

Original Article



Effects of a Six-Week Plyometric Training Program on Speed, Strength, and Balance ability on Hard and Soft Surfaces in Adolescent Female Basketball Players

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Abstract:

This study investigated the effects of 6 weeks of plyometric training (PT) performed on soft (unstable) and hard (stable) surfaces compared with conventional training on the balance, explosive power, and muscle strength of adolescent female basketball players. The participants were randomly assigned to three groups: soft-surface PT (n = 14), hard-surface PT (n = 14), and conventional training (n = 14). Performance outcomes included 30 m sprint time, vertical jump height, plantar flexion and dorsiflexion maximal voluntary isometric contraction (MVIC) torque, Y-balance dynamic balance, and center of pressure-based static balance. Ground reaction forces, MVIC torques, and balance parameters were measured using high-precision force sensors to ensure accurate quantification of biomechanical performance. Statistical analyses were performed using two-way repeated-measures ANOVA with post-hoc comparisons to evaluate group × time interaction effects across all outcome variables. Results demonstrated that soft- and hard-surface PT significantly improved sprint performance, vertical jump height, and plantar flexion MVIC torque compared with conventional training, while dorsiflexion MVIC increased similarly across all the groups. Notably, soft-surface training elicited greater enhancements in vertical jump height, dynamic balance (posteromedial and posterolateral directions), and static balance under single- and double-leg eyes-closed conditions. These improvements were attributed to enhanced neuromuscular coordination, motor unit recruitment, and sensorimotor integration induced by the instability of the soft surface, which amplified proprioceptive stimulation and facilitated rapid postural adjustments. The findings suggest that PT on an unstable surface provides unique advantages in optimizing neuromuscular control and postural stability beyond those achieved with stable-surface or conventional training. Thus, soft-surface PT may serve as an effective adjunct to traditional conditioning programs, enhancing sport-specific explosive power and balance, particularly in movements that require rapid changes of direction, sudden stops, and controlled landings. These results provide practical guidance for designing evidence-based and individualized training interventions to improve performance and reduce injury risk among adolescent female basketball athletes.

Keywords: Plyometric training; balance; adolescent female athletes; soft surface; neuromuscular control; explosive power

1. Introduction

Basketball is an intermittent high-intensity team sport that demands rapid accelerations, decelerations, changes in direction, and frequent jumping and landing. These dynamic and multidirectional movements require athletes to

possess well-developed postural control and balance ability, which are crucial for executing technical movements and preventing injuries during competition [1, 2]. For adolescent female basketball players, who are in a critical stage of

physical development, improving balance ability is particularly essential not only for enhancing sport performance but also for mitigating the elevated risk of lower limb injuries, such as ankle sprain and anterior cruciate ligament tear [3]. However, current youth training programs frequently prioritize strength and skill development while placing insufficient emphasis on balance-oriented interventions, resulting in a potential gap in motor control development.

Balance is a multifactorial neuromuscular function that involves the visual, vestibular, and proprioceptive systems working together to maintain stability under static and dynamic conditions [4]. Given its strong dependence on coordinated neuromuscular responses, balance can be substantially influenced by training modalities that target rapid force production, proprioceptive acuity, and sensorimotor integration. In this context, plyometric training (PT)—a modality that leverages the stretch–shortening cycle to enhance neuromuscular performance—has been widely applied to improve lower-limb power, coordination, and agility [5, 6]. Although traditional PT is frequently performed on stable surfaces (e.g., hardwood floors), recent evidence suggests that executing plyometric movements on unstable surfaces (e.g., foam pads, sand, or balance platforms) may offer superior proprioceptive stimulation and postural control demands [7, 8]. The added instability is believed to increase the activation of stabilizing muscles and enhance sensory–motor integration, contributing to improved balance ability [9]. However, despite increasing interest in surface-dependent adaptations to PT, empirical evidence remains scarce, and available studies have predominantly focused on adult or male athletes [10, 11]. Research investigating how different support surfaces influence neuromuscular and balance adaptations in adolescent females is particularly lacking, representing a critical gap that the present

study aims to address.

With the advancement of wearable and platform-based sensor technologies, such as force plates and inertial measurement units, biomechanical assessments have become increasingly precise and objective. These tools enabling the quantification of subtle variations in postural sway, ground reaction forces, and movement symmetry [12, 13]. Moreover, they provide valuable insight into the neuromuscular adaptations induced by PT under different surface conditions, thereby offering a more comprehensive understanding of sensorimotor control mechanisms in youth athletes [13].

Despite growing interest in surface-dependent adaptations to PT, empirical evidence remains limited, particularly among youth female athletes. Existing studies have primarily emphasized performance metrics such as jump height or sprint speed, or explored injury prevention effects, while often neglecting how surface characteristics influence balance performance. Moreover, the distinct physiological and biomechanical traits of adolescent females—including lower baseline muscle strength, greater joint laxity, and specific neuromuscular control patterns—necessitate population-focused investigation [14]. Whether plyometric exercises conducted on unstable surfaces can more effectively target balance control mechanisms in this group compared with traditional stable-surface training remains unclear.

Therefore, the present study aimed to investigate the effects of 6 weeks of PT performed under different support conditions (stable versus unstable surfaces) on the speed, strength, and balance ability of adolescent female basketball players. Dynamic balance was assessed using the Y-balance test, while static balance was evaluated with center-of-pressure measures during single-leg stance. In addition, lower limb explosive performance was recorded to examine the concurrent effects on physical fitness. We hypothesized that PT performed on a soft,

unstable surface would produce greater improvements in static and dynamic balance compared with training on a hard, stable surface, due to increased proprioceptive demands and neuromuscular activation. Regarding explosive strength, we expected that both soft- and hard-surface PT would enhance performance relative to conventional training; however, the unstable surface was anticipated to induce additional neuromuscular coordination gains that may offer comparable or potentially greater benefits under certain movement conditions. The findings of the current study are expected to offer practical insights into evidence-based conditioning strategies for adolescent female athletes and contribute to an increased understanding of how surface properties modulate the efficacy of PT in youth sport development.

2. Materials and Methods

2.1 Participants

An a priori power analysis was conducted using G*Power 3.1.9.7 (University of Düsseldorf, Germany) for a repeated-measures ANOVA with three groups and two time points. Based on previous findings on surface-dependent plyometric adaptations [10], we used an expected effect size of $f = 0.40$, $\alpha = 0.05$, power = 0.80, and an assumed correlation of 0.5 between repeated measures. The analysis indicated that at least 21 participants were required. To ensure sufficient power and accommodate potential attrition, 42 participants were ultimately recruited from Changzhi Sports School in Changzhi City, Shanxi Province, China (Table 1).

Table 1. Basic Information of the Participants.

Number	Age (years)	Height (cm)	Mass (kg)
14	15.3 ± 1.2	161.3 ± 6.4	54.5 ± 6.2
14	14.7 ± 1.5	160.7 ± 7.6	53.2 ± 4.5
14	16.1 ± 1.4	163.8 ± 5.6	55.6 ± 7.1

The inclusion and exclusion criteria for participant recruitment was shown in table 2. All the participants were screened for contraindications prior to enrollment and required

to provide written informed consent in accordance with the guidelines of the Ethics Committee of Changzhi Medical College.

Table 2. Inclusion and Exclusion Criteria for Participant Recruitment.

Category	Criteria
Inclusion criteria	Female basketball players aged 13–16 years
	No lower limb injuries in the past 3 months
	Right leg-dominant
Exclusion criteria	Neurological or vestibular disorders
	Cardiovascular/systemic contraindications to exercise
	Medications affecting neuromuscular control

The participants were instructed to abstain from strenuous physical activities within 24 h prior to testing, obtain at least 8 hours of sleep and avoid

staying up late the night before testing, and refrain from consuming any beverages or medications that may affect neural function (e.g., alcohol, cola, coffee, tea, or similar substances)

within 4 h before the test. Before the experiment, all the participants were fully informed about the study's objectives and procedures and signed a written informed consent form. The study protocol was reviewed and approved by the Institutional Ethics Committee of Changzhi Medical College, with approval number RT2023041 on July 13, 2023.

2.2 Experimental Procedures

All instructions, familiarization procedures, and safety briefings were provided individually to each participant to ensure consistent understanding of the testing and training protocols. The participants were randomly assigned to three groups prior to the intervention: the PT group on a soft surface ($n = 14$), the PT group on a hard surface ($n = 14$), and the conventional training group ($n = 14$). Under the soft-surface condition, a 5 cm-thick T-foam mat was laid across the surface in all areas where the participants and training equipment made contact. Under the hard-surface condition, the participants performed plyometric exercises on a rigid, flat, and non-cushioned surface composed of standard indoor training flooring without any elastic or shock-absorbing layers. This setup ensured minimal compliance and ground deformation, serving as a control condition to isolate the effect of surface instability introduced by the T-foam mat into the soft surface group.

Training surface specification: Plyometric training was performed on two clearly defined support surfaces. The soft (unstable) surface consisted of an Airex® Balance Pad (closed-cell EVA foam; $50 \times 41 \times 6$ cm; Airex AG, Sins, Switzerland), providing a compliant and perturbing support commonly used in balance and plyometric interventions [10, 11]. The hard (stable) surface consisted of a competition-grade hardwood gym floor (maple, 25 mm thickness) over a concrete subfloor. During training sessions,

exercises designated for the soft-surface group were executed directly on Airex pads, whereas exercises for the hard-surface group were performed on the hardwood gym floor.

As illustrated in Figure 1, baseline testing was conducted during the first visit. After a standardized 10 min warm-up and a brief rest, the participants performed a series of pre-intervention assessments, including a 30 m sprint test, standing vertical jump, maximal voluntary isometric contraction (MVIC) torque of plantar flexion and dorsiflexion, dynamic balance, and static balance. The order of tests was randomized, with rest intervals of approximately 3–5 min between tests to minimize carryover fatigue. Each test was repeated three times, and the mean value was used for subsequent analysis. Rest intervals of approximately 1–2 min were provided between repetitions.

All pretests were conducted on the Friday prior to the start of intervention. The training interventions were then implemented on a thrice-weekly basis (Monday, Wednesday, and Friday) for 6 weeks. Post-testing was conducted in randomized order on the day following the final training session, using the same protocols as the baseline assessments.

2.3 PT

The PT program was designed using a progressive overload approach, with gradually increasing intensity and volume over a 6 week period. The training consisted of five exercises that targeted lower limb explosive power, performed three times per week (Monday, Wednesday, and Friday). The following exercises were included: (1) squat jumps, (2) single-leg step-up jumps onto a 40 cm box (alternating legs), (3) double-leg box jumps onto 40 cm or 60 cm boxes, (4) forward hurdle jumps over a 60 cm barrier, and (5) vertical reach jumps. The detailed weekly training plan is presented in Table 2.

Table 2. Plyometric training program.

Week	Exercise	Sets × Repetition	Rest Interval
Week 1	Squat Jumps	3 × 8	3 min
	Single-leg Box Jumps (40 cm box)	3 × 8	
	Double-leg Box Jumps (40 cm box)	3 × 12	
	Forward Hurdle Jumps (60 cm height)	3 × 8	
	Vertical Reach Jumps	3 × 8	
Week 2	Squat Jumps	3 × 10	3 min
	Single-leg Box Jumps (40 cm box)	3 × 8	
	Double-leg Box Jumps (40 cm box)	3 × 12	
	Forward Hurdle Jumps (60 cm height)	3 × 10	
	Vertical Reach Jumps	3 × 10	
Week 3	Squat Jumps	3 × 12	3 min
	Single-leg Box Jumps (40 cm box)	3 × 8	
	Double-leg Box Jumps (40 cm box)	3 × 12	
	Forward Hurdle Jumps (60 cm height)	3 × 10	
	Vertical Reach Jumps	3 × 12	
Week 4	Squat Jumps	3 × 12	3 min
	Single-leg Box Jumps (40 cm box)	3 × 8	
	Double-leg Box Jumps (60 cm box)	3 × 12	
	Forward Hurdle Jumps (60 cm height)	3 × 12	
	Vertical Reach Jumps	3 × 12	
Week 5	Squat Jumps	3 × 12	3 min
	Single-leg Box Jumps (40 cm box)	3 × 10	
	Double-leg Box Jumps (60 cm box)	3 × 12	
	Forward Hurdle Jumps (60 cm height)	3 × 12	
	Vertical Reach Jumps	3 × 12	
Week 6	Squat Jumps	3 × 12	3 min
	Single-leg Box Jumps (40 cm box)	3 × 10	
	Double-leg Box Jumps (60 cm box)	3 × 12	
	Forward Hurdle Jumps (60 cm height)	3 × 12	
	Vertical Reach Jumps	3 × 12	

2.4 Conventional Lower Limb Training

The conventional lower limb training program

included the following exercises: (1) squats, (2) stretching exercises, (3) single-leg squats, (4) push-ups, and (5) basic jump training.

Each exercise was performed in four sets of fifteen repetitions, with a rest interval of 90 s between sets and 3 min between different exercises.

2.5 Data Collection

2.5.1 30 m Sprint Test

The participants began the 30 m sprint test from a standing start position, approximately 1 m behind the starting timing gate. Both the start and finish lines were equipped with dual infrared timing gates to ensure accurate time measurement. Each participant performed three sprint trials, with a rest interval of 3 min between trials to prevent fatigue effects. Only valid trials were recorded, and sprint times were documented to the nearest 0.01 s.

2.5.2 Standing Vertical Jump Test

The participants stood approximately 0.5 m behind the force platform (9287C, Kistler, Winterthur, Switzerland) equipped with integrated force sensors and waited for the tester's verbal cue. Upon hearing the command "ready," the participant would step forward onto the force platform and positioned both feet parallel on the two plates, with hands placed on the hips and the torso upright. At the instruction of the tester, the participant would perform a countermovement, followed by an explosive vertical jump by using both legs simultaneously.

During the jumping task, the participants were instructed to maintain core engagement, keep the trunk upright, and avoid any lateral body rotation. The tester verbally encouraged each participant to jump as high as possible during every trial. Three trials were performed, with a 2 min rest interval between each trial. High-frequency kinetic data collected by the embedded force sensors were used to derive the velocity–time profile through double integration of the ground reaction force,

and jump height was calculated using the impulse–momentum method [15]. The mean value of the three trials was used for subsequent analysis.

2.5.3 Plantar Flexion and Dorsiflexion MVIC Torques

Plantar flexion and dorsiflexion MVIC torques were assessed with the participants in the prone position. The right knee and foot were secured in the anatomical neutral position (starting position). The MVIC torque of the ankle plantar flexors and dorsiflexors was measured using a CON-TREX isokinetic dynamometer (CMV AG, Switzerland) equipped with high-precision torque and angle sensors to capture real-time biomechanical data during maximal effort contractions. Each contraction was performed three times for 3 s, with a 1 min rest interval between trials.

2.5.4 Dynamic Balance Test

Dynamic balance was assessed using the Y-balance test protocol. The participants stood barefoot on their left (supporting) leg on the test platform, with the toes aligned at the starting line. While maintaining the single-leg stance, the participant was instructed to reach as far as possible in the anterior, posteromedial, and posterolateral directions by sliding the reach indicator with the non-stance foot.

During the test, the participants were required to place both hands on their hips, keep their gaze forward, and avoid using the reaching foot for support or touching the ground. Three valid trials were recorded in each direction. To account for individual differences in limb length, reach distances were normalized as a percentage of leg length. Leg length was measured from the anterior superior iliac spine to the distal tip of the medial malleolus on the dominant side.

2.5.5 Static Balance Test

Static balance was assessed using the Super Balance system (Acmeway, Beijing, China). The participants stood on the platform with their feet

shoulder-width apart, hands on their hips, and eyes directed forward. The test protocol included four conditions: (1) double-leg stance with eyes open, (2) double-leg stance with eyes closed, (3) single-leg stance (dominant leg) with eyes open, and (4) single-leg stance (dominant leg) with eyes closed.

Each double-leg stance trial lasted for 30 s, while each single-leg stance trial lasted for 10 s. Three valid trials were recorded under each condition. During double-leg stance, the participants were instructed to keep both feet flat on the platform without lifting them and maintain their hands on their hips throughout the test. During single-leg stance, the non-supporting leg was required to remain off the ground, with hands on the hips. A 30 s rest interval was provided between each test condition to prevent fatigue.

2.6 Statistics

All statistical analyses were performed using SPSS 25.0 software (SPSS Inc., Chicago, IL, USA). Prior to formal analysis, the Shapiro–Wilk test was applied to assess the normality of each variable within groups. Only data that met the assumption of normality were subjected to parametric testing.

To examine baseline differences among the three groups, one-way ANOVA was used for normally distributed variables. To assess the effects of PT on speed, strength, and balance ability across different time points (pre- and post-intervention)

and among the three intervention groups, two-way repeated measures ANOVA was conducted. When significant major effects or interactions were detected, Bonferroni-adjusted post hoc tests were performed for pair-wise comparisons.

For data that did not meet the normality assumption, the Friedman test was applied. In cases wherein significant differences were found, nonparametric post hoc tests with adjusted *p*-values were conducted. The level of statistical significance was set at $p < 0.05$.

3. Results

3.1. Effects of PT on 30 m Sprint Time and Vertical Jump Height

As shown in Figure 1, 6 weeks of PT resulted in significant interaction effects between group and time on 30 m sprint time and vertical jump height. Significant major effects of intervention condition and time were also observed.

For 30 m sprint performance, post hoc analyses indicated that sprint times were significantly decreased in all the three groups compared with their pretraining values, with the two PT groups demonstrating significantly greater improvements than the conventional training group.

For vertical jump performance, post hoc analyses demonstrated significant increases in jump height across all the groups. However, the greatest improvement was observed in the soft-surface PT group, followed by the hard-surface PT group and then the conventional training group.

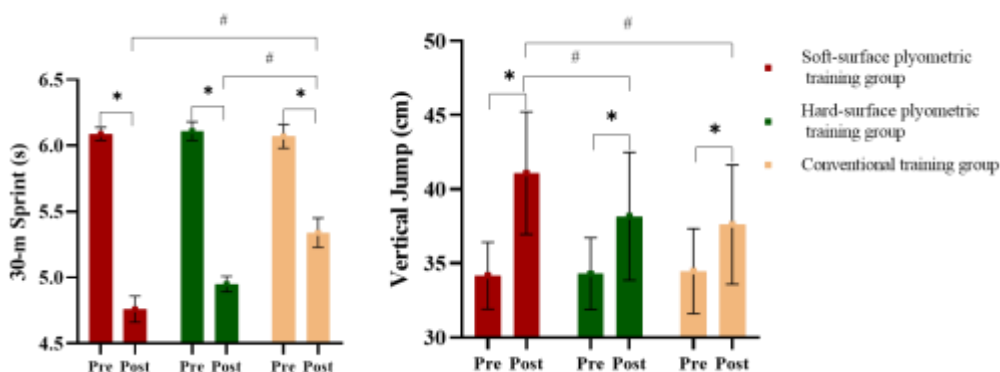


Figure 1. Effects of Plyometric Training Under Different Support Surfaces on 30-m Sprint Time and Vertical Jump Height (Mean $\pm$ SD).

* Indicates a significant difference between pre- and post-training within the same support surface condition ($p < 0.05$); # indicates a significant difference between groups after training ($p < 0.05$)

3.2 Effects of PT on Plantar Flexion and Dorsiflexion MVIC Torques

The two-way ANOVA revealed a significant interaction between group and time for plantar flexion MVIC torque, but not for dorsiflexion MVIC torque. Post hoc analyses indicated that plantar flexion MVIC torque after the intervention was significantly higher than at baseline in the

soft- and hard-surface PT groups, and higher than that of the post-intervention conventional training group (Figure 2). Significant major effects of time and group were also observed for plantar flexion MVIC torque. By contrast, only a major effect of time was found for dorsiflexion MVIC torque, indicating that dorsiflexion MVIC torque significantly increased across all three intervention protocols (Figure 2).

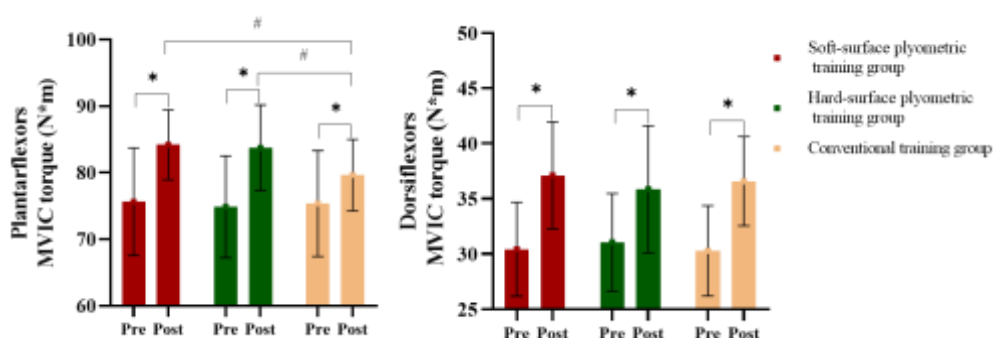


Figure 2. Effects of Plyometric Training Under Different Support Surfaces on Plantarflexion and Dorsiflexion MVIC Torque (Mean $\pm$ SD)

* Indicates a significant difference between pre- and post-training within the same support surface condition ($p < 0.05$); # indicates a significant difference between groups after training ($p < 0.05$).

3.3 Effects of PT on Dynamic Balance

As indicated in Table 3, the two-way ANOVA revealed no significant group $\times$ time interactions in reach distances across the three directions (anterior, posteromedial, and posterolateral) of the Y-balance test. However, significant group $\times$ time interactions were observed in completion time for all three directions. Post hoc analyses indicated that for the anterior direction, the soft-surface and hard-surface PT groups required significantly less time to complete the task compared with the conventional training group, with no significant difference between the two plyometric groups. In addition, all three groups exhibited significant reductions in completion time from pre- to post-intervention.

For the posteromedial direction, both PT groups completed the task at significantly less time than the conventional training group. Compared with the baseline, significant reductions in completion time were observed in both plyometric groups, with the soft-surface PT group demonstrating greater improvement (shorter time) than the hard-surface PT group.

Similarly, in the posterolateral direction, the soft-surface and hard-surface PT groups required significantly less time than the conventional training group. Significant pre-to-post reductions in completion time were observed across all the three groups, with the soft-surface group outperforming the hard-surface group.

Table 3. Effects of Plyometric training on the

distance and the duration of the movement-phase in Y-balance test (Mean $\pm$ SD)

	Direction	Intervention	Soft-surface plyometric training group	Hard-surface plyometric training group	Conventional training group	P-value
Reach distance (%)	Anterior	Pre	65.2 $\pm$ 4.8	64.7 $\pm$ 4.6	65.5 $\pm$ 4.7	0.348
		Post	66.8 $\pm$ 5.7	66.2 $\pm$ 6.4	66.4 $\pm$ 5.5	
	Posteromedial	Pre	116.5 $\pm$ 7.3	116.1 $\pm$ 9.0	116.8 $\pm$ 7.8	0.326
		Post	118.3 $\pm$ 10.7	118.1 $\pm$ 11.7	118.5 $\pm$ 10.5	
	Posterolateral	Pre	131.7 $\pm$ 6.8	130.5 $\pm$ 5.6	130.9 $\pm$ 4.5	0.203
		Post	133.1 $\pm$ 7.2	131.6 $\pm$ 7.1	130.7 $\pm$ 6.8	
Time (s)	Anterior	Pre	5.12 $\pm$ 1.35 ^a	5.24 $\pm$ 1.02 ^a	5.07 $\pm$ 1.27 ^a	0.032
		Post	3.11 $\pm$ 1.23 ^b	3.36 $\pm$ 1.47 ^b	4.75 $\pm$ 1.37 ^c	
	Posteromedial	Pre	7.54 $\pm$ 2.32 ^a	7.46 $\pm$ 2.44 ^a	7.51 $\pm$ 3.01 ^a	0.024
		Post	5.61 $\pm$ 2.41 ^b	6.02 $\pm$ 2.57 ^c	7.14 $\pm$ 2.64 ^a	
	Posterolateral	Pre	5.18 $\pm$ 1.84 ^a	5.31 $\pm$ 1.62 ^a	5.27 $\pm$ 1.77 ^a	0.037
		Post	3.21 $\pm$ 1.24 ^b	3.95 $\pm$ 1.45 ^c	4.67 $\pm$ 1.51 ^d	

Different letters denote significant differences between groups or time points, while identical letters indicate no significant difference (repeated-measures ANOVA).3.4. Effects of PT on Static Balance

3.4 Effects of PT on Static Balance

Two-way ANOVA showed no significant group $\times$ time interactions for static balance under bipedal and unipedal eyes-open conditions. By contrast, significant group $\times$ time interactions were observed for mean anteroposterior (AP) displacement and mean mediolateral (ML) displacement under bipedal eyes-closed condition. Post hoc comparisons indicated that from pre- to post-intervention, the soft-surface

and hard-surface PT groups exhibited significant reductions in AP and ML displacements. Post-intervention values in both PT groups were significantly lower than those in the conventional training group, with no difference between the two PT groups (Table 4).

Under unipedal eyes-closed condition, significant group $\times$ time interactions were found for mean displacement (AP, ML) and mean velocity (AP, ML). Post hoc tests showed that both PT groups exhibited significant pre-to-post reductions in displacement and velocity. Post-intervention values were lower than those of the conventional group. Moreover, the soft-surface PT group demonstrated greater improvements (smaller displacement and velocity) than the hard-surface PT group (Table 4).

Table 4. The effect of Plyometric training on the static balance (Mean $\pm$ SD)

	Parameters	Intervention	Soft-surface plyometric training group	Hard-surface plyometric training group	Conventional training group	P-value
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Bipedal stance with eyes open	Mean AP displacement (mm)	Pre	12.41 ± 4.11	11.92 ± 5.64	12.75 ± 4.34	0.605
		Post	10.37 ± 3.72	11.03 ± 4.67	11.64 ± 3.85	
	Mean ML displacement (mm)	Pre	6.37 ± 4.68	6.45 ± 3.57	6.13 ± 4.21	0.476
		Post	5.51 ± 4.23	5.68 ± 4.71	5.59 ± 4.67	
	Mean AP velocity (mm/s)	Pre	8.67 ± 1.50	8.52 ± 1.37	8.62 ± 1.43	0.308
		Post	8.41 ± 1.28	8.27 ± 1.33	8.34 ± 1.37	
Bipedal stance with eyes closed	Mean AP displacement (mm)	Pre	23.61 ± 12.31 ^a	24.13 ± 11.75 ^a	23.54 ± 13.84 ^a	0.042
		Post	19.62 ± 13.39 ^b	20.41 ± 12.97 ^b	22.05 ± 12.75 ^a	
	Mean ML displacement (mm)	Pre	6.61 ± 2.80 ^a	6.37 ± 2.64 ^a	6.58 ± 2.37 ^a	0.035
		Post	4.17 ± 1.94 ^b	5.34 ± 2.03 ^b	6.08 ± 2.11 ^a	
	Mean AP velocity (mm/s)	Pre	9.38 ± 1.38	9.49 ± 2.17	9.35 ± 1.78	0.561
		Post	9.12 ± 1.61	9.26 ± 1.57	9.38 ± 1.86	
Unipedal stance with eyes open	Mean AP displacement (mm)	Pre	3.68 ± 2.81	3.62 ± 2.37	3.55 ± 2.64	0.516
		Post	3.71 ± 3.54	3.84 ± 2.34	3.86 ± 2.67	
	Mean ML displacement (mm)	Pre	108.37 ± 15.76	107.34 ± 13.85	108.83 ± 14.51	0.157
		Post	107.27 ± 14.84	107.56 ± 12.38	107.18 ± 16.48	
	Mean AP velocity (mm/s)	Pre	28.45 ± 5.47	29.35 ± 6.78	28.57 ± 5.86	0.574
		Post	28.16 ± 4.33	28.76 ± 6.47	28.49 ± 5.67	
Unipedal stance with eyes closed	Mean AP displacement (mm)	Pre	16.41 ± 5.38 ^a	15.87 ± 6.12 ^a	16.38 ± 5.76 ^a	0.038
		Post	11.52 ± 4.67 ^b	13.36 ± 5.65 ^c	15.93 ± 5.17 ^a	
	Mean ML displacement (mm)	Pre	108.15 ± 16.34 ^a	107.67 ± 15.94 ^a	108.37 ± 16.25 ^a	0.029
		Post	97.75 ± 15.29 ^b	100.46 ± 17.38 ^c	106.18 ± 15.08 ^a	
	Mean AP velocity (mm/s)	Pre	67.75 ± 15.16 ^a	68.19 ± 13.75 ^a	67.83 ± 14.86 ^a	0.005
		Post	52.18 ± 58.53 ± 14.68 ^c	65.28 ± 13.57 ^a		

			13.76 ^b			
	Mean ML velocity (mm/s)	Pre	65.48 ± 16.42 ^a	65.97 ± 17.23 ^a	66.07 ± 17.12 ^a	0.018
		Post	51.16 ± 15.23 ^b	58.54 ± 16.85 ^c	65.48 ± 15.67 ^a	

Different letters denote significant differences between groups or time points, while identical letters indicate no significant difference (repeated-measures ANOVA).

4. Discussion

The current study investigated the effects of 6 weeks of PT performed on soft and hard surfaces compared with conventional training on balance performance. It further explored the underlying mechanisms associated with muscle strength and motor function. Results showed that both PT modalities produced greater improvements than conventional training across multiple indicators, with soft-surface PT yielding more pronounced gains in balance enhancement and neuromuscular optimization. High-precision force sensors were integrated to continuously monitor ground reaction forces during training and testing sessions, providing reliable biomechanical evidence to validate these outcomes. These findings highlight the critical role of surface characteristics in modulating training adaptations and offer empirical guidance for designing sport-specific training programs for adolescent female basketball players, with implications for performance enhancement and injury prevention. Compared with previous plyometric training studies, which rarely incorporated surface-dependent biomechanical analysis, the present study provides one of the first sensor-based evaluations of neuromuscular and balance adaptations across different support surfaces in adolescent female athletes. This helps fill an important gap in the literature where the interaction between surface properties and neuromechanical performance has been insufficiently explored.

After six weeks of intervention, all groups showed significant reductions in 30 m sprint time and increases in vertical jump height, with both PT groups outperforming the conventional training group. Notably, participants in the soft-surface PT group achieved greater improvements in vertical jump height than those in the hard-surface group, consistent with the principles of neuromuscular adaptation. As a classic “rapid eccentric–concentric contraction” training modality, PT enhances the storage and release efficiency of elastic potential energy, accelerates motor unit recruitment, improves synchronization of muscle fiber activation, and consequently, enhances lower limb explosive power and movement speed [16]. Force sensor data indicated that participants in the soft-surface group exhibited smoother force-time curves and shorter force development latency, reflecting more efficient elastic energy utilization and faster force transmission during take-off. The inherent instability of a soft surface imposes higher demands on neuromuscular regulation during training. The additional proprioceptive stimulation provided by an unstable surface facilitates the synchronized activation of motor units and promotes faster neural adjustments to dynamic postural changes [17]. This was further supported by sensor-based analyses, which revealed more variable yet adaptive load distribution patterns across training sessions, reflecting progressive refinement of neuromuscular control [18]. This adaptation enhances contraction precision and optimizes the timing and efficiency of force output. Consequently, compared with hard-surface training, soft-surface PT provides distinct advantages in improving neuromuscular

coordination and force production efficiency, offering a more targeted approach to developing sport-specific explosive power in adolescent basketball players [10].

The muscle strength results further revealed that soft- and hard-surface PT significantly increased plantar flexion MVIC torque, with greater improvements than conventional training. However, dorsiflexion MVIC torque increased significantly across all the groups, and PT did not produce additional benefits beyond those of conventional training. This difference can reflect the biomechanical characteristics of basketball-specific movements. Actions, such as jumping, sprinting, and sudden stopping, primarily rely on the rapid activation of the plantar flexor muscles (e.g., gastrocnemius, soleus), and PT effectively enhances their eccentric control and concentric explosive strength, leading to concurrent gains in power and functional performance [19]. Conversely, dorsiflexor muscles contribute mainly to gait stability and shock absorption during landing, where conventional training may sufficiently satisfy adaptive needs, explaining the absence of added benefits from PT [20, 21]. Integrating torque and force sensor data provided a detailed representation of muscle activation dynamics, enabling quantification of torque development rates and force fluctuation patterns across different muscle groups. These findings suggest that PT-induced strength adaptations are task-specific, with improvement magnitudes largely determined by the functional role and force-generating demands of each muscle group during sport-specific actions [22].

Results from the Y-balance test showed that participants in the soft-surface PT group completed the posteromedial and posterolateral directions significantly faster than those in the hard-surface group, and both PT groups outperformed the conventional training group. This indicates that PT-related dynamic balance improvements stem primarily from enhanced

neuromuscular responsiveness and coordination efficiency rather than increased joint mobility [23]. Supporting this, force sensor-derived ground reaction force profiles demonstrated reduced mediolateral sway and improved stability control during balance tests in the soft-surface group. Stability in the posteromedial and posterolateral directions relies on precise coordination between the ankle plantar flexor–dorsiflexor and hip adductor–abductor muscles. The instability of the soft surface continuously stimulates proprioceptive receptors (e.g., muscle spindles, Golgi tendon organs), promoting faster central nervous system regulation of motor unit recruitment and contraction patterns. This neural adaptation improves movement execution efficiency, reflected by the reduced task completion time. These results align closely with the functional demands of basketball, which require rapid directional changes and sudden stops. Sensor-assisted analyses further showed that participants trained on soft surfaces exhibited faster postural corrections and lower asymmetry indices, suggesting improved inter-limb coordination and proprioceptive feedback integration. Thus, soft-surface PT provides a unique advantage in enhancing multidirectional dynamic balance by improving neuromuscular control efficiency and reaction speed [24].

The static balance results further demonstrated that under the double-leg eyes-closed condition, both the soft- and hard-surface PT groups exhibited significantly smaller AP and ML displacements compared with the conventional training group. Under the single-leg eyes-closed condition, the soft-surface group demonstrated greater improvements in displacement and sway velocity than the hard-surface group, and both groups outperformed the conventional training group. These findings support the theoretical framework that proprioceptive and vestibular compensations are enhanced under visual deprivation. Repetitive proprioceptive stimulation

of muscles and joints through PT can promote the central nervous system's sensitivity to postural perturbations and improve the speed of postural correction [25]. The use of embedded force sensors in the balance testing platform enabled the quantification of subtle shifts in the center of pressure, providing a more objective assessment of changes in postural stability. Moreover, the instability of a soft surface amplifies this sensory input, compelling the body to establish a more efficient sensorimotor integration mechanism, and enabling stable posture maintenance even in the absence of visual feedback [26]. Thus, soft-surface PT not only strengthens balance control under visually deprived conditions but also improves proprioceptive and vestibular compensatory functions. Such an adaptation exhibits high practical relevance for maintaining stability during basketball play, where visual reliance is frequently limited.

Despite the positive short-term benefits observed, several limitations should be acknowledged. The relatively small sample size and short intervention duration (six weeks) may limit generalizability. Additionally, variations in participants' baseline athletic ability were not fully controlled or stratified, potentially introducing confounding effects. Furthermore, although differences in AP and ML sway during static balance testing may be linked to underlying biomechanical characteristics, their specific mechanisms were not further explored. Future research should adopt multi-sensor fusion approaches integrating force sensors, inertial measurement units, and surface electromyography to comprehensively examine neuromechanical interactions and adaptive mechanisms during PT. Expanding the sample size, extending the intervention period, and incorporating advanced analytical tools such as 3D motion capture and neurophysiological assessment will help elucidate the neuromechanical mechanisms underlying PT adaptations across different surface conditions.

5. Conclusions

The present study demonstrated that PT performed on different support surfaces exerts beneficial effects on balance, explosive power, and muscle strength among adolescent female basketball players. In particular, training on a soft support surface elicited greater improvements in static and dynamic balance and enhanced neuromuscular control efficiency compared with training on a hard surface. These outcomes were quantified using force platforms and biomechanical sensors, enabled precise assessment of ground reaction forces, postural sway, and muscle activation patterns, thereby providing objective evidence of neuromuscular adaptations. These results suggest that the unstable properties of a soft surface may facilitate superior proprioceptive stimulation and neural adaptation, optimizing intermuscular coordination and postural control.

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