Comparative effects of unilateral versus bilateral lower limb strength training on cartwheel performance in artistic gymnastics athletes

Efectos comparativos del entrenamiento de fuerza unilateral y bilateral de las extremidades inferiores sobre el rendimiento en volteretas laterales en atletas de gimnasia artística

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Abstract

Introduction: Muscle-strengthening exercises in gymnastics are important in supporting somersault movements because they increase power and balance.
Objective: To examine the effects of 8 weeks of unilateral versus bilateral lower-limb strength training on young gymnasts' maximal strength, dynamic balance, and cartwheel performance
Methodology: This study adopts a three-arm randomized controlled trial (RCT) with a pre-test, post-test, and blinded assessor design. Forty-two gymnasts (n=14 each) were randomized to either the unilateral training (UTG), bilateral training (BTG), or control (CG) groups. Using one-leg (unilateral) or two-leg (bilateral) lower-limb exercises, UTG and BTG trained three times a week for eight weeks, while CG continued their routine. The results included 1RM squat and deadlift, dynamic balance (Y-Balance Test, YBT), and cartwheel skill (Cartwheel Performance Assessment Tool, CPAT).
Results: Group × time interactions were significant for all outcomes ($p < 0.001$). CPAT increased by 2.2 points compared to CG ($p < 0.001$, $d = 1.32$) and 1.6 points compared to BTG ($p = 0.002$, $d = 0.94$), indicating that UTG had greater skill gains. Compared to BTG (5.9%, $p = 0.004$, $d = 1.02$), UTG's dynamic balance improved more (9.4%, $p < 0.001$, $d = 1.68$). Bilateral training yielded greater strength gains: 1RM deadlift and squat increased by 6.6 kg ($p = 0.02$) and 7.7 kg ($p = 0.01$) over UTG.
Discussion: While bilateral training maximized absolute strength, unilateral training improved skill and balance by more effectively mirroring the demands of gymnastic skills.
Conclusions: While bilateral exercises develop foundational strength, unilateral lower-limb exercises may improve skill execution and stability more effectively in young gymnasts.

Keywords

Bilateral training; unilateral training; artistic gymnastic; cartwheel performance; balance.

Resumen

Introducción: Los ejercicios de fortalecimiento muscular en la gimnasia son importantes para apoyar los movimientos de salto mortal porque aumentan la potencia y el equilibrio.
Objetivo: Examinar los efectos de 8 semanas de entrenamiento de fuerza unilateral versus bilateral de miembros inferiores sobre la fuerza máxima, el equilibrio dinámico y el rendimiento de la voltereta lateral de gimnastas jóvenes. Metodología: Cuarenta y dos gimnastas (n=14 cada una) fueron asignadas aleatoriamente a los grupos de entrenamiento unilateral (UTG), entrenamiento bilateral (BTG) o control (CG). Mediante ejercicios de extremidades inferiores con una pierna (unilateral) o con ambas piernas (bilateral), UTG y BTG entrenaron tres veces por semana durante ocho semanas, mientras que CG continuó con su rutina. Los resultados incluyeron 1RM en sentadilla y peso muerto, equilibrio dinámico (Test de Equilibrio Y, YBT) y habilidad para la voltereta lateral (Herramienta de Evaluación del Rendimiento de la Voltereta Lateral, CPAT). Resultados: Las interacciones grupo × tiempo fueron significativas para todos los resultados ($p < 0,001$). El CPAT aumentó 2,2 puntos en comparación con el grupo control ($p < 0,001$, $d = 1,32$) y 1,6 puntos en comparación con el grupo control ($p = 0,002$, $d = 0,94$), lo que indica que el grupo control tuvo mayores ganancias de habilidad. En comparación con el grupo control (5,9 %, $p = 0,004$, $d = 1,02$), el equilibrio dinámico del grupo control mejoró más (9,4 %, $p < 0,001$, $d = 1,68$). El entrenamiento bilateral produjo mayores ganancias de fuerza: el 1RM en peso muerto y sentadilla aumentó 6,6 kg ($p = 0,02$) y 7,7 kg ($p = 0,01$) en comparación con el grupo control. Discusión: Mientras que el entrenamiento bilateral maximizaba la fuerza absoluta, el entrenamiento unilateral mejoraba la habilidad y el equilibrio al reflejar con mayor eficacia las exigencias de las habilidades gimnásticas.
Conclusiones: Mientras que los ejercicios bilaterales desarrollan la fuerza fundamental, los ejercicios unilaterales de miembros inferiores pueden mejorar la ejecución de habilidades y la estabilidad de manera más efectiva en gimnastas jóvenes.

Palabras clave

Entrenamiento bilateral; entrenamiento unilateral; gimnasia artística; ejecución de volteretas; equilibrio.

Introduction

Gymnastics is a challenging sport that requires a combination of remarkable strength, balance, and motor control (Kumaat et al., 2025). Gymnasts "must use a combination of motor control, balance, and strength" to perform elite routines, which call for precise postures and fluid movements on apparatus (Fajar et al., 2025; Wijaya et al., 2024). In fact, developmental models emphasize that before specializing, young athletes should first master basic movement skills and general physical literacy. According to longitudinal data, gymnastics training can enhance strength, agility, and coordination, which over time can lead to improved neuromuscular control (Root et al., 2019). However, young gymnasts frequently develop side-to-side asymmetries (such as dominant leg flexibility and strength gains) due to repeatedly performing particular skills over time (Kyselovičová et al., 2023). These asymmetries highlight the importance of balanced training for fostering stability and preventing overuse imbalances (Rusdiawan et al., 2024)

Resistance training is safe and beneficial for kids and teenagers under proper supervision. According to recent meta-analyses, well-designed youth strength training programs enhance muscle strength and motor function without sacrificing growth (Granacher et al., 2016; León-Reyes et al., 2025). Particularly in gymnastics, basic strength and power are essential (Gasparetto et al., 2022; Santos et al., 2016). For instance, a 12-week gymnastics-specific training program for gymnasts aged 5–7 significantly increased their muscular strength and explosive power, as measured by the standing long jump, compared to a control group (Kara, 2021). According to systematic reviews, strength training programs that incorporate plyometrics or combined strength and skill exercises in elementary school athletes result in notable improvements in jumping, sprinting, and coordination (León-Reyes et al., 2025). Crucially, these results highlight the importance of early motor coordination development because coordination abilities "represent a determining factor in strength training as exercises become more specific and complex (Iorga et al., 2023; León-Reyes et al., 2025). Therefore, in accordance with long-term athlete development principles, youth training should advance from foundational movement exercises toward high-level, gymnastics-specific skills.

Gymnasts can perform bilateral or unilateral exercises as part of their strength training regimen. While unilateral training (single-leg squats, split squats, lunges, and bounding) targets each limb separately, bilateral training (such as two-legged squats and leg presses) loads both limbs simultaneously. Power generation for tumbling and vaulting in gymnastics is supported by lower-limb strength; interventions have demonstrated 12%–18 % increases in explosive power after specific programs (Kara, 2021). There are two main types of training: unilateral training (like lunges and split squats), which focuses on balance and fixing differences between limbs, and bilateral training (like squats and deadlifts), which aims to increase overall strength by using both limbs at the same time. According to neurophysiology, neural inhibition during bilateral efforts is reflected in the bilateral deficit phenomenon, where combined unilateral force surpasses bilateral output (Muirhead et al., 2024). Recent meta-analyses confirm modality-specific adaptations: unilateral training produces greater gains in unilateral power (ES = 0.91) and dynamic balance, while bilateral training improves bilateral jump performance (ES = 0.72) (Zhang et al., 2023).

The bilateral deficit is a well-known phenomenon in which the maximal bilateral force output is less than the sum of the unilateral forces of each limb (Muirhead et al., 2024). The evidence suggests that during bilateral efforts, the nervous system of many athletes prevents full activation (Muirhead et al., 2024). By taking advantage of this, unilateral training can result in different neuromuscular adaptations, frequently permitting a higher combined training load per limb. Recent research suggests that unilateral programmes typically result in greater gains in single-leg strength and power than comparable bilateral regimens (Belegišanin et al., 2025). Recent meta-analytic results, for example, demonstrate that bilateral training more strongly benefits bilateral tasks, but unilateral training significantly outperforms bilateral training in improving unilateral power and jumping metrics (Zhang et al., 2023). Practically speaking, athletes who perform primarily unilateral exercises tend to increase their jump heights and strength in one leg, while bilateral programmes improve two-legged maximal strength and explosive output when both legs work together (Zhang et al., 2023). These modality-specific results are consistent with training specificity: forced practice in a precise competition pattern optimises transfer. By concentrating on each side independently, unilateral work can address limb imbalances and may more accurately replicate the push-off and landing forces used in many gymnastics routines. On the other hand, bilateral lifts can increase total lower-body power, facilitating general takeoff and tumbling motions.

Despite these realizations, most previous studies have concentrated on performance metrics in general rather than gymnastics skills. Research has not thoroughly examined the effects of unilateral versus bilateral lower-body training on gymnastics-specific skills, such as a cartwheel. A recent study of collegiate athletes revealed no discernible difference between unilateral and bilateral programs regarding gains in leg-press strength or vertical jumping (Čillík et al., 2023; Zhao et al., 2023). This study was published in reputable international journal and highlights the contradictory findings as well as the necessity for sport-specific research. Moreover, the broader question of how bilateral versus unilateral adaptations impact athletic performance has not received sufficient research. There is little evidence connecting bilateral deficit phenomena to actual performance, as noted by Železnik et al. (2022), who urge "further research … incorporating sport-specific performance outcomes" on (Železnik et al., 2022). In other words, it is currently unknown if training in either direction results in appreciable improvements in the actual execution of skills.

Cartwheel proficiency in artistic gymnastics requires a combination of explosive strength and fine motor control, along with coordinated leg drive, hand support, and controlled balance throughout the rotation (Berisha, 2021). Unilateral strength training, which tests balance and single-leg power, may influence cartwheel technique differently than bilateral training due to this complexity (Bettariga et al., 2023). However, no experimental study has examined the effects of these approaches on a quantified cartwheel measure or directly compared them in young gymnasts. By innovatively using gymnastics-related performance tests, the current study addresses this gap by assessing both training modalities in a controlled trial of young gymnasts. Specifically, the Lower Quarter Y-Balance Test (YBT) was used to measure balance and dynamic stability, while the Cartwheel Performance Assessment Tool (CPAT), which rates movement quality, quantified cartwheel skill. Athletes use one leg to reach in various directions in the YBT, a validated dynamic-balance measure that accurately simulates the whole-body balancing demands of gymnastics (Milčić et al., 2025).

This study highlights the value of focused strength and motor control training for young gymnasts. Still, it is unclear whether bilateral or unilateral lower body training improves gymnastic skills. The goal of this randomized controlled trial was to see how 8 weeks of strength training on one leg compared to both legs affects young artistic gymnasts' maximum strength (1RM squat/deadlift), balance (Y-Balance Test), and ability to do cartwheels (Cartwheel Performance Assessment Tool). The direct comparison of these training modalities on gymnastics-specific outcomes makes this study unique. We wanted to understand how bilateral and unilateral strength training methods affect motor control, strength growth, and skill performance in young gymnasts by looking at tumbling (CPAT) changes and dynamic balance (YBT) performance after a few weeks of strength training. For young gymnasts seeking to master complex acrobatic skills, the findings will help guide decisions about training specificity.

Method

Participants

This study adopts a three-arm randomized controlled trial (RCT) with a pre-test, post-test, and blinded assessor design. The study population comprised students from the Zasis Gymnastic Club. Out of 150 available individuals, 42 were selected using random sampling techniques. These participants were assigned to three groups through ordinal pairing: Unilateral Training Group (UTG, n=14), Bilateral Training Group (BTG, n=14), and Control Group (CG, n=14). The intervention lasts 8 weeks, with assessments conducted at baseline (T0), mid-intervention (T1: 4 weeks), and post-intervention (T2: 8 weeks).

Procedure

An open invitation was used to recruit participants from the Zasis Gymnastics Club, followed by a systematic screening procedure to confirm eligibility. Forty-two athletes who passed the preliminary screening received comprehensive information about the study's goals, risks, and advantages. We obtained written informed consent from all participants; for minors (less than 16 years old), we obtained parental consent and additional written approval from legal guardians.

To reduce fatigue, baseline assessments (T0) were carried out over two sessions prior to randomization. The Cartwheel Proficiency Assessment Tool (CPAT), a validated 10-point scale that evaluates technique, alignment, and landing stability, was filled out by participants on the first day. Each cartwheel performance was scored by two certified gymnastics judges who were blind to the group assignment. To ensure accuracy, high-speed (240 fps) video recordings were used. Strength coaches oversaw the performance of 1-repetition maximum (1RM) tests for squats and deadlifts on the second day to determine the initial load prescriptions for the intervention groups. The Y-Balance Test was used to assess dynamic balance. Participants' maximal reaches in the anterior, posterolateral, and posteromedial directions were measured to the closest centimeter.

After baseline testing, participants were divided into three groups using ordinal pairing randomization: Unilateral Training Group (UTG, n=14), Bilateral Training Group (BTG, n=14), or Control Group (CG, n=14). To guarantee correct form and safety, UTG and BTG participants practiced exercise techniques with low loads during a one-week familiarization phase prior to the intervention.

The 8-week intervention consisted of three supervised sessions, each lasting 70 to 90 minutes. Every two weeks, the UTG performed unilateral exercises (such as single-leg squats and reverse lunges) with loads that were progressively increased by 10% based on perceived exertion (RPE ≤ 7). The BTG executed bilateral exercises (like deadlifts and back squats) with volume matched to the UTG using the volume-load equation (sets × reps × load). Both experimental groups were trained under the guidance of certified strength coaches who monitored technique and compliance. The CG continued their regular gymnastics training, which included conditioning, flexibility, and skill drills, without participating in any additional strength training. Those who missed more than 20% of the sessions were eliminated, and attendance logs were used to track adherence. The upcoming intervention program is detailed in Table 1.

Table 1. Intervention program in each group

Group	Exercice	Intensity	Sets/ exercise	Interval	Duration
UTG	Single-leg squats Reverse lunges with knee drive Eccentric pistol squats Concentric Step-ups	Week 1-2 : 65% 1RM Week 3-4: 75% 1RM Week 5-6: 85% 1RM Week 7-8: 95% 1RM	3	90 seconds per set and 5 minutes per exercise	70 to 90 minutes per session
BTG	Back squats Deadlifts Jump squats Lateral jumps	Week 1-2 : 65% 1RM Week 3-4: 75% 1RM Week 5-6: 85% 1RM Week 7-8: 95% 1RM	3		
CG	Continues regular gymnastics training without additional strength interventions.				

CPAT reassessment and 1RM tests to modify training loads were part of the mid-intervention testing (T1) at week 4. The T0 protocol was replicated in post-intervention testing (T2) at week 8, with all outcomes being reassessed under the same circumstances. Throughout the study, assessors were kept in the dark about group assignments.

Instrument and Data Collection

To evaluate cartwheel performance, lower limb strength, and dynamic balance, the study employed strictly validated tools and standardised procedures. The Cartwheel Proficiency Assessment Tool (CPAT), a 10-point criterion-referenced scale approved for artistic gymnastics, was utilised to assess cartwheel performance. The CPAT looks at four areas: how well the person takes off (like hand placement, shoulder stability, and trunk rotation), how they fly through the air (including hip/spine alignment, leg separation of at least 90 degrees, and head position), how they land (with both feet touching at the same time, knees bent 20-30 degrees, and maintaining balance), and how smoothly they perform the cartwheel overall. High-speed cameras (Sony α7 IV, 240 fps) recorded the participants' three maximal-effort cartwheels in both frontal and sagittal planes on a gymnastics floor certified by the FIG. Each trial was scored independently by two FIG-certified judges who were blinded to group assignment; their inter-rater reliability was excellent (ICC = 0.89, $p < 0.001$). For analysis, the trial with the highest score was retained.

In accordance with NSCA guidelines, maximal strength was determined through 1-repetition maximum (1RM) testing for deadlifts and squats. Participants warmed up with incremental loads for squats (50% and 70% of their estimated 1RM) before attempting increasingly heavier lifts (5–10% increases per attempt) until they reached failure, which was defined as compromised depth or spinal alignment. A similar procedure was followed for deadlift 1RM, which required complete hip extension without knee flexion. Certified strength coaches monitor all attempts using safety bars and spotters, interspersing 5-minute rest periods between trials to minimise fatigue. The record for the heaviest load successfully lifted was 1RM.

The Y-Balance Test (YBT) is a reliable tool (ICC = 0.85–0.91) that assesses how far someone can reach in three directions: forward (ANT), toward the back and middle (PM), and toward the back and side (PL). It was used to evaluate balance while moving. For three practice trials and three recorded trials per direction, participants stood barefoot on their dominant leg while using the non-stance leg to push a movable block. Reach distances (in centimetres) were calculated between the centre of the stance foot and the farthest position of the block. $[(ANT + PM + PL) / (3 \times \text{leg length})] \times 100$ was the formula used to normalise composite scores to leg length (ASIS to medial malleolus, measured via Harpenden anthropometric callipers±1 mm).

Three timepoints were used for data collection: baseline (T0), mid-intervention (T1: week 4), and post-intervention (T2: week 8). To reduce fatigue, baseline evaluations were conducted over two days, with 1RM tests on day two and CPAT and YBT on day one. While T2 replicated the entire T0 protocol, CPAT and 1RM were re-evaluated at T1 to adjust training loads. Group assignment and kinematic information from video recordings were not visible to assessors. An ICC of less than 0.85 verified the reliability of the YBT and 1RM test-retest. Reproducibility was assured; bias was minimised, and this methodical approach upheld the methodological and ethical rigour required for high-impact sports science research.

Data analysis

Using multiple imputation (five iterations) to address missing data for participants lost to follow-up, the data analysis process was guided by intention-to-treat principles. Levene's test confirmed the homogeneity of variance, and the Shapiro-Wilk test demonstrated that the distributions were normal ($p > 0.05$). A linear mixed-effects model (LMM) with restricted maximum likelihood estimation (REML) was used to account for interaction effects (time × group), group allocation (UTG, BTG, CG), and repeated measures (T0, T1, and T2) concerning the primary outcome (CPAT scores). To accommodate participant variability, random intercepts were included. To minimise Type I error, post hoc pairwise comparisons were adjusted using the Bonferroni method.

Researchers conducted a multivariate analysis of variance (MANOVA) for related to dynamic balance (Y-Balance composite score) and strength (1RM squat, 1RM deadlift). Significant MANOVA results prompted the use of Tukey's HSD post hoc tests in subsequent univariate ANOVAs. Effect sizes were shown with 95% confidence intervals (CIs) as Cohen's d for comparisons between pairs and partial eta-squared (η^2p) for ANOVA. All analyses were performed using SPSS version 28, with a significance threshold set at $p < 0.05$ (two-tailed). To make the results easier to understand in a clinical setting, they were shared following CONSORT guidelines, which included information on the size of the effects and how precise the estimates are (CIs).

Results

A study involving 42 artistic gymnastics athletes was conducted, dividing them into three groups: Unilateral Training Group (UTG), Bilateral Training Group (BTG), and Control Group (CG). Descriptive analyses were performed to ensure comparability at baseline. The demographic characteristics of the participants, including gender, height, weight, and training experience, were statistically comparable across all groups, which indicates successful randomization and internal validity. The mean age of the participants ranged from 11.9 to 12.3 years, and a balanced sex distribution was observed in each group.

Table 2. Demographic and Baseline Characteristics of Subjects

Variable	UTG (n=14)	BTG (n=14)	CG (n=14)	Total (N=42)	p-value
Ages(years)	12.3 ± 2.5	11.9 ± 2.3	12.1 ± 2.4	12.1 ± 2.4	0.82
Gender					0.75
- Boys	7 (50.0%)	8 (57.1%)	6 (42.9%)	21 (50.0%)	
- Girls	7 (50.0%)	6 (42.9%)	8 (57.1%)	21 (50.0%)	
Body height (cm)	142.5 ± 9.2	143.8 ± 8.7	141.2 ± 10.1	142.5 ± 9.3	0.74
Body weight (kg)	38.7 ± 6.5	40.1 ± 5.9	39.2 ± 6.8	39.3 ± 6.4	0.88
Training experience (years)	3.2 ± 1.5	3.5 ± 1.4	3.0 ± 1.6	3.2 ± 1.5	0.65

Three groups of 14 participants each—the Unilateral Training Group (UTG), Bilateral Training Group (BTG), and Control Group (CG)—were randomly selected from a total of 42 participants. With an age range of 8 to 16 years, there was no discernible difference in age between the groups (UTG: 12.3 ± 2.5 years; BTG: 11.9 ± 2.3 years; CG: 12.1 ± 2.4 years; p = 0.82). There was no gender bias in the group allocation, as the sex distribution was proportionately balanced, with an equal percentage of males and females (50%) in each group (p = 0.75). The participants' mean height and weight did not significantly differ among the groups (height: p = 0.74; weight: p = 0.88), indicating that their baseline anthropometric status was uniform. There were no statistically significant differences in the participants' mean training experience, which ranged from 3.0 to 3.5 years (p = 0.65). Internal validity was maintained when examining the effects of the specific exercise programs because the participants' backgrounds and training experience were similar across all groups at the start.

Table 3. Performance and Power Baseline Parameters

Variable	UTG	BTG	CG	p-value
CPAT Initial Score (0-10)	5.8 ± 1.0	5.7 ± 1.2	5.9 ± 1.1	0.91
1RM Squat (kg)	45.2 ± 8.1	46.5 ± 7.8	44.8 ± 8.3	0.79
1RM Deadlift (kg)	48.3 ± 9.0	49.1 ± 8.5	47.9 ± 9.2	0.83
Y-Balance Composite (%)	72.4 ± 5.8	71.9 ± 6.2	73.1 ± 5.5	0.69

All three groups showed similar baseline strength and performance characteristics before the intervention. There was no significant difference in baseline Cartwheel Proficiency Assessment Tool (CPAT) scores between the UTG (5.8 ± 1.0), BTG (5.7 ± 1.2), and CG (5.9 ± 1.1) groups (p = 0.91), suggesting baseline technical homogeneity among participants. Similar distributions were seen in the 1RM values for the squat and deadlift, which averaged roughly 45–49 kg for each group and did not differ statistically significantly (p = 0.79 for the squat and p = 0.83 for the deadlift). Additionally, there was no discernible difference in the composite Y-Balance Test scores between the groups (UTG: 72.4 ± 5.8%, BTG: 71.9 ± 6.2%, CG: 73.1 ± 5.5%; p = 0.69), indicating that the participants' dynamic balance status was equal at the study's beginning. All things considered, these findings lend credence to the notion that the three groups' initial circumstances are sufficiently uniform to permit a reliable assessment of the intervention's effects.

The study examined changes in CPAT scores, lower extremity muscle strength, and dynamic balance during the intervention period, comparing baseline performance characteristics and strength between groups. Table 4 summarizes primary and secondary findings at three measurement time points.

Table 4. Changes in Performance, Strength, and Balance Outcomes Across Timepoints by Group

Variable	Group	T0 (Baseline)	T1(4 weeks)	T2 (8 weeks)	Time × Group Interaction (p-value)	Effect Size (η^2p)
CPAT Score (0–10)	UTG	5.8 ± 1.0	7.2 ± 1.1*	8.5 ± 0.9**	<0.001	0.42
	BTG	5.7 ± 1.2	6.8 ± 1.0*	7.9 ± 1.2**		
	CG	5.9 ± 1.1	6.1 ± 1.0	6.3 ± 1.1		
1RM Squat (kg)	UTG	45.2 ± 8.1	53.6 ± 7.8*	62.4 ± 8.5**	<0.001	0.38
	BTG	46.5 ± 7.8	58.3 ± 8.2*	70.1 ± 9.0**		
	CG	44.8 ± 8.3	46.2 ± 7.9	47.5 ± 8.6		
1RM Deadlift (kg)	UTG	48.3 ± 9.0	56.1 ± 8.7*	65.8 ± 9.3**	<0.001	0.35
	BTG	49.1 ± 8.5	60.5 ± 8.9*	72.4 ± 9.5**		
	CG	47.9 ± 9.2	49.3 ± 8.8	50.1 ± 9.0		
Y-Balance Composite (%)	UTG	72.4 ± 5.8	78.2 ± 5.1*	83.6 ± 4.9**	0.002	0.28
	BTG	71.9 ± 6.2	76.5 ± 5.5*	80.1 ± 5.3**		

*p < 0.05 vs. T0 (within-group); **p < 0.01 vs. CG (between-group, post hoc adjusted); Effect sizes (η^2p) indicate the proportion of variance explained by the intervention.

All outcome variables exhibited a significant time × group interaction ($p < 0.01$), indicating that the effects of the intervention varied notably between groups. For every outcome measured, the Unilateral Training Group (UTG) and the Bilateral Training Group (BTG) demonstrated substantial within-group improvements from baseline (T0) to mid-intervention (T1) and post-intervention (T2).

In particular, CPAT scores markedly improved in BTG (from 5.7 ± 1.2 to 7.9 ± 1.2) and UTG (from 5.8 ± 1.0 to 8.5 ± 0.9), while the Control Group (CG) showed only slight change (5.9 ± 1.1 to 6.3 ± 1.1). Strength metrics exhibited similar patterns: UTG and BTG achieved significant gains in 1RM squat (UTG: +17.2 kg; BTG: +23.6 kg) and deadlift (UTG: +17.5 kg; BTG: +23.3 kg), whereas CG experienced only minimal gains. Furthermore, dynamic balance (Y-Balance composite) exhibited slight improvements in CG but significant enhancements in UTG (from 72.4% to 83.6%) and BTG (from 71.9% to 80.1%). All variables showed moderate to large effects, as indicated by effect sizes (η^2_p = 0.28–0.42).

Pairwise post hoc comparisons among groups were conducted to further clarify the extent and significance of these changes at the post-intervention stage (T2), as shown in Table 5.

Table 5. Post Hoc Comparisons of Group Differences at Post-Intervention

Comparison	Outcome	Mean Difference	Adjusted p-value	Effect Size (Cohen's *d*)	Statistical analysis
UTG vs. CG at T2	CPAT Score	+2.2 ± 0.4	<0.001**	1.32 (0.78–1.86)	Bonferroni
BTG vs. CG at T2	CPAT Score	+1.6 ± 0.5	0.002**	0.94 (0.45–1.43)	Bonferroni
UTG vs. BTG at T2	CPAT Score	+0.6 ± 0.3	0.03*	0.56 (0.12–1.00)	Tukey's HSD
BTG vs. UTG at T2	1RM Squat (kg)	+7.7 ± 2.1	0.01*	0.89 (0.35–1.43)	Tukey's HSD
BTG vs. UTG at T2	1RM Deadlift (kg)	+6.6 ± 2.0	0.02*	0.74 (0.25–1.23)	Tukey's HSD
UTG vs. CG at T2	Y-Balance Composite	+9.4% ± 1.8	<0.001**	1.68 (1.10–2.26)	Bonferroni
BTG vs. CG at T2	Y-Balance Composite	+5.9% ± 1.5	0.004**	1.02 (0.52–1.52)	Bonferroni
UTG vs. BTG at T2	Y-Balance Composite	+3.5% ± 1.2	0.04*	0.61 (0.15–1.07)	Tukey's HSD

p < 0.05; **p* < 0.01; CI = Confidence Interval; Bonferroni was used for comparisons between groups at the same time (LMM); Tukey's HSD was used for comparisons between groups in post-MANOVA univariate analysis; Small effect: *d* = 0.2; medium effect: *d* = 0.5; large effect: *d* ≥ 0.8

Significant differences between groups were found at T2 based on post hoc comparisons. UTG demonstrated a moderate advantage over BTG (+0.6, $p = 0.03$, $d = 0.56$) and outperformed CG in the CPAT score (+2.2 points, $p < 0.001$, $d = 1.32$). However, BTG outperformed UTG in the 1RM squat (+7.7 kg, $p = 0.01$, $d = 0.89$) and 1RM deadlift (+6.6 kg, $p = 0.02$, $d = 0.74$), demonstrating greater strength gains.

With a Y-Balance score 9.4% higher than CG ($p < 0.001$, $d = 1.68$) and a 3.5% advantage over BTG ($p = 0.04$, $d = 0.61$), UTG once again demonstrated the strongest effect for dynamic balance. Additionally, BTG performed 5.9% better than CG ($p = 0.004$, $d = 1.02$). These results demonstrate the efficacy of both interventions, with bilateral training being better for developing strength and unilateral training producing larger gains in gymnastic performance and balance.

Discussion

The superiority of UT for cartwheel proficiency (CPAT: Δ +0.6 vs. BT, $d = 0.56$) and dynamic balance (YBT: Δ +3.5% vs. BT, $d = 0.61$) highlights the kinematic specificity of unilateral exercises in relation to gymnastics skills. Cartwheels demand asymmetric force application, single-leg stabilisation during the support phase, and rapid weight transfer—elements directly replicated in UT drills (e.g., reverse lunges, step-ups). This specificity likely enhanced intermuscular coordination and proprioceptive acuity, facilitating skill transfer. Conversely, BT's advantage in 1RM strength (squat: Δ +7.7 kg, $d = 0.89$; deadlift: Δ +6.6 kg, $d = 0.74$) stems from higher absolute loads, driving bilateral hypertrophy and neural drive.

The current results clearly show that young gymnasts who engaged in unilateral training (UTG) demonstrated greater improvements in their cartwheels and balance (as measured by the Y-Balance Test) compared to those who participated in bilateral training (BTG) or the control group. Meanwhile, the BTG group significantly enhanced their overall strength, as indicated by their one-repetition maximum (1RM) in squats and deadlifts. This pattern supports the notion that training adaptations are specific to practiced movements. Meta-analytic evidence indicates bilateral exercises primarily increase bilateral strength, whereas unilateral resistance exercises preferentially enhance unilateral power and stability (Liao et al., 2022; Zhang et al., 2023). To put it another way, practicing one limb at a time highlights balance and neuromuscular coordination, which are essential for performing cartwheels. Conversely, bilateral loading permits higher absolute loads, which results in larger increases in total muscle force. According to recent research, unilateral training improves lower-limb explosive power, agility, and Y-balance performance more than bilateral contrast training, while bilateral training improves bilateral jumping and strength (Freitas et al., 2024; Wiriawan et al., 2024). These findings align with our results: BTG's strength improvements are linked to the heavier weights used in bilateral squats and deadlifts, while UTG's better cartwheel and Y-Balance performance show the benefits of better balance and coordination from unilateral exercises like lunges and split squats.

Neuromuscular adaptations also explain these differential effects. Intermuscular coordination is promoted by unilateral training, which places greater demands on stability and frequently uses the core and stabilizer muscles more. Additionally, it might cause cross-education, in which the untrained side gains strength from the trained limb (Hendy & Lamon, 2017). For instance, unilateral training increased strength in the trained limb by approximately 45% and in the contralateral limb by approximately 31% (Carroll et al., 2006; Manca et al., 2021). According to Duan et al., (2024) UTG may have improved on both sides of the Y-Balance Test due to these brain changes. On the other hand, bilateral lifting usually results in more hypertrophic stimulus and maximizes mechanical loading on the global musculature (Krzysztofik et al., 2019). Earlier research shows that bilateral exercises maximize maximal force development, so the significant strength gains in BTG (1RM squat/deadlift) most likely reflect this increased absolute loading (Liao et al., 2022)

These findings have significant gymnastics-related implications. Numerous skills performed by artistic gymnasts call for one-legged stance, dynamic balance, coordination (such as cartwheels, leaps, and jumps), and strong bilateral movements (such as vault run-ups and dismounts). Unilateral training may more directly address gymnastics' balance and body control requirements, as evidenced by our finding that UTG performed better than BTG in the Cartwheel Performance Assessment and Y-Balance Test.

Asymmetric force application or single-limb support is often necessary for even seemingly bilateral gymnastics skills (e.g., push-off with one foot or hand support during a cartwheel). Unilateral exercises replicate these demands and may enhance joint stability and proprioception in functional ranges specific to gymnastic manoeuvres. These workouts include single-leg hops, Bulgarian split squats, and lateral lunges (Aguilera-Castells et al., 2019). Additionally, improved performance on the balance beam and uneven floor movements may result from increased unilateral leg strength and balance (Beurskens et al., 2015; Pajek et al., 2016). Heavy bilateral lifts remain beneficial for developing the raw lower-body power required for high-impact landings and sprinting vaults, as evidenced by BTG's superior gains in bilateral strength (Moran et al., 2021). Accordingly, our findings support the idea that women's artistic gymnastics training should be tailored to the equipment's requirements (Freitas et al., 2024). For instance, when preparing for floor or beam routines, coaches may prioritize unilateral and balancing exercises while saving bilateral maximal strength work to develop overall power.

Both unilateral and bilateral resistance training interventions improved every performance metric compared to the untrained control group. This evidence demonstrates that, in comparison to no intervention, any organized, progressive training program is advantageous for young gymnasts. Research shows that properly supervised youth resistance training can safely improve young athletes' strength, power, body composition, and injury resilience, supporting early integration of strength and stability training into gymnastics preparation (Pierce et al., 2021). Therefore, in practice, particular objectives should guide the decision between unilateral and bilateral modes. Unilateral exercises may be prioritized if the goal is to improve balance, coordination, or gymnastics skills (Bradic et al., 2011; Gaspari et al., 2024); bilateral lifts should be included if the goal is to increase maximal force and power (Lee et al., 2021). A periodized program that combined the two modalities would ideally be able to take advantage of their complementary advantages (Liu et al., 2024).

This study has several advantages. By examining sport-related results (like cartwheel performance and Y-balance) along with regular strength tests, it directly compares one-sided and two-sided training in young gymnasts, providing useful real-world insights. We increase the methodological rigor by using randomized group assignment and trustworthy field tests (CPAT, YBT, and 1RM). Interestingly, the large effect sizes show that the differences are practically meaningful for athletic performance and are statistically significant. The study's homogeneous analysis obscures significant interindividual variability in gymnasts' reactions to unstable training (UT) or balanced training (BT), despite its strong group-level results. Several important factors probably moderate these responses. Biological maturation is important because athletes who mature early may be better able to withstand the high mechanical stress of BT because of their advanced bone density and tendon resilience. In contrast, those who mature later may benefit more from UT's lower joint loads and focus on neuromuscular control. By fixing existing imbalances that affect skill consistency or increase the chance of injury, UT may lead to greater improvements for those with significant strength differences between limbs, especially if the difference is more than 10%. Results are also moderated by training history: elite gymnasts may need UT's new coordination challenge to break plateaus, while novices may benefit from either stimulus because of "beginner gains.". Last but not least, an athlete's injury history matters. UT's balance requirements may be especially helpful as rehabilitative conditioning for athletes who have had previous ankle or knee injuries, as these athletes frequently display proprioceptive deficits.

There are several limitations to consider. The generalizability of the findings to other age groups, skill levels, or male gymnasts may be restricted due to the small sample size and the selection of participants from a specific demographic (young artistic gymnasts). Although the intervention period was sufficient to induce changes, longer or more intense training could yield different benefits. The transfer of improvements to in-competition performance has not yet been verified, as performance gains were assessed using specific tests (CPAT and YBT) rather than actual competitive routines. Future research should explore upper-body and core training, which are also crucial in gymnastics, since the current training regimens focus primarily on lower-body exercises. Additionally, while both training groups exhibited improvements, the examination of individual variability was lacking, as different gymnasts may respond differently based on their injury status, maturity level, or previous training history. The underlying significance of the individuality principle in training, which holds that every athlete reacts differently to a particular stimulus because of innate physiological, psychological, and experiential differences, is highlighted by this oversight (Issurin, 2010; Kraemer & Ratamess, 2004). Tailored programs that consider factors like biological maturity, injury history, and prior conditioning are crucial for optimizing performance adaptations and reducing the risk of overtraining or reinjury in elite gymnastics, where the training load and technical demands are exceptionally high (Mujika et al., 2018). Future studies that address these limitations will enhance the application of unilateral and bilateral training in young gymnasts.

Conclusions

Youth gymnasts can significantly benefit from both unilateral and bilateral resistance training. Bilateral training enhances absolute strength, whereas unilateral training effectively improves cartwheel performance and dynamic balance, which aligns with the sport's unilateral demands. The importance of strength and stability training for young gymnasts is underscored by findings indicating that both training methods are more effective than no training. The study suggests that training modes should align with the neural and mechanical demands of the target activity. To enhance skill execution on the floor and beam, coaches should integrate single-leg drills, lunges, and stability exercises into their youth training programs. Resistance training is safe and advantageous for developing athletes when conducted under proper supervision. The small number of participants, the short training duration, and the focus on preteen gymnasts may make it difficult to generalise the results to other groups. Future research could explore combined training regimens, longer intervention durations, and effects on competition performance. A balanced strength-training approach based on gymnastic skills specificity is most beneficial for young artistic gymnasts.

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