised as minimal (<0.20), small (0.20–0.50), moderate (0.50–0.80), large (0.80–1.20), and very large (>1.20) (Cohen, 2013). Statistical analyses were performed using MATLAB 25.1 (R2025a) and JASP (JASP Team, 2025; Navarro et al., 2025). The significance level was set at $p < 0.05$.

Results

At the start of the study, we did not observe any significant differences between the TG and CG in terms of the variables examined in the study. This suggests that prior to the 8-week training intervention, the groups were successfully randomised and homogeneously assigned, and the height, weight, age, and maturity offset of the junior athletes were levelled (Table 1).

The 2 × 2 mixed factorial ANOVA results revealed significant time × group interaction effects for several variables (Table 3). Specifically, significant interactions were observed for RSI ($p = 0.008$), GCT ($p = 0.040$), LPow ($p = 0.047$), PGRF ($p = 0.001$), LPF ($p < 0.001$), TPF ($p = 0.006$), PPT ($p = 0.028$), and SLC ($p = 0.003$). These interaction effects indicate that the training and control groups were affected differently by time. For main effects, significant group differences were found for JH ($p < 0.001$), RSI ($p < 0.001$), GCT ($p = 0.048$), LPow ($p = 0.006$), Tpow ($p = 0.019$), PGRF ($p < 0.001$), LPF ($p = 0.001$), TPF ($p = 0.008$), and SLC ($p = 0.001$) (Table 3). Significant main effects of time were observed for RSI ($p = 0.001$), GCT ($p < 0.001$), Tpow ($p = 0.021$), PCOMD ($p = 0.003$), PGRF ($p < 0.001$), LPF ($p < 0.001$), TPF ($p < 0.001$), LTTD ($p = 0.046$), Kvert ($p = 0.002$), BPT ($p = 0.001$), PPT ($p = 0.009$), and SLC ($p = 0.029$) (Table 3). Table 3 also presents the descriptive statistics of the force-time measures.

Table 4 shows the mean differences of the pre- and post-test scores for each variable (17 in total) for each group (i.e., TG (left) and CG (right)) separately, as well as the exact p-values and the effect sizes as Cohen's d. We observed significant differences in 12 variables in the TG between pre- and post-tests. For example, there was a significant decrease in GCT ($p < 0.001$, d=-1.255) and its subcomponents BPT ($p = 0.001$, d=-1.066) and PPT ($p < 0.001$, d= −1.078), and a significant increase in RSI from 1.13 to 1.48 m/s ($p < 0.001$, d=1.507). We also observed significant increases in vertical stiffness as Kvert ($p = 0.004$, d=0.983), while a significant decrease in PCOMD ($p = 0.005$, d=-0.989), consistent with the vertical stiffness findings. In addition, significant increases in PGRF ($p < 0.001$, d=1.715), LPF ($p < 0.001$, d= 1.666), TPF ($p < 0.001$, d=1.561), LTTD ($p = 0.010$, d=-0.724), LPow ($p = 0.032$, d=0.606), Tpow ($p = 0.033$, d=0.657) with moderate to very large effect sizes were observed during the DJ test.

Four variables did not have a significant difference in the DJ test, for example, JH ($p = 0.382$, d=0.267) and SLC ($p = 0.534$, $d = 0.212$). In addition to these findings, there was also no significant difference in maximal isometric strength between pre- and post-test for TG in the IMTP test ($p = 0.602$, d=0.147). When comparing the pre- and post-test scores of the CG, no statistically significant differences were observed for any of the variables studied other than SLC (Table 4).

Additionally, according to the classification of spring-like behaviour (Pedley et al., 2022), 11 TG athletes were classified as good, 7 as moderate, and 2 as poor at the beginning, whereas at the end of 8 weeks of plyometric training, 17 athletes were classified as good, 2 as moderate, and 1 as poor. Figure 1 presents the spring-like behaviour classifications before and after 8 weeks of plyometric training.

Discussion

This study investigated the improvements in several strength qualities and vertical stiffness of junior male basketball players after 8-week low-to moderate-intensity

Table 3. The descriptive statistics and repeated measure ANOVA results of force-time measures for group and time conditions.

			Descriptive statistics		Main effect—interaction (*p*-value)		
Metric	Group	Time	Mean	SD	Group	Time	Interaction
JH	TG	Pre	31.80	4.11	<0.001	0.468	0.607
		Post	32.85	5.16			
	CG	Pre	27.06	2.83			
		Post	27.24	3.19			
RSI	TG	Pre	1.13	0.24	<0.001	0.001	0.008
		Post	1.48	0.32			
	CG	Pre	0.97	0.19			
		Post	1.01	0.14			
GCT	TG	Pre	301.7	57.4	0.048	<0.001	0.040
		Post	220.2	35.1			
	CG	Pre	303.5	92.4			
		Post	279.7	61.1			
LPow	TG	Pre	35.53	6.94	0.006	0.284	0.047
		Post	41.56	11.39			
	CG	Pre	32.16	6.25			
		Post	30.30	13.39			
Tpow	TG	Pre	35.51	6.17	0.019	0.021	0.482
		Post	41.43	7.80			
	CG	Pre	31.66	7.10			
		Post	34.89	13.25			
PCOMD	TG	Pre	23.08	4.20	0.238	0.003	0.336
		Post	14.69	4.83			
	CG	Pre	23.25	10.90			
		Post	18.78	11.31			
PGRF	TG	Pre	4.25	0.86	<0.001	<0.001	0.001
		Post	5.69	0.96			
	CG	Pre	4.27	0.88			
		Post	4.30	0.62			
LPF	TG	Pre	4.21	0.89	0.001	<0.001	<0.001
		Post	5.65	1.03			
	CG	Pre	4.27	0.88			
		Post	4.25	0.60			
TPF	TG	Pre	3.82	0.58	0.008	<0.001	0.006
		Post	5.06	0.97			
	CG	Pre	3.90	0.79			
		Post	4.04	0.79			
LTTD	TG	Pre	27.22	12.27	0.565	0.046	0.086
		Post	16.34	12.17			
	CG	Pre	20.01	17.43			
		Post	19.16	17.36			
Kvert	TG	Pre	290.2	131.4	0.238	0.002	0.321
		Post	604.6	513.5			
	CG	Pre	279.9	120.0			
		Post	447.3	336.9			
BPT	TG	Pre	145.5	40.5	0.101	0.001	0.162
		Post	95.9	24.1			
	CG	Pre	149.4	60.5			
		Post	128.4	51.4			
PPT	TG	Pre	155.2	24.2	0.060	0.009	0.028
		Post	124.4	21.6			
	CG	Pre	154.1	35.2			
		Post	151.4	32.2			
Braking Impulse	TG	Pre	0.38	0.07	0.785	0.053	0.509
		Post	0.32	0.06			
	CG	Pre	0.37	0.09			
		Post	0.34	0.13			
Propulsion Impulse	TG	Pre	0.40	0.05	1.000	0.530	0.213
		Post	0.37	0.05			

(*Continued*)

Table 3. (Continued).

			Descriptive statistics		Main effect—interaction (*p*-value)		
Metric	Group	Time	Mean	SD	Group	Time	Interaction
	CG	Pre	0.38	0.05			
		Post	0.39	0.10			
SLC	TG	Pre	0.88	0.08	0.001	0.029	0.003
		Post	0.90	0.10			
	CG	Pre	0.88	0.07			
		Post	0.76	0.12			
Max. Strength	TG	Pre	2014	375.8	0.961	0.573	0.862
		Post	2062	406.8			
	CG	Pre	2029	206.0			
		Post	2054	261.5			

JH: jump height (cm), RSI: reactive strength index (m/s), GCT: ground contact time (ms), LPow: average power eccentric phase (W/kg), Tpow: average power concentric phase (W/kg), PCOMD: peak centre of mass displacement (cm), PGRF: peak vertical ground reaction force (Body Weight (BW)), LPF: landing peak force (BW), TPF: take-off peak force (BW), LTTD: landing to take-off time difference (%), Kvert: normalised vertical stiffness (N/m/kg), BPT: braking phase time (ms), PPT: propulsion phase time (ms), Braking Imp.: braking impulse (BW*s), Propulsion Imp.: propulsion impulse (BW*s), SLC: spring like correlation (unitless), Max. Strength: maximal isometric strength (Newton).

Table 4. The post hoc analysis of group × time interaction effects (conditional on group) on force-time measures.

		Training Group			Control Group		
Measure	Comparison	Mean Diff.	*p*-value	Cohen's *d*	Mean Diff.	*p*-value	Cohen's *d*
JH	Post-Pre	1.05	.382	0.267	0.18	.880	0.046
RSI	Post-Pre	0.35	<.001	1.507	0.04	.614	0.172
GCT	Post-Pre	−80.4	<.001	−1.255	−23.8	.213	−0.372
LPow	Post-Pre	6.03	.032	0.606	−1.86	.497	−0.187
Tpow	Post-Pre	5.92	.033	0.657	3.23	.235	0.358
PCOMD	Post-Pre	−8.39	.005	−0.989	−4.47	.124	−0.527
PGRF	Post-Pre	1.44	<.001	1.715	0.03	.915	0.036
LPF	Post-Pre	1.44	<.001	1.666	−0.02	.941	−0.023
TPF	Post-Pre	1.24	<.001	1.561	0.14	.601	0.176
LTTD	Post-Pre	−10.88	.010	−0.724	−0.86	.832	−0.057
Kvert	Post-Pre	314.4	.004	0.983	167.4	.113	0.524
BPT	Post-Pre	−49.6	.001	−1.066	−21.1	.139	−0.457
PPT	Post-Pre	−30.8	<.001	−1.078	−2.71	.732	−0.104
Braking Imp.	Post-Pre	−0.06	.067	−0.656	−0.03	.351	−0.328
Propulsion Imp.	Post-Pre	−0.03	.187	−0.454	0.01	.657	0.151
SLC	Post-Pre	0.02	.534	0.212	−0.12	<.001	−1.270
Max. Strength	Post-Pre	47.5	.602	0.147	25.1	.783	0.078

JH: jump height (cm), RSI: reactive strength index (m/s), GCT: ground contact time (ms), LPow: average power eccentric phase (W/kg), Tpow: average power concentric phase (W/kg), PCOMD: peak centre of mass displacement (cm), PGRF: peak vertical ground reaction force (Body Weight (BW)), LPF: landing peak force (BW), TPF: take-off peak force (BW), LTTD: landing to take-off time difference (%), Kvert: normalised vertical stiffness (N/m/kg), BPT: braking phase time (ms), PPT: propulsion phase time (ms), Braking Imp.: braking impulse (BW*s), Propulsion Imp.: propulsion impulse (BW*s), SLC: spring like correlation (unitless), Max. Strength: maximal isometric strength (Newton).

plyometric training. The results of the study showed that in the plyometric TG, GCT and its subcomponents BPT and PPT decreased significantly, RSI values increased accordingly, and significant increases were observed in the average power in the braking and propulsion phases with moderate to very large effect sizes. PCOMD decreased significantly with large effect and Kvert increased significantly with large effect size. However, there was no significant change in the IMTP test outcomes after training intervention. In

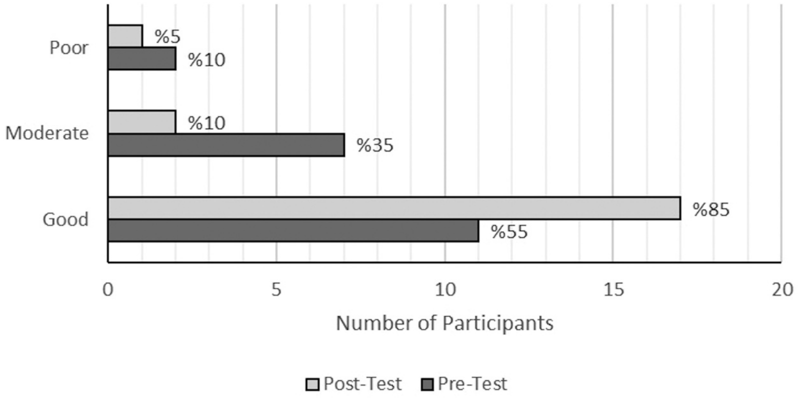

Figure 1. Changes in spring-like behaviour of junior athletes in the training group following an 8-week plyometric training programme.

the pre- and post-test comparison of the CG, no significant change was observed in any of the parameters (except SLC) with minimal to moderate effect sizes.

The SSC is largely associated with rapid force generation and reactive strength (Healy et al., 2019). The reactive strength describes the ability to produce high forces in a short period of time, usually against high eccentric loads (Lockie et al., 2015). Mostly, the RSI represents an individual athlete's ability to perform SSC at a high level of performance (Jarvis et al., 2022). According to our hypothesis, we expected that the strength qualities would improve after 8-week plyometric training. Our hypothesis was partially supported by the present results, as the comparisons between the pre- and post-test scores of the RSI which reflects reactive strength yielded significant differences, with very large effect size. Conversely, JH did not exhibit improvement following the plyometric training intervention; thus, the observed changes in RSI can be attributed to alterations in GCT. Maximal strength, as evaluated by the IMTP test, did not undergo significant changes following the 8-week training period. Plyometric training usually includes jumps on the vertical and horizontal axes, such movements utilise SSC, hence the template of plyometric training is directly oriented towards training reactive strength. Our findings were also consistent with the current literature in terms of the effect of plyometric training on reactive strength (Chaabene et al., 2021; Jeffreys et al., 2019; Lloyd et al., 2012). On the other hand, conflicting results were presented on the effects of plyometric training on maximal isometric strength (e.g., Lum et al., 2022; Talukdar et al., 2021).

Although the IMTP test is commonly used to assess maximal strength, the effects of plyometric training on maximal strength, as assessed using the IMTP test, are few. In a recent meta-analysis of plyometric training and basketball (Ramirez-Campillo et al., 2022), the effects of plyometric training on maximal strength were evaluated using isokinetic tests in 5 studies (Arazi & Asadi, 2011; Asadi et al., 2017; Matavulj et al., 2001; Meszler & Váczi, 2019; Wilkerson et al., 2004). In these studies, 3 reported significant differences in only 1 measure in various degrees of maximal isokinetic strength measures, yet Arazi and Asadi (2011) reported that plyometric training did not directly improve maximal strength. In Asadi et al. (2017), the authors clearly stated that maximal strength improved on a 45° leg press test. None of those 5 studies used IMTP as their test in their studies. The IMTP test is safer (De Witt et al., 2018) and highly valid (Comfort et al., 2015) than the 1RM tests and provides an opportunity to examine force-time curves when testing maximal forces (Comfort et al., 2019). In our study, we investigated the effect of plyometric training on maximal strength using the IMTP test and found that plyometric training did not improve maximal strength in junior male basketball players. In line with our findings, there are no studies on the effect of plyometric training on maximal strength assessed by IMTP test outcomes in basketball, whereas there are very few studies in other sports. Specifically, in 2 studies (Lum et al., 2022; Secomb et al., 2017), it was reported that plyometric training did not improve maximal strength assessed through the IMTP, while in 1 study (Talukdar et al., 2021), it was reported that it showed a moderate effect size improvement in a cohort of 52 girls (hockey, football, water polo, netball, and athletics) with a mean age of 13.3 years. To the best of our knowledge, the IMTP test has never been used to assess maximal strength after plyometric training intervention in the context of basketball.

The GCT is a very useful parameter in assessing jumping performance and SSC classification (Schmidtbleicher, 1992). Although GCT provides much data on its own, with the use of force platforms in jump testing, we have additional information about the GCT and its subcomponents in braking and propulsion phases. The SSC consists of 2 distinct subphases: the braking phase represents the eccentric phase and the propulsion phase represents the concentric phase (Komi, 2003). Knowing the effect of plyometric training on these phases (e.g., BPT and PPT) could be critical for assessing the effects of plyometric training. In our study, we reported the effects of plyometric training on BPT and PPT with large effect sizes (d=-1.066, d=-1.078, respectively). In addition, there were differences with very large effect sizes on the LPF (d=1.666) and TPF (d=1.561), which has the potential to decrease the ground contact times on the braking and propulsion. Rojano Ortega et al. (2022) also reported positive effects of plyometric training on PPT. Nevertheless, if we look at the literature, only a few studies have reported plyometric training improves the braking forces for lower limbs (e.g., Chelly et al., 2010, 2014). The athletes can tolerate higher forces during the braking phase and can quickly transfer that force to the propulsion phase (Cormie et al., 2010). One study (Matic et al., 2015) reported that athletes who spent less time on the ground produced higher forces during braking and propulsion phases. However, the number of studies investigating the effects of plyometric training on the braking and propulsion phases is rather limited; therefore, further studies are needed to investigate the effects of plyometric training using force plates.

Another hypothesis of our study was that 8-week of plyometric training with optimal drop heights would improve Kvert. Our results showed that Kvert increased significantly with an improvement of 108% in normalised units. Rojano Ortega et al. (2022) examined the effects of 8-week plyometric training on Kvert and lower extremity force production. The results of the findings of that study were consistent with the findings of our study. However, the improvements in Kvert in our study were greater. This may be due to both gender differences and training drills with optimal loads. Other studies also showed that plyometric training improves Kvert and jump performance (Brazier et al., 2019; Lloyd et al., 2012). In addition to performance assessment, Kvert can be a useful tool for practitioners for profiling to optimise training loads involving high neuromuscular demands (Fletcher & Maloney, 2025). The timing of impact peaks is a major factor in SLB classification. In our study, the SLC values for TG did not improve on average; however, participants exhibited an improved SLB classification compared to baseline (good: 55% to 85%; moderate: 35% to 10%; poor: 10% to 5%), primarily due to a shift in impact peaks from the initial 20% to the latter 80% of ground contact time.

The effectiveness of plyometric training was suggested to be related to the drop height (Ramirez-Campillo et al., 2018a). Drop height is an intensity variable of plyometric training that should be adjusted to suit the individual (Flanagan & Comyns, 2008). Ramirez-Campillo et al. (2018b) highlighted that plyometric training performed at ODH was more efficient than that performed at constant height, reporting a 15% greater improvement in DJ measures with higher effect sizes. Additionally, Flanagan and Comyns (2008) stated that DJ exercises performed at heights below and above the ODH may limit the gains of athletes and increase the risk of injury, respectively. However, the literature on comparing fixed drop height with ODH is limited. For instance, a review study found that only 2% of published studies included ODH, 40% used fixed height, and ODH is a parameter that needs to be further studied Ramirez-Campillo et al. (2020). In a recent meta-analysis by Ramirez-Campillo et al. (2022), ODH was not used in any of the studies that examined its effects on jumping performance in basketball. In that study, the effect sizes ranged from 0.45 to 0.84 for the jumping variables studied, such as vertical jump power. In our study, we generally observed larger effect sizes (e.g., Cohen's *d* for GCT = −1.255, Table 4).

While RSI and its constituent metrics (i.e., JH and GCT) provide extensive information on the athlete's ability to utilise the SSC function, performing RSI measurements with an incremental DJ protocol has the potential to provide a more complete picture of athletes' reactive strength quality. Such a protocol allows additional information in the form of a reactive strength profile of the athlete, maximal RSI, and ODH, which can be useful in everyday practice to determine training intensity and readiness to train (Byrne et al., 2017; Flanagan & Comyns, 2008; Pedley et al., 2017). Although the DJ test is usually assessed using a force platform, it can also be performed using more accessible, low-cost, and easy-to-maintain tools, such as the My Jump app (Haynes et al., 2019), photocell-based systems such as the Optojump (Byrne et al., 2017), and jump mats (Markwick et al., 2015). These tools, or portable force plates, could enable coaches and sports scientists to incorporate an incremental DJ protocol into their everyday practice. In doing so, they can help determine optimal training intensity and load, as well as group athletes with similar profiles for training (Flanagan & Comyns, 2008).

Our study had several limitations. First, the design of our study included junior male basketball players. Therefore, adult male participants may be studied in future studies. Also, the results obtained at the end of this study may differ by gender. Gender differences may be a research topic for future studies. The secondary limitation of our study was the design of the plyometric training. We used ODH as a design parameter in our study design but did not compare it to a fixed drop height with a 3rd experimental group. A comparison with a training programme designed over a fixed drop height may be considered a research topic for future studies.

Conclusion

An 8-week, low-to-moderate intensity plyometric training programme using optimal drop heights improved reactive strength and vertical stiffness in junior male basketball players. However, this intervention did not result in improvements in maximal isometric strength. This study addresses a research gap by reporting the effects of plyometric training on reactive strength, vertical stiffness, and maximal isometric strength in this population. Results indicate that while RSI improved following training, these improvements were due to a reduction in GCT rather than an increase in JH, as the latter did not change significantly. Finally, the observed modifications in ground contact time biomechanics also reflected improved spring-like behaviour in the athletes, with 6 of the 9 participants advancing to a higher classification level.

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