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Research article

Unilateral Plyometric Jump Training Shows Significantly More Effective than Bilateral Training in Improving Both Time to Stabilization and Peak Landing Force in Single-Leg Lend and Hold Test: A Randomized Multi-Arm Study Conducted Among Young Male Basketball Players

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Abstract

Enhancing peak landing forces and ensuring faster stabilization in the lower limbs during jumping activities can significantly improve performance and decrease the risk of injury among basketball players. This study aimed to compare the effects of unilateral (uPJT) and bilateral plyometric jump training (bPJT) programs on various performance measures, including countermovement jump (CMJ), squat jump (SJ), and single-leg land and hold (SLLH) test outcomes, assessed using force plates. A randomized multi-arm study design was employed, comprising two experimental groups (n = 25; uPJT and n = 25; bPJT) and one control group (n = 25), conducted with youth male regional-level basketball players (16.3 ± 0.6 years old). Participants underwent assessment twice, both before and after an 8-week intervention training period. The uPJT program exclusively involved plyometric drills (e.g., vertical jump exercises; horizontal jump exercises) focusing on single-leg exercises, whereas the bPJT program utilized drills involving both legs simultaneously. The outcomes analyzed included CMJ peak landing force, CMJ peak power, SJ peak force, SJ maximum negative displacement, SLLH time to stabilization, and SLLH peak landing force. The control group exhibited significantly greater SLLH time to stabilization compared to both the uPJT ($p < 0.001$) and bPJT ($p < 0.030$) groups. Additionally, time to stabilization was also significantly higher in bPJT than in uPJT ($p = 0.042$). Comparisons between groups in regards SLLH peak landing force after intervention revealed that the value was significantly smaller in uPJT than in bPJT ($p = 0.043$) and control ($p < 0.001$). In the remaining outcomes of CMJ and SJ, both uPJT and bPJT showed significant improvement compared to the control group ($p > 0.05$), although there was no significant difference between them. In conclusion, our study suggests that utilizing uPJT is equally effective as bPJT in enhancing performance in bilateral jump tests. However, it significantly outperforms bPJT in improving time to stabilization and peak landing forces during single-leg land and hold test. uPJT could be advantageous not for maximizing performance but also for potentially decreasing injury risk by enhancing control and balance during single-leg actions, which are common in basketball.

Key words: Basketball, athletic performance, resistance training, balance, jumping.

Introduction

Basketball is an intermittent sport in terms of physiological and physical demands (Stojanovic et al., 2018). Players are often exposed to very intense neuromuscular actions, such as jumping to rebound or shooting (Cherni et al., 2021). Therefore, the forces that players experience are a significant concern (Mercer et al., 2022). Ensuring the most appropriate conditions to cope with these demands in both match and training contexts is crucial. Among other aspects, improving peak landing forces and time to stabilization is crucial for enhancing performance and reducing injury risk in basketball players (Garbenytė-Apolinskienė et al., 2018; Guo et al., 2021). Some studies have suggested that high peak landing forces during jumps are associated with increased risk of lower extremity injuries, including ankle sprains, knee ligament injuries, and stress fractures (Withrow et al., 2006). Additionally, prolonged time to stabilization after landing has been linked to decreased dynamic stability and heightened susceptibility to injury (DuPrey et al., 2016). By optimizing landing mechanics and neuromuscular control, athletes can mitigate excessive forces on their joints and tissues, thus reducing the likelihood of injury (Hewett et al., 2013). Moreover, enhancing the ability to rapidly stabilize after landing facilitates quicker recovery of balance and readiness for subsequent movements (Buckthorpe, 2021), potentially leading to improved performance outcomes. Therefore, interventions aimed at reducing peak landing forces and enhancing time to stabilization should be integral components of injury prevention and performance enhancement programs for basketball players (Garbenytė-Apolinskienė et al., 2018).

Incorporating resistance training into basketball strength and conditioning programs can significantly enhance athletes' ability to manage the physical demands of matches and training sessions (Caparrós et al., 2022). This training approach may guide adaptations that improve force absorption (amortization) and increases the ability to handle strength demands in unilateral exercises for instance (Burgos-Jara et al., 2023). Among the various forms of resistance training, plyometric jump training (PJT) is particularly beneficial. It is versatile in its implementation and has been shown in numerous studies to effectively enhance muscular strength and power (Kons et al., 2023; Cao et al., 2024). Studies indicate that PJT interventions lead to significant improvements in jump height (Markovic and Newton, 2007), and power (Aksovic et al., 2021). Moreover, PJT can be effective in enhancing jumping performance while concurrently may improving peak landing forces and time to stabilization (Ramirez-Campillo et al., 2022). Importantly, plyometric training also fosters adaptations in landing mechanics, promoting the attenuation of

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peak landing forces through enhanced eccentric muscle strength and neuromuscular control (Buckthorpe and Della Villa, 2021). Additionally, plyometrics have been demonstrated to reduce the time to stabilization after landing, facilitating quicker recovery of balance and readiness for subsequent movements (Huang et al., 2021).

When implementing PJT, one can enhance it by incorporating both unilateral (uPJT) and bilateral exercises (bPJT), each with different implications for jumping performance, peak landing forces, and stabilization time (Ramírez-Campillo et al., 2015). bPJT exercises involve both lower limbs simultaneously, while uPJT exercises engage one limb at a time. Research suggests that bPJT generally elicit greater improvements in bilateral vertical jump height and power output compared to uPJT due to the involvement of larger muscle mass and the ability to generate higher forces (Ramirez-Campillo et al., 2018). However, uPJT has been shown to also enhance dynamic strength and promote improvements in stability (Drouzas et al., 2020). Additionally, a study comparing uPJT and bPJT revealed that uPJT was significantly more effective in improving single and double-leg jumping performance, as well as increasing isometric leg press maximal force and rate of force development, compared to bPJT (Bogdanis et al., 2019). This trend was also confirmed in another study, which found that uPJT was more effective in increasing muscle strength and power (Drouzas et al., 2020). Besides enhancements in muscle strength and power, unilateral exercises can help address strength asymmetries and balance deficits between limbs, which are common in athletes (Gonzalo-Skok et al., 2017). uPJT may also contribute to distribute landing forces more evenly between limbs, potentially reducing peak forces on each limb (Zhang et al., 2023).

Despite the possibilities mentioned above, there is a scarcity of research investigating experimental studies that compare the effects of uPJT and bPJT on key outcomes more closely related to landing forces or time to stabilization. These factors can help mitigate injury risk in basketball players while ensuring optimized performance. Understanding the effects of both training approaches on performance outcomes related to jumping can help identify whether adaptations are specific to the drills implemented. Since jumping performance and landing are essential in basketball, as they occur frequently during matches, it is paramount to understand how uPJT or bPJT can affect jumping performance outcomes, landing forces, and time to stabilization. This understanding can provide valuable insights for future strength and conditioning programs. Thus, this study purposes to compare the effects of uPJT and bPJT programs on various performance measures, including countermovement jump (CMJ), squat jump (SJ), and single-leg land and hold (SLLH) test outcomes, assessed using force plates. We hypothesize that uPJT will significantly outperform bPJT in unilateral tests and bilateral tests (Drouzas et al., 2020).

Methods

Study design

The research followed a randomized controlled approach, where two experimental intervention groups (uPJT and bPJT) were introduced alongside the standard training regimen. A control group exclusively underwent regular basketball training (Figure 1). Participants were recruited through convenience sampling from existing basketball teams in the region. To assign participants to groups, a simple randomization method using 1:1 allocation ratio was employed using opaque envelopes distributed randomly among basketball players before the initial assessment, thus providing equal opportunities for assignment to any group. The randomization process was conducted by a researcher who was not involved in subsequent evaluations, ensuring fairness and impartiality. This researcher was solely responsible for the randomization and did not participate in the experiments. Evaluations took place one week before the intervention began and immediately after the eighth week. These assessments were conducted by independent researchers who were unaware of the participants' group allocations.

Participants

The initial sample size was calculated in advance to accommodate an effect size of 0.2, considering three separate groups and two measurements. The goal was to achieve a statistical power of 0.85 while maintaining a significance level of 0.05 for F tests, particularly ANOVA repeated measures, within-between interaction. Utilizing G*power software (version 3.1.9., Universität Düsseldorf, Germany), the analysis recommended that the study enroll 72 participants.

Following recruitment into the regional basketball teams, a total of 87 eligible participants were initially identified. However, after applying the specified inclusion criteria, which included (i) attendance at both evaluation points, (ii) a minimum of three years of experience in the sport, (iii) participants were required to attend at least 80% of basketball training sessions and 90% of the experimental interventions for those in the experimental groups; (iv) absence of injury or illness during the experiment or the month before its start, (v) non-enrollment in additional strength and conditioning training programs basketball training, and (vi) being male, 75 participants met the criteria and were enrolled in the study. These participants were then distributed randomly among the three groups.

In total, the 75 male basketball players had an average age of 16.3 ± 0.6 years old, a height of 178.4 ± 7.1 cm, a body mass of 66.3 ± 8.3 kg and a body max index of 20.8 ± 1.7 kg/m^2. These athletes typically competed at the regional level, engaging in 3 to 4 training sessions per week. Detailed characteristics of the participants in each group are outlined in Table 1.

Prior to participation, the basketball players and their respective parents or legal guardians were briefed on the study's protocol and its purpose. Upon voluntary agreement to take part, the legal guardians provided their consent by signing an informed consent document. The research complies with the ethical guidelines established in the Declaration of Helsinki and obtained approval for its protocol from the Ethics Committee of Chendu Institute of Physical Education, identified by code number 124/2024.

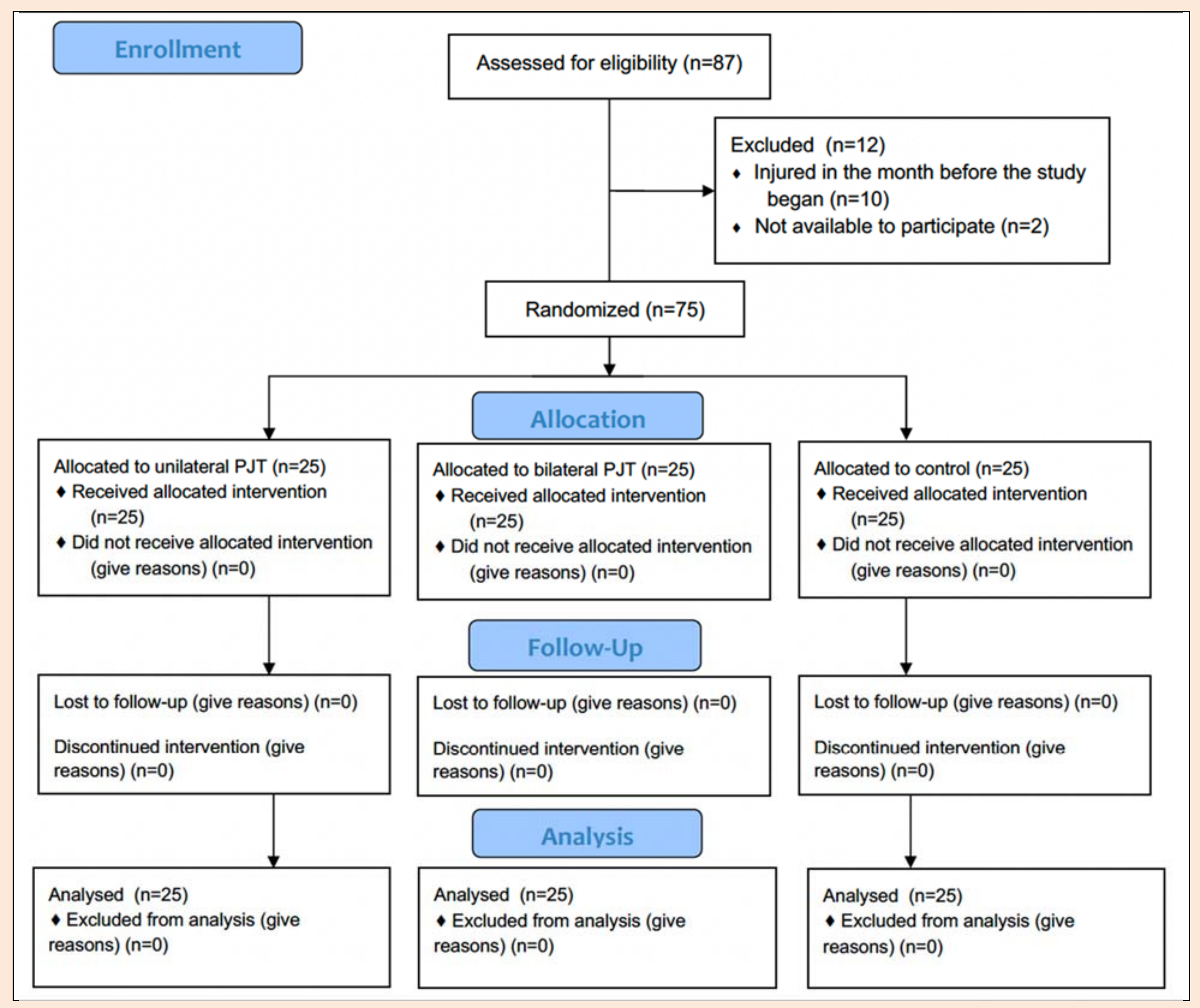

Figure 1. Participants flow diagram.

Table 1. Descriptive statistics (mean ± standard deviation) for participant characteristics within each group.

	uPJT (n = 25)	bPJT (n = 25)	Control (n = 25)
Age (years)	16.2 ± 0.6	16.4 ± 0.6	16.4 ± 0.5
Body mass (kg)	61.9 ± 6.9	69.6 ± 8.5	67.5 ± 7.8
Height (cm)	175.1 ± 7.1	180.6 ± 7.1	179.5 ± 6.0
BMI (kg/m²)	20.1 ± 1.0	21.3 ± 1.9	20.9 ± 1.8

uPJT: unilateral plyometric jump training; bPJT: bilateral plyometric jump training; BMI: body mass index.

Assessment procedure

The evaluations were performed on two occasions, before and after the intervention, consistently on the same days of the week to maintain uniformity in conditions. These assessments were conducted indoors in the afternoon. Preceding the evaluations was a 48-hour rest period after the most recent training session. The evaluations followed a structured sequence: (i) gathering demographic information, and anthropometric measurements, (iii) warming up, comprising 5 minutes of running, 10 minutes of dynamic stretching, and 5 minutes of jumping drills, (iv) single-leg land and hold (SLLH) test; (v) squat jump (SJ); and (vi) countermovement jump (CMJ). A 5-minute break was provided between each assessment. All participants underwent the assessments in the same order and sequence during both evaluation periods.

Anthropometric measurements

Height and body mass were assessed as basic anthropometric measurements. Height was measured using a stadiometer (Seca 217, Seca, Hamburg), while body mass was recorded with an electronic scale (SECA 813; Seca GmbH & Co., Hamburg, Germany) to the nearest 0.1 kg, with participants wearing t-shirt and basketball shorts for consistency. The height was measured by lowering the movable headpiece until it lightly touched the top of the player's head, ensuring the subject was in a Frankfurt horizontal plane, and then recording the height to the nearest millimeter.

Single leg lend and hold (SLLH)

The assessment began with participants standing on force plates (ForceDecks, Vald Performance, Brisbane, Australia), positioned 30 cm in front of them. They assumed a stance with feet together, hands on hips, and eyes fixed straight ahead. Each participant was instructed to maintain complete stillness for 2 - 3 seconds before performing a single-leg jump as directed by the instructor. Participants held the position until instructed otherwise, with the duration recorded (a minimum of 3 seconds). This sequence was repeated three times, with a 30-second interval between each repetition. Data collected included time to stabilization (s) and peak drop landing force (N), calculated using the VALD ForceDecks software (Wrona et al., 2023). The average of the three attempts was used for further data analysis.

Squat jump test (SJ)

Participants executed an unloaded squat with maximum range of motion on ForceDecks force plates (Vald Performance, Brisbane, Australia), maintaining a straight torso position. While participants were encouraged to adopt their usual comfortable foot position, the width between their feet was measured to ensure consistent positioning for subsequent assessments. Athletes completed three repetitions, with a 30-second rest period between each repetition. Results obtained from each trial included peak force (N), and maximum negative displacement (cm). The average peak force and maximum negative displacement force of the three attempts, calculated by the VALD ForceDecks software, was chosen for statistical analysis.

Countermovement jump testing (CMJ)

The participant began from a typical standing posture on the research platform, hands placed on hips, and eyes focused straight ahead. They were directed to maintain complete stillness for 2 - 3 seconds before and between each jump. Upon instruction from the instructor, the participant executed a two-legged jump, striving for maximum height. This sequence was repeated three times, interspaced by 30 seconds. Outcome variables such as peak power, and peak landing force were determined using the VALD ForceDecks software. The average of the three attempts was calculated for the outcomes of peak power (W/kg) and peak landing force (N) for further data analysis.

Training intervention

Basketball players allocated to the experimental groups engaged in additional uPJT or bPJT sessions, overseen by certified researchers with substantial expertise in sports sciences and training. These sessions occurred twice weekly, with a 48-hour interval between them, preceding the regular basketball training session. Prior to the experimental interventions, participants completed a standardized warm-up comprising 5 minutes of running, 10 minutes of dynamic stretching, and 5 minutes of jumping drills.

Table 2 summaries the training protocol executed by both experimental groups throughout the 8-week intervention. Both the uPJT and bPJT groups adhered to identical training organization sequences. Each week, on the first training day, horizontal-based plyometric drills were performed, followed by vertical-based plyometric drills on the second training day. The exercises remained consistent throughout the entire 8 weeks; however, starting from the fourth week, the volume was augmented by adding an extra set to all exercises. Within each training session, a 3-minute rest interval was provided between sets and exercises. All exercises were executed with maximum effort, guaranteeing proper exertion. Altogether, each experimental group completed 40 jumps in the first training session of the week (which increased to 60 after the fourth week), and 60 jumps in the second training session of the week (increasing to 90 jumps after the fourth week), totaling 100 jumps per week from the first to the fourth week, and 150 jumps from the fourth to the eighth week. The plyometric training sessions took place on synthetic indoor basketball courts.

Statistical procedures

After examining potential outliers, descriptive statistics were presented, describing means and standard deviations. Prior to executing the inferential statistics, the sample's normality was assessed and confirmed via the Kolmogorov-Smirnov test ($p > 0.05$), while homogeneity assumption was validated using Levene's test ($p > 0.05$). Considering the study's design (two assessments across three groups), a mixed ANOVA was employed to inspect interactions between time and groups. This analysis included calculation of partial eta squared (η_p^2). Additionally, post-hoc tests were executed using the Bonferroni test. Statistical analyses were conducted using JASP software (version 0.18.3, University of Amsterdam, The Netherlands), with a significance level set at $p < 0.05$.

Results

Significant interactions between time and groups were found in CMJ peak landing force ($F_{2,72} = 13.420$; $p < 0.001$; $\eta_p^2 = 0.272$), CMJ peak power ($F_{2,72} = 14.064$; $p < 0.001$; $\eta_p^2 = 0.281$), SJ peak force ($F_{2,72} = 38.773$; $p < 0.001$; $\eta_p^2 = 0.519$), SJ maximum negative displacement ($F_{2,72} = 21.020$; $p < 0.001$; $\eta_p^2 = 0.369$), SLLH time to stabilization ($F_{2,72} = 40.045$; $p < 0.001$; $\eta_p^2 = 0.527$) and SLLH peak landing force ($F_{2,72} = 36.540$; $p < 0.001$; $\eta_p^2 = 0.504$). Table 3 shows the descriptive statistics of the main outcomes in the baseline and post-intervention.

Post-hoc analysis revealed that the control group exhibited significantly greater CMJ peak landing forces compared to both the uPJT ($p = 0.004$) and bPJT ($p = 0.033$) groups. Moreover, the control group showed significantly smaller CMJ peak power compared to both the uPJT ($p < 0.001$) and bPJT ($p = 0.044$) groups.

Comparisons between groups during post-intervention revealed significantly smaller SJ peak force in control group than in uPJT ($p = 0.033$) and bPJT ($p = 0.029$) groups. In the case of SJ maximum negative displacement, only significantly smaller displacement was found in uPJT comparing to control ($p = 0.048$).

Post-hoc analysis revealed that the control group exhibited significantly greater SLLH time to stabilization compared to both the uPJT ($p < 0.001$) and bPJT ($p < 0.030$) groups. Additionally, time to stabilization was also significantly higher in bPJT than in uPJT ($p = 0.042$).

Table 2. Description of the training protocol in both experimental groups.

	Unilateral session 1	Unilateral session 2	Bilateral session 1	Bilateral session 2
Week 1	Unilateral horizontal jump (2×5 per leg); unilateral 3-bounce jumps per leg (2×5 per leg)	Unilateral reactive pogo jumps (2×5 per leg); unilateral countermovement jumps (2×5 per leg); unilateral drop jumps at 10 cm (2×5 per leg)	Bilateral horizontal jumps (2×10); bilateral thee horizontal jumps (2×10)	Unilateral reactive pogo jumps (2×10); bilateral countermovement jumps (2×10); bilateral drop jumps at 10 cm (2×10)
Week 2	Unilateral horizontal jump (2×5 per leg); unilateral 3-bounce jumps per leg (2×5 per leg)	Unilateral reactive pogo jumps (2×5 per leg); unilateral countermovement jumps (2×5 per leg); unilateral drop jumps at 10 cm (2×5 per leg)	Bilateral horizontal jumps (2×10); bilateral thee horizontal jumps (2×10)	Unilateral reactive pogo jumps (2×10); bilateral countermovement jumps (2×10); bilateral drop jumps at 10 cm (2×10)
Week 3	Unilateral horizontal jump (2×5 per leg); unilateral 3-bounce jumps per leg (2×5 per leg)	Unilateral reactive pogo jumps (2×5 per leg); unilateral countermovement jumps (2×5 per leg); unilateral drop jumps at 10 cm (2×5 per leg)	Bilateral horizontal jumps (2×10); bilateral thee horizontal jumps (2×10)	Unilateral reactive pogo jumps (2×10); bilateral countermovement jumps (2×10); bilateral drop jumps at 10 cm (2×10)
Week 4	Unilateral horizontal jump (2×5 per leg); unilateral 3-bounce jumps per leg (2×5 per leg)	Unilateral reactive pogo jumps (2×5 per leg); unilateral countermovement jumps (2×5 per leg); unilateral drop jumps at 10 cm (2×5 per leg)	Bilateral horizontal jumps (2×10); bilateral thee horizontal jumps (2×10)	Unilateral reactive pogo jumps (2×10); bilateral countermovement jumps (2×10); bilateral drop jumps at 10 cm (2×10)
Week 5	Unilateral horizontal jump (3×5 per leg); unilateral 3-bounce jumps per leg (3×5 per leg)	Unilateral reactive pogo jumps (3×5 per leg); unilateral countermovement jumps (3×5 per leg); unilateral drop jumps at 10 cm (3×5 per leg)	Bilateral horizontal jumps (3×10); bilateral thee horizontal jumps (3×10)	Unilateral reactive pogo jumps (3×10); bilateral countermovement jumps (3×10); bilateral drop jumps at 10 cm (3×10)
Week 6	Unilateral horizontal jump (3×5 per leg); unilateral 3-bounce jumps per leg (3×5 per leg)	Unilateral reactive pogo jumps (3×5 per leg); unilateral countermovement jumps (3×5 per leg); unilateral drop jumps at 10 cm (3×5 per leg)	Bilateral horizontal jumps (3×10); bilateral thee horizontal jumps (3×10)	Unilateral reactive pogo jumps (3×10); bilateral countermovement jumps (3×10); bilateral drop jumps at 10 cm (3×10)
Week 7	Unilateral horizontal jump (3×5 per leg); unilateral 3-bounce jumps per leg (3×5 per leg)	Unilateral reactive pogo jumps (3×5 per leg); unilateral countermovement jumps (3×5 per leg); unilateral drop jumps at 10 cm (3×5 per leg)	Bilateral horizontal jumps (3×10); bilateral thee horizontal jumps (3×10)	Unilateral reactive pogo jumps (3×10); bilateral countermovement jumps (3×10); bilateral drop jumps at 10 cm (3×10)
Week 8	Unilateral horizontal jump (3×5 per leg); unilateral 3-bounce jumps per leg (3×5 per leg)	Unilateral reactive pogo jumps (3×5 per leg); unilateral countermovement jumps (3×5 per leg); unilateral drop jumps at 10 cm (3×5 per leg)	Bilateral horizontal jumps (3×10); bilateral thee horizontal jumps (3×10)	Unilateral reactive pogo jumps (3×10); bilateral countermovement jumps (3×10); bilateral drop jumps at 10 cm (3×10)

Table 3. Descriptive statistics (mean ± standard deviation) of the main outcomes in the baseline and post-intervention.

		uPJT (n = 25)	bPJT (n = 25)	Control (n = 25)	F | *p* | η_p^2
CMJ peak landing force (N)	**Pre**	1709.5 ± 554.1	1739.7 ± 398.3	1701.4 ± 333.8	$F_{2,72} = 0.053$; $p = 0.948$; $\eta_p^2 = 0.001$
	Post	1418.2 ± 504.2	1503.3 ± 331.2	1818.5 ± 428.7	$F_{2,72} = 6.089$; $p = 0.004$; $\eta_p^2 = 0.145$
CMJ peak power (W/kg)	**Pre**	41.4 ± 5.0	40.9 ± 5.0	40.7 ± 4.7	$F_{2,72} = 0.129$; $p = 0.879$; $\eta_p^2 = 0.004$
	Post	48.2 ± 6.6	45.0 ± 4.6	41.3 ± 4.3	$F_{2,72} = 10.642$; $p<0.001$; $\eta_p^2 = 0.228$
SJ peak force (N)	**Pre**	532.5 ± 109.3	568.2 ± 79.6	586.0 ± 89.2	$F_{2,72} = 2.116$; $p = 0.128$; $\eta_p^2 = 0.056$
	Post	613.8 ± 75.5	614.9 ± 51.3	560.8 ± 84.7	$F_{2,72} = 4.624$; $p = 0.013$; $\eta_p^2 = 0.114$
SJ maximum negative displacement (cm)	**Pre**	−38.5 ± 7.2	−37.3 ± 7.3	−35.7 ± 6.6	$F_{2,72} = 1.020$; $p = 0.366$; $\eta_p^2 = 0.028$
	Post	−33.7 ± 5.0	−34.8 ± 5.8	−37.6 ± 5.7	$F_{2,72} = 3.269$; $p = 0.044$; $\eta_p^2 = 0.083$
SLLH time to stabilization (s)	**Pre**	0.54 ± 0.10	0.49 ± 0.14	0.49 ± 0.16	$F_{2,72} = 1.519$; $p = 0.226$; $\eta_p^2 = 0.040$
	Post	0.31 ± 0.07	0.39 ± 0.12	0.47 ± 0.14	$F_{2,72} = 13.354$; $p<0.001$; $\eta_p^2 = 0.271$
SLLH peak landing force (N)	**Pre**	845.9 ± 153.4	850.3 ± 154.8	903.2 ± 165.9	$F_{2,72} = 1.015$; $p = 0.368$; $\eta_p^2 = 0.027$
	Post	723.5 ± 114.6	832.6 ± 165.0	946.8 ± 175.3	$F_{2,72} = 13.162$; $p<0.001$; $\eta_p^2 = 0.268$

CMJ: countermovement jump; SJ: squat jump; SLLH: single leg lend and hold test; uPJT: unilateral plyometric jump training; bPJT: bilateral plyometric jump training.

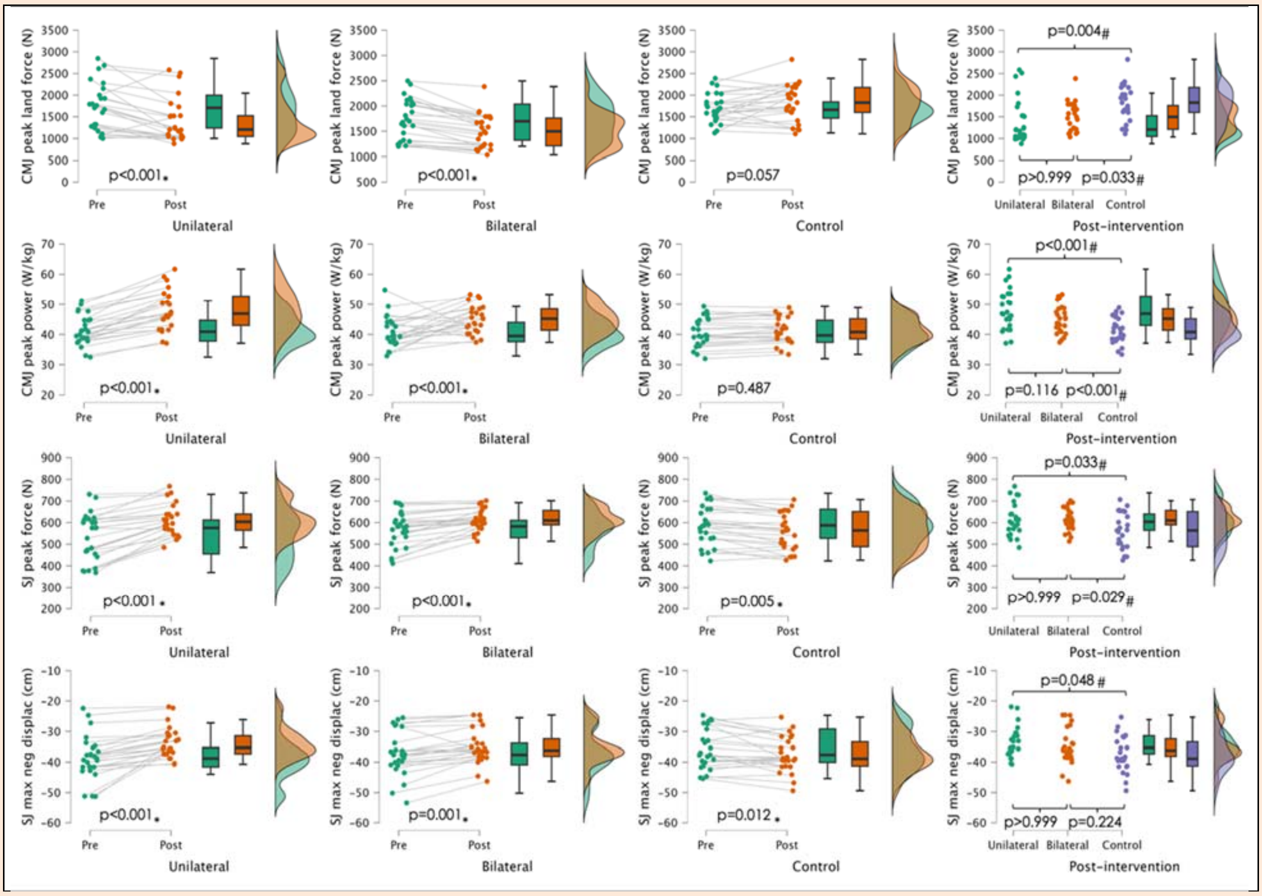

Figure 2. Descriptive analysis of the within- and between-group comparisons in the countermovement jump (CMJ) and squat jump (SJ) outcomes. *significantly different within-group ($p < 0.005$); #significantly different between groups ($p < 0.005$).

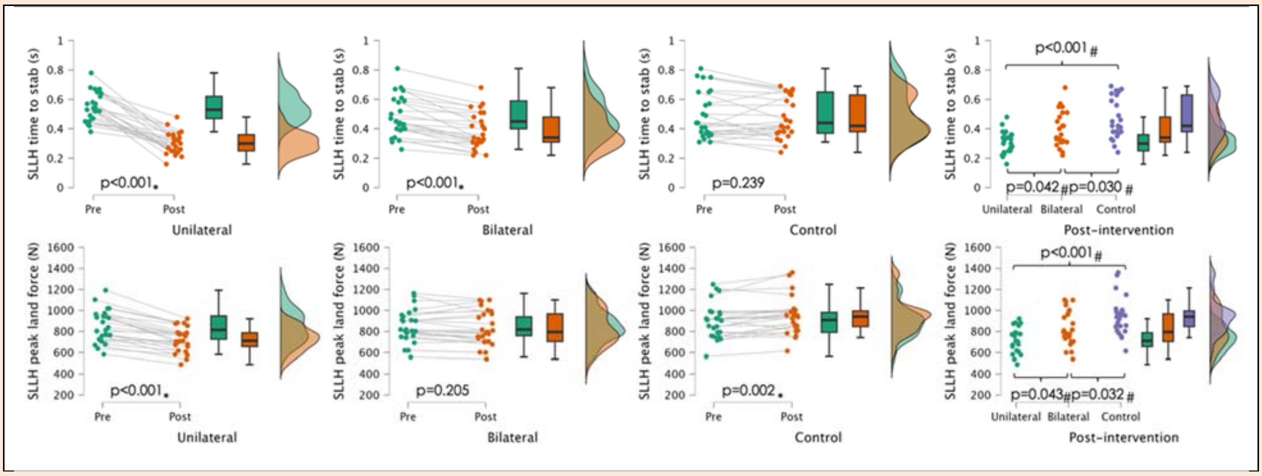

Figure 3. Descriptive analysis of the within- and between-group comparisons in the single leg lend and hold test (SLLH) outcomes. *significantly different within-group ($p < 0.005$); #significantly different between groups ($p < 0.005$).

Comparisons between groups in regards SLLH peak landing force after intervention revealed that the value was significantly smaller in uPJT than in bPJT ($p = 0.043$) and control ($p < 0.001$). Moreover, control group had significantly greater SLLH peak landing force than bPJT ($p = 0.032$).

Figure 2 presents the within-group variations in CMJ and SJ outcomes. uPJT ($p < 0.001$) and bPJT ($p < 0.001$) significantly improved the CMJ peak landing forces. Additionally, uPJT ($p < 0.001$) and bPJT ($p < 0.001$) significantly improved the CMJ peak power. Considering the CMJ peak force, uPJT ($p < 0.001$) and bPJT ($p < 0.001$) significantly improved the outcome, while the control group significantly declined the performance ($p = 0.005$). Also, in the SJ maximum negative displacement uPJT ($p < 0.001$) and bPJT ($p = 0.001$) significantly improved the outcome, while the control group significantly declined the performance ($p = 0.012$).

Figure 3 illustrates the within-group variations in

SLLH outcomes. uPJT ($p < 0.001$) and bPJT ($p < 0.001$) significantly improved the SLLH time to stabilization. In the case of SSLH peak landing force, uPJT significantly improved after intervention ($p < 0.001$) and control significantly declined ($p = 0.002$).

Discussion

The recent research findings indicated that both uPJT and bPJT significantly enhanced peak power and peak force in CMJ and SJ. Additionally, they were equally effective in improving peak landing force in CMJ and maximum negative displacement in SJ compared to the control group. However, an important finding was that uPJT showed significant superiority over bPJT and the control group in enhancing peak landing force in SLLH and time to stabilization. This suggested a particular interest in implementing uPJT in basketball strength and conditioning programs. Such programs might not only have improved performance but also mitigated injury risks by enhancing stability and the capacity to absorb forces during landing, crucial in a sport characterized by frequent jumps during matches and training sessions.

Our study findings suggest that uPJT yielded significantly better outcomes in enhancing peak landing forces in the SLLH compared to both bPJT and control groups. While no prior studies have examined this hypothesis, previous research comparing uPJT and bPJT has consistently shown unilateral training to be more effective (Bogdanis et al., 2019; Drouzas et al., 2020). Specifically, uPJT has been associated with superior improvements in both single- and double-leg jumping performance, isometric leg press maximal force, and rate of force development when compared to bilateral training (Bogdanis et al., 2019). Proposing some hypotheses to support our findings, during uPJT, the central nervous system coordinates complex motor unit recruitment patterns specific to the engaged limb, leading to optimized force generation and control (Drozd et al., 2024). This recruitment fosters greater activation of stabilizing muscles around the hip, knee, and ankle, crucial for maintaining balance and absorbing landing forces effectively (Estevan et al., 2020). Additionally, unilateral training fosters asymmetrical adaptations, which are essential for basketball activities involving single-leg tasks like jumping to the basket, running or cutting movements (Bettariga et al., 2023). Conversely, bilateral training may not sufficiently address the specific demands placed on each limb independently, potentially leading to imbalanced force distribution and inadequate stabilization during unilateral tasks. Hence, uPJT may offers a more suitable biomechanically and neurologically approach, enhancing peak landing force through optimized muscle activation, neuromuscular coordination, and task-specific adaptations.

Moreover, uPJT showed significantly more effective than both bPJT and the control group in enhancing time to stabilization in SLLH. While our findings diverge from previous research for being the first to study time to stabilization, a study comparing uPJT and bPJT in balance showed that the combination of both approaches significantly outperformed isolated training in enhancing anterior-posterior and medial-lateral stance (Ramírez-Campillo et al., 2015). The results of our study can be explained for some reasons, as example, uPJT exercises inherently demand greater neuromuscular coordination and proprioceptive feedback compared to bilateral counterparts (Zhang et al., 2023). The necessity to stabilize and control the body unilaterally imposes a heightened demand on proprioceptive receptors, enhancing their sensitivity and efficiency in detecting and correcting imbalances (Lee and Carroll, 2007).

Furthermore, by specifically targeting each limb independently, uPJT exercises may promote balanced muscular development, reducing the risk of compensatory movements and enhancing the efficiency of force absorption upon landing (Hewett et al., 2006). This balanced strength distribution may contribute to more stable single-leg landing and hold, thereby improving performance. The dynamic nature of unilateral jumps requires rapid activation and coordination of smaller stabilizer muscles, which are important for controlling movement during landing and protecting the main joint structures from impact (Hewett et al., 2002).

uPJT and bPJT had similar positive adaptations in CMJ and SJ variables observed. These findings contrast with a previous study indicating that uPJT significantly outperformed bPJT in enhancing muscular force and power (Bogdanis et al., 2019). Both types of training likely enhance neuromuscular coordination and motor unit recruitment, leading to improved force production and power generation during jumping activities such as the CMJ and SJ (Zhang et al., 2023). Additionally, PJT promotes the development of fast-twitch muscle fibers, which are crucial for explosive movements like jumping (McKinlay et al., 2018). Moreover, both uPJT and bPJT exercises elicit adaptations in the stretch-shortening cycle, enhancing the utilization of stored elastic energy and improving the efficiency of muscular contractions during landing and takeoff phases of jumps (Duchateau and Amiridis, 2023).

While our study highlights the significant benefits of uPJT in enhancing peak landing forces and time to stabilization compared to both bPJT and control groups, several limitations warrant consideration. Firstly, our study did not research potential age- and sex-based differences in response to uPJT, despite evidence suggesting variability in neuromuscular adaptations between males and females and competitive levels/trainability. Understanding these differences could design training programs more effectively. Furthermore, the study lacked a comprehensive assessment of neural mechanisms that can explain the adaptations observed. Future research should include a broader range of measures monitored over training process to provide a comprehensive evaluation of the impact on the magnitude of adaptations. Lastly, while our study focused on basketball players, generalizing findings to other athletic populations should be done cautiously, as sport-specific demands may influence training outcomes differently. In future research, exploring the efficacy of uPJT across various sports and skill levels would enhance the applicability of findings to a broader athletic population. Despite these limitations, our findings highlight the potential practical implications of uPJT as a valuable component of basketball strength and conditioning programs, warranting further investigation and refinement to optimize performance outcomes and mitigate injury risks effectively.

Conclusion

In conclusion, our study findings support the efficacy of both uPJT and bPJT in enhancing various aspects of vertical jumping performance, particularly within the realm of basketball strength and conditioning programs. Specifically, uPJT demonstrated superior outcomes in enhancing peak landing forces in the SLLH and time to stabilization compared to both bPJT and control groups. These results suggest that uPJT may offer a biomechanically and neurologically more suitable approach, enhancing peak landing force through optimized muscle activation, neuromuscular coordination, and task-specific adaptations. Despite the strength of our findings, our study has limitations, including the lack of investigation into potential age- and sex-based differences in response to uPJT and the absence of a comprehensive assessment of neural mechanisms underlying the observed adaptations. Future research should address these limitations and explore the efficacy of uPJT across various sports and skill levels. As a practical implication, uPJT appears to be advantageous to introduce compared to bilateral training alone, or at least, a combination of both should be considered to maximize performance adaptations.

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The authors declare that there are no conflicts of interest. The experiments comply with the current laws of the country where they were performed. The data that support the findings of this study are available on request from the corresponding author.

References

Aksovic, N., Bjelica, B., Milanovic, F., Jovanovic, N. and Zelenovic, M. (2021) Plyometric training effects on explosive power, sprint and direction change speed in basketball: A review. *Turkish Journal of Kinesiology* **7**, 73-79. https://doi.org/10.31459/turkjkin.929325

Bettariga, F., Maestroni, L., Martorelli, L., Jarvis, P., Turner, A. and Bishop, C. (2023) The Effects of a Unilateral Strength and Power Training Intervention on Inter-Limb Asymmetry and Physical Performance in Male Amateur Soccer Players. *Journal of Science in Sport and Exercise* **5**, 328-339. https://doi.org/10.1007/s42978-022-00188-8

Bogdanis, G.C., Tsoukos, A., Kaloheri, O., Terzis, G., Veligekas, P. and Brown, L.E. (2019) Comparison Between Unilateral and Bilateral Plyometric Training on Single- and Double-Leg Jumping Performance and Strength. *Journal of Strength and Conditioning Research* **33**, 633-640. https://doi.org/10.1519/JSC.0000000000001962

Buckthorpe, M. (2021) Recommendations for Movement Re-training After ACL Reconstruction. *Sports Medicine* **51**, 1601-1618. https://doi.org/10.1007/s40279-020-01400-x

Buckthorpe, M. and Della Villa, F. (2021) Recommendations for Plyometric Training after ACL Reconstruction - A Clinical Commentary. *International Journal of Sports Physical Therapy* **16**, 879-895. https://doi.org/10.26603/001c.23549

Burgos-Jara, C., Cerda-Kohler, H., Aedo-Muñoz, E. and Miarka, B. (2023) Eccentric Resistance Training: A Methodological Proposal of Eccentric Muscle Exercise Classification Based on Exercise Complexity, Training Objectives, Methods, and Intensity. *Applied Sciences* **13**, 7969. https://doi.org/10.3390/app13137969

Cao, S., Wang, Z., Guo, J., Geok, S.K., Sun, H. and Liu, J. (2024) The effects of plyometric training on physical fitness and skill-related performance in female basketball players: a systematic review and meta-analysis. *Frontiers in Physiology* **15**, 1-16. https://doi.org/10.3389/fphys.2024.1391394

Caparrós, T., Peña, J., Baiget, E., Borràs-Boix, X., Calleja-Gonzalez, J. and Rodas, G. (2022) Influence of Strength Programs on the Injury Rate and Team Performance of a Professional Basketball Team: A Six-Season Follow-Up Study. *Frontiers in Psychology* **12**, 1-11. https://doi.org/10.3389/fpsyg.2021.796098

Cherni, Y., Hammami, M., Jelid, M.C., Aloui, G., Suzuki, K., Shephard, R.J. and Chelly, M.S. (2021) Neuromuscular Adaptations and Enhancement of Physical Performance in Female Basketball Players After 8 Weeks of Plyometric Training. *Frontiers in Physiology* **11**, 1-14. https://doi.org/10.3389/fphys.2020.588787

Drouzas, V., Katsikas, C., Zafeiridis, A., Jamurtas, A.Z. and Bogdanis, G.C. (2020) Unilateral Plyometric Training is Superior to Volume-Matched Bilateral Training for Improving Strength, Speed and Power of Lower Limbs in Preadolescent Soccer Athletes. *Journal of Human Kinetics* **74**, 161-176. https://doi.org/10.2478/hukin-2020-0022

Drozd, M., Kędra, N., Motowidło, J., Ficek, K., Bichowska-Pawęska, M. and Zając, A. (2024) A Comparison of a Step Load Unilateral and Bilateral Resistance Training Program on the Strength and Power of the Lower Limbs in Soccer Players. *Applied Sciences* **14**, 1732. https://doi.org/10.3390/app14051732

Duchateau, J. and Amiridis, I.G. (2023) Plyometric Exercises: Optimizing the Transfer of Training Gains to Sport Performance. *Exercise and Sport Sciences Reviews* **51**, 117-127. https://doi.org/10.1249/JES.0000000000000320

DuPrey, K.M., Liu, K., Cronholm, P.F., Reisman, A.S., Collina, S.J., Webner, D. and Kaminski, T.W. (2016) Baseline Time to Stabilization Identifies Anterior Cruciate Ligament Rupture Risk in Collegiate Athletes. *The American Journal of Sports Medicine* **44**, 1487-1491. https://doi.org/10.1177/0363546516629635

Estevan, I., Monfort-Torres, G., Farana, R., Zahradnik, D., Jandacka, D. and García-Massó, X. (2020) Children's Single-Leg Landing Movement Capability Analysis According to the Type of Sport Practiced. *International Journal of Environmental Research and Public Health* **17**, 6414. https://doi.org/10.3390/ijerph17176414

Garbenytė-Apolinskienė, T., Šiupšinskas, L., Salatkaitė, S., Gudas, R. and Radvila, R. (2018) The effect of integrated training program on functional movements patterns, dynamic stability, biomechanics, and muscle strength of lower limbs in elite young basketball players. *Sport Sciences for Health* **14**, 245-250. https://doi.org/10.1007/s11332-017-0409-y

Gonzalo-Skok, O., Tous-Fajardo, J., Suarez-Arrones, L., Arjol-Serrano, J.L., Casajús, J.A. and Mendez-Villanueva, A. (2017) Single-Leg Power Output and Between-Limbs Imbalances in Team-Sport Players: Unilateral Versus Bilateral Combined Resistance Training. *International Journal of Sports Physiology and Performance* **12**, 106-114. https://doi.org/10.1123/ijspp.2015-0743

Guo, L., Zhang, J., Wu, Y. and Li, L. (2021) Prediction of the Risk Factors of Knee Injury During Drop-Jump Landing With Core-related Measurements in Amature Basketball Players. *Frontiers in Bioengineering and Biotechnology* **9**, 1-10. https://doi.org/10.3389/fbioe.2021.738311

Hewett, T.E., Ford, K.R. and Myer, G.D. (2006) Anterior Cruciate Ligament Injuries in Female Athletes. *The American Journal of Sports Medicine* **34**, 490-498. https://doi.org/10.1177/0363546505284183

Hewett, T.E., Paterno, M. V. and Myer, G.D. (2002) Strategies for Enhancing Proprioception and Neuromuscular Control of the Knee. *Clinical Orthopaedics and Related Research* **402**, 76-94. https://doi.org/10.1097/00003086-200209000-00008

Hewett, T.E., Di Stasi, S.L. and Myer, G.D. (2013) Current Concepts for Injury Prevention in Athletes After Anterior Cruciate Ligament Reconstruction. *The American Journal of Sports Medicine* **41**, 216-224. https://doi.org/10.1177/0363546512459638

Huang, P.-Y., Jankaew, A. and Lin, C.-F. (2021) Effects of Plyometric and Balance Training on Neuromuscular Control of Recreational Athletes with Functional Ankle Instability: A Randomized Controlled Laboratory Study. *International Journal of Environmental Research and Public Health* **18**, 5269. https://doi.org/10.3390/ijerph18105269

Kons, R.L., Orssatto, L.B.R., Ache-Dias, J., De Pauw, K., Meeusen, R., Trajano, G.S., Pupo, J. and Detanico, D. (2023) Effects of Plyometric Training on Physical Performance: An Umbrella Review. *Sports Medicine - Open* **9**, 4. https://doi.org/10.1186/s40798-022-00550-8

Lee, M. and Carroll, T.J. (2007) Cross education: possible mechanisms for the contralateral effects of unilateral resistance training. *Sports Medicine* **37**, 1-14. https://doi.org/10.2165/00007256-200737010-00001

Markovic, G. and Newton, R.U. (2007) Does plyometric training improve vertical jump height? A meta-analytical review * Commentary. *British Journal of Sports Medicine* **41**, 349-355. https://doi.org/10.1136/bjsm.2007.035113

McKinlay, B.J., Wallace, P., Dotan, R., Long, D., Tokuno, C., Gabriel, D.A. and Falk, B. (2018) Effects of Plyometric and Resistance Training on Muscle Strength, Explosiveness, and Neuromuscular Function in Young Adolescent Soccer Players. *Journal of Strength and Conditioning Research* **32**, 3039-3050. https://doi.org/10.1519/JSC.0000000000002428

Mercer, R.A.J., Russell, J.L., McGuigan, L.C., Coutts, A.J., Strack, D.S. and McLean, B.D. (2022) Understanding 'monitoring' data-the association between measured stressors and athlete responses within a holistic basketball performance framework. *Plos One* **17**, e0270409. https://doi.org/10.1371/journal.pone.0270409

Ramírez-Campillo, R., Burgos, C.H., Henríquez-Olguín, C., Andrade, D.C., Martínez, C., Álvarez, C., Castro-Sepúlveda, M., Marques, M.C. and Izquierdo, M. (2015) Effect of Unilateral, Bilateral, and Combined Plyometric Training on Explosive and Endurance Performance of Young Soccer Players. *Journal of Strength and Conditioning Research* **29**, 1317-1328. https://doi.org/10.1519/JSC.0000000000000827

Ramirez-Campillo, R., García-Hermoso, A., Moran, J., Chaabene, H., Negra, Y. and Scanlan, A.T. (2022) The effects of plyometric jump training on physical fitness attributes in basketball players: A meta-analysis. *Journal of Sport and Health Science* **11**, 656-670. https://doi.org/10.1016/j.jshs.2020.12.005

Ramirez-Campillo, R., Sanchez-Sanchez, J., Gonzalo-Skok, O., Rodríguez-Fernandez, A., Carretero, M. and Nakamura, F.Y. (2018) Specific Changes in Young Soccer Player's Fitness After Traditional Bilateral vs. Unilateral Combined Strength and Plyometric Training. *Frontiers in Physiology* **9**, 1-10. https://doi.org/10.3389/fphys.2018.00265

Stojanovic, E., Stojiljkovic, N., Scanlan, A.T., Dalbo, V.J., Berkelmans, D.M. and Milanovic, Z. (2018) The Activity Demands and Physiological Responses Encountered During Basketball Match-Play: A Systematic Review. *Sports medicine (Auckland, N.Z.)* **48**, 111-135. https://doi.org/10.1007/s40279-017-0794-z

Withrow, T.J., Huston, L.J., Wojtys, E.M. and Ashton-Miller, J.A. (2006) The Relationship between Quadriceps Muscle Force, Knee Flexion, and Anterior Cruciate Ligament Strain in an in Vitro Simulated Jump Landing. *The American Journal of Sports Medicine* **34**, 269-274. https://doi.org/10.1177/0363546505280906

Wrona, H.L., Zerega, R., King, V.G., Reiter, C.R., Odum, S., Manifold, D., Latorre, K. and Sell, T.C. (2023) Ability of Countermovement Jumps to Detect Bilateral Asymmetry in Hip and Knee Strength in Elite Youth Soccer Players. *Sports* **11**, 77. https://doi.org/10.3390/sports11040077

Zhang, W., Chen, X., Xu, K., Xie, H., Li, D., Ding, S. and Sun, J. (2023) Effect of unilateral training and bilateral training on physical performance: A meta-analysis. *Frontiers in Physiology* **14**, 1-22. https://doi.org/10.3389/fphys.2023.1128250

Key points

- Unilateral PJT enhances single-leg stabilization and landing force better than bilateral PJT.
- Both unilateral and bilateral PJT methods improve vertical jump performance in youth basketball players.

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