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Effect of unilateral and bilateral plyometric training on jumping, sprinting, and change of direction abilities: a meta-analysis

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Abstract

Background Plyometric training is a commonly employed method to enhance explosive strength in athletes. However, to date, no study has provided a comprehensive and systematic evaluation of the effects of unilateral (UNI) versus bilateral (BI) plyometric training.

Objectives This meta-analysis investigates the impact of UNI and BI plyometric training on jumping, sprinting, and Change of Direction (COD) abilities.

Study eligibility criteria To be eligible for inclusion in the meta-analysis, the study had to be:(1)healthy individuals; (2)UNI and BI plyometric training ; (3)conducted on rigid surfaces; (4)the outcome indicators were jumping ability, sprinting, and change of direction ability; (5)randomized controlled trials (RCTs).

Study appraisal and synthesis methods We used the random-effects model for meta-analyses. Effect sizes (standardized mean difference), calculated from measures of horizontally oriented performance, were represented by the standardized mean difference and presented alongside 95% confidence intervals (CI).

Data sources PubMed, Web of Science, Scopus, ProQuest, CNKI and Google Scholar.

Results A total of 11 papers met the inclusion criteria. The meta-analysis revealed that UNI contrast training was more effective than BI contrast training in improving single-leg jump performance (ES = 0.53, 95% CI: 0.02–1.04; Z = 2.05, p = 0.04), double-legs jump performance (ES = -0.07, 95% CI: -0.23–0.09; Z = 0.88, p = 0.38),sprint performance (ES = -0.04, 95% CI: -0.07–-0.01; Z = 2.32, p = 0.02), as well as COD (ES = − 0.08, 95% CI: − 0.12 to − 0.03; Z = 3.29, p = 0.001 < 0.01). Conversely, BI contrast training showed a greater effect on bilateral jump performance (ES = -0.07, 95% CI: -0.12–-0.03; Z = 3.39, p = 0.0007). Training with low-ground-contact frequencies (LGCF, fewer than 900 contacts) was found to significantly enhance vertical jump performance (ES = 0.64, 95% CI: 0.01–1.27; Z = 2.00, p = 0.05).

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Conclusions UNI and BI plyometric training offer modality-specific benefits for enhancing single-leg jumping, sprinting, and COD performance, whereas BI is more effective for optimizing bilateral jump performance. The LGCF protocol significantly enhances vertical jump performance.

Keywords Unilateral training, Plyometric training, Lower Limb Athletic Performance

Introduction

Plyometric Training (PT) is a widely utilized method for enhancing athletic power output, optimizing neuromuscular control through the Stretch-Shortening Cycle (SSC) to improve force production [1–4]. In recent years, the differential effects of Unilateral (UNI) and Bilateral (BI) plyometric training have garnered significant attention. While bilateral training is commonly employed for maximizing external loading in lower-limb strength development [5, 6], unilateral training is considered more sport-specific due to its closer resemblance to movement patterns in sports such as basketball cuts and soccer kicks [7–9]. Compared to bilateral training, unilateral training involves a narrower base of support, imposing higher demands on multi-joint neuromuscular coordination and stability [10, 11].

Empirical studies have demonstrated that unilateral training confers significant advantages in improving single-leg jumping and Change of Direction (COD) abilities. For instance, Bogdanis et al. (2019) found that unilateral plyometric training outperformed bilateral training in enhancing single-leg jump performance and Rate of Force Development (RFD) [12]. Similarly, Vasileios (2020) reported more pronounced improvements in lower-limb strength and power following unilateral training in adolescent soccer players [13]. However, bilateral training remains superior in tasks requiring coordinated bilateral lower-limb force production, such as squat jumps [14].

Despite existing research comparing unilateral and bilateral training [15], no systematic meta-analysis has yet comprehensively evaluated their effects on jumping, sprinting, and COD abilities [16]. Current studies are often limited by small sample sizes and inconsistent findings. For example, some studies have found no significant effects of unilateral training on horizontal jumping [13], while others support its efficacy [17]. This inconsistency may be attributed to factors such as training volume, intervention duration, and participant characteristics [18, 19].

Therefore, the present study aims to systematically assess the effects of unilateral versus bilateral plyometric training on jumping, sprinting, and COD abilities through meta-analytic methods, providing scientific evidence for coaches to design training programs. The specific objectives include:

1. Comparing the effects of unilateral and bilateral training on single-leg and double-leg jumping, as well as vertical and horizontal jump performance;
2. Investigating the moderating role of training volume (e.g., Total ground contact frequency) on training outcomes;
3. Analyzing their impacts on sprint performance and COD ability.

Materials and methods

This meta-analysis strictly adheres to the PRISMA guidelines [20], and the protocol has been registered with PROSPERO (ID: CRD42024586349).

Search strategy

The databases were searched by 2 researchers each using an independent double-blind approach, and 6 databases were used for the literature search with a search time frame from January 1, 2010 to December 31, 2024 (Table 1).

Eligibility criteria

Inclusion criteria for this meta-analysis were based on the PICOS (Participants, Intervention, Comparison, Outcome, Study design) format of evidence-based medicine.

Studies were included if they met the following criteria: (1) participants were healthy individuals; (2) the experimental group underwent unilateral plyometric training as the intervention, followed by specialized training (e.g., soccer, basketball, volleyball) or regular physical education classes, similar to the control group; (3) the control group received bilateral plyometric training only, with similar activities, including specialized training or regular physical education courses; (4) all studies were conducted on rigid surfaces to eliminate the potential interference from different training surfaces; (5) outcome measures included jump, sprint, change of direction, etc.; (6) studies were randomized controlled trials (RCTs).

Studies were excluded if they met any of the following criteria: (1) non-randomized controlled trials, self-controlled trials, or crossover trials; (2) insufficient data availability; (3) conference papers, reviews, or meta-analyses; (4) inability to obtain full-text articles; (5) studies conducted on non-healthy populations. A total of 11 studies met the inclusion criteria and were included in

Table 1 Literature search criteria settings

Search items	Content
Data source	PubMed, Web of Science, Scopus, ProQuest,CNKI,Google Scholar
Retrieval	"plyometric"("plyometrics" OR "PT" OR "pliometrique" OR "entrainement pliometrique" OR "salto pliometrico" OR "velocidad")
	"unilateral"("single-leg" OR "single leg")
	"bilateral" ("double-leg" OR "double leg")
	"sports performance"("lower limb strength" OR "Lower limb explosive strength" OR "explosive" OR "Power")
	"jump performance"("hop" OR "countermovement jump" OR "CMJ" OR "countermovement vertical jump" OR "CVJ" OR "squat jump" OR "SJ" OR "standing long jump" OR "SLJ" OR "drop jump" OR "deep jump" OR "DJ")
	"sprint performance"("10 m" OR "20 m" OR "30 m" OR "40 m" OR "50 m")
	"agility performance"("change of direction" OR "COD" OR "505"OR "cut" OR "T agility test" OR "T test")
Language of Literature	Unlimited
Type of literature	Joumal,Thesis
Search date	January 1, 2010 to December 31, 2024

the analysis. The detailed inclusion and exclusion process is illustrated in Fig. 1.

Literature screening and data extraction

The literature screening was conducted using Endnote X9(Thomson ResearchSoft, Stanford, CT, USA), while data extraction was performed with Excel. Two researchers independently carried out the screening and data extraction, with cross-checking of results. In cases of discrepancies between the two researchers, a third researcher was responsible for final data extraction and reconciliation.

During the screening process, irrelevant studies were excluded, and the remaining potentially relevant studies

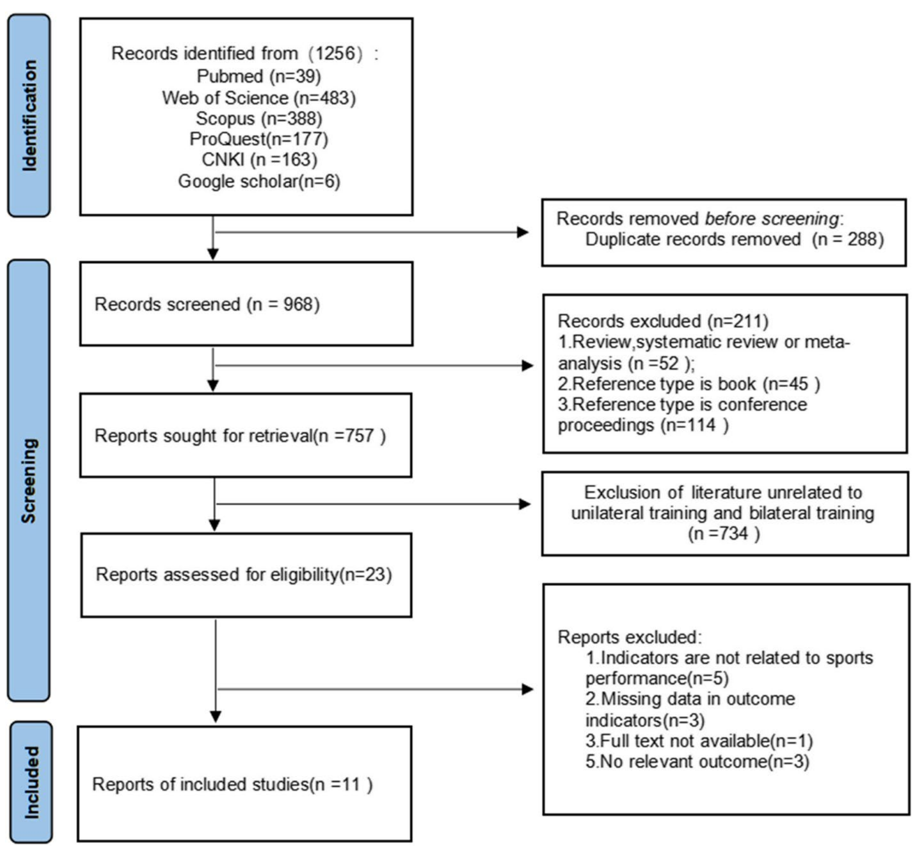


Fig. 1 Flowchart for inclusion and exclusion of studies

underwent a comprehensive full-text review to determine their eligibility for inclusion in the final analysis. The extraction included: (1) authors' names and publication years; (2) characteristics of subjects (age or maturation stage, sex, number of research subjects); (3) pre- and posttest data of included indicators; (4) training programs (intervention period, training frequency, training time, training methods of experimental group and control,grouptotal ground contact frequency(TGCF)).

Assessment of risk of bias

The Physiotherapy Evidence Database (PEDro) was used to assess the risk of bias and methodological quality of studies included in the meta-analysis, and the scale assessed the validity of studies on a scale from 0 (high risk of bias) to 10 (low risk of bias). The scale was evaluated by three persons independently for the included studies, and if the evaluations differed, they met to discuss. The first item was not counted in the total score, and a total score ≥ 6 represented a low risk of bias threshold and high quality of the literature.

Statistical analysis

This study utilized RevMan 5.4 software (The Nordic Cochrane Centre, Denmark) for effect size pooling, subgroup analyses, and heterogeneity testing. To ensure objectivity, only analyses including data from at least two groups were included. All measurement units were converted to the International System of Units (SI) and standardized using unified formulas.

For continuous outcome measures, either the Mean Difference (MD) or Standardized Mean Difference (SMD; Hedges' g) was selected as the effect size. The MD was calculated when all studies employed identical measurement units, while the SMD was applied when measurement tools or units were inconsistent [21, 22]. Effect sizes were derived from baseline-to-endpoint changes in means, standard deviations, and sample sizes for both experimental and control groups. The formula for MD is:

$$\mathrm{MD} = \overline{\mathrm{X}_{\mathrm{E}}} - \overline{\mathrm{X}_{\mathrm{C}}}$$

where $\overline{\mathrm{X}_{\mathrm{E}}}$ and $\overline{\mathrm{X}_{\mathrm{C}}}$ represent the means of the experimental and control groups, respectively. According to Cohen's criteria, effect sizes of 0.2, 0.5, and 0.8 were interpreted as small, moderate, and large effects, respectively [23].

Heterogeneity across studies was evaluated using the I^2 statistic, with the following thresholds:$I^2 < 25\%$: Low heterogeneity;$25\% \leq I^2 < 50\%$: Mild heterogeneity;$50\% \leq I^2 < 75\%$: Moderate heterogeneity;$I^2 \geq 75\%$: High heterogeneity [24].

A fixed-effect model (FE) was applied when $I^2 < 25\%$, whereas a random-effects model (RE) was used for $I^2 \geq 25\%$ [25]. Statistical significance was set at $p < 0.05$.

Total Ground Contact Frequency (TGCF) was defined as the total number of foot–ground contacts per plyometric cycle, reflecting training volume [26, 27]. Adapted from Chen et al. (2023) [28], TGCF was stratified into three groups:

Low Ground Contact Frequency (LGCF): <900 total cycles
Medium Ground Contact Frequency (MGCF): 900–1400 total cycles
High Ground Contact Frequency (HGCF): >1400 total cycles.

To ensure comparability, subgroup analyses were restricted to categories containing at least two studies; subgroups with fewer than two studies were systematically excluded.

Risk of bias across all studies

Publication bias was quantified by Stata SE12.0 software Egger's test, $p < 0.05$ significant publication bias.

Results

Study selection

A preliminary search identified 1256 articles, which were screened for duplicates. After removing duplicates, the following databases were searched: PubMed ($n = 39$),Web of Science ($n = 483$), Scopus ($n = 388$), ProQuest ($n = 177$),CNKI ($n = 163$),and Google Scholar ($n = 6$). A total of 10 studies met the inclusion criteria and were included in the meta-analysis (Fig. 1).

Study characteristics

Following the PRISMA guidelines, this meta-analysis incorporated 11 independent studies derived from 67 experimental protocols (Table 2). A total of 328 healthy participants (31.7% male, 49.4% female,18.9% not reported) were included. The age range varied between studies, 1 studies evaluated youth ($9 \leq 12$ years)Preadolescent;7 studies evaluated youth ($13 \leq 18$ years), and 3 studies evaluated adults (18–65 years).The experimental group received unilateral enhanced training, whereas the control group underwent bilateral training. Each session lasted 20–90 min, delivered 2–3 times per week over 6–12 weeks. This frequency aligns with evidence-based guidelines for optimizing training adaptations while minimizing attrition risks.The sample comprises students and athletes who practice different sports such as volleyball, basketball, badmintonl, Powerlifte, Endurance

Table 2 List of basic characteristics of the included literature

Study	Project	Group	N	Sex	Age (years)	Height (cm)	Weight (kg)	Study duration (weeks)	Mean frequency (per week)	Sessions (min)	Exercises	Sets	Repetitions	Jumps / session	Test used
Gonzalo-Skok (2018) [8]	Basket-ball	UNI	9	M	13.2 ± 0.5	171.7 ± 7.2	59.6 ± 11.7	6	2	35–45	Single-leg Drop Jump,Tuck Jump,Hurdle jump etc	2–3	2–5	Total volume: 960	5 m Sprint,10 m Sprint,25 m Sprint,CMJ,HJ,V-CUT,COD180,
		BI	9		13.3 ± 0.6	172.8 ± 7.9	59.1 ± 12.8				Drop Jump,Tuck Jump,Hurdle jump etc				
Drouzas (2020) [13]	Soccer	UNI	23	M	9.9 ± 1.8	142.2 ± 8.7	39.3 ± 8.2	10	2	15	Single-leg Jumps over hurdles,Jumps in four squares etc	3–5	6–10	Total volume: 720	Jumping sideways,Side hop,Double-leg jump,Single-leg hop,Double-leg CMJ,Single-leg CMJ,Double-leg SJ,Single-leg SJ, 5 m. Sprint,10 m. Sprint,20 m. Sprint,Modified Agility T-test
		BI	23		10.0 ± 0.5	139.2 ± 7.0	36.1 ± 7.8				Jumps over hurdles,Jumps in four squares etc				
Ahmad (2020) [29]	volleyball	UNI	33	F	16.16 ± 1.65	167.14 ± 6.57	59.51 ± 9.03	8	2					Total volume: 543	CVJ,CVJ-L,CVJ-R,SJ,5-RBJ(ES),SLJ(ES),T agility test(ES)
		BI	33		16.18 ± 1.80	164.07 ± 2.34	55.17 ± 5.62								
Abston (2020) [30]	Power-lifte	UNI	7	M,F	18–25	_	_	6	3		Single-leg Squat Jumps Countermovement Jumps Depth Jumps	4	6–8	Total volume: 528	20 m Sprint
		BI	7			_	_				Squat Jumps Countermovement Jumps Depth Jumps				
Kong (2018) [31]	volleyball	UNI	25	F	14.56 ± 1.45	159.14 ± 6.57	53.55 ± 9.03	8	2	30	Single-leg Squat jump,Ankle hop,Broad jump stick land,Forward hopping etc	3–4	5–20	Total volume: 1819	CVJ,CVJ-L,CVJ-R,SJ,5-RBJ,SLJ,T-agility test
		BI	21		14.48 ± 1.50	160.07 ± 4.34	51.80 ± 8.36				Squat jump,Ankle hop,Broad jump stick land,Forward hopping etc				

Table 2 (continued)

Study	Project	Group	N	Sex	Age (years)	Height (cm)	Weight (kg)	Study duration (weeks)	Mean frequency (per week)	Sessions (min)	Exercises	Sets	Repetitions	Jumps / session	Test used
Greenwood (2021) [32]	Endurance Running	UNI	9	12F, 15 M	35 ± 6	1.70 ± 0.1	74.3 ± 15.1	11	2–3	20–40	Single-leg Jumps,ankle hops,Squat jumps,hurdle jumps,Box jumps etc	1–4	5–10	Total volume: 1856	CMJ
		BI	9								Jumps,ankle hops,Squat jumps,hurdle jumps,Box jumps etc				
Xu (2023) [17]	badminton	UNI	10	M	20.80 ± 0.79	179.20 ± 3.55	71.20 ± 5.49	10	2	60	Single-leg Depth jump,Jump over bar, jump foeward etc	2	5–10	Total volume: 1340	SLJ,30 m Sprint,10 low center of gravity quad runs,Run on both sides about 8 times,CMJ-L,R,B
		BI	10		21.10 ± 0.99	177.90 ± 5.20	72.50 ± 9.99				Depth jump,Jump over bar, jump foeward etc				
Makaruk (2011) [11]		UNI	16	F	20.6 ± 1.3	1.67 ± 0.4	59.2 ± 4.9	12	2	40–45	Single-leg hop,rope jumps, Z jumps,Horizontal leg bounds,jumps,box Jump etc	2–8	4–15	Total volume: 1610	alternate leg tests,Five alternate leg bounds (m),CMJ (m)
		BI	18		20.9 ± 1.7	1.66 ± 0.5	57.3 ± 4.2				hop,rope jumps, Zig-zag jumps,Horizontal leg bounds,jumps,box Jump etc				
Li (2021) [33]	Basketball	UNI	10	M	20.6 ± 1.51	185.6 ± 3.63	79.95 ± 6.56	8	2	45	Single-leg Vertical jump,Depth jump, Jump over bar etc	2	8	Total volume: 768	CMJ,CODD,V-Cut
		BI	10		20.4 ± 1.35	186.1 ± 4.06	80.71 ± 5.02				Vertical jump,Depth jump, Jump over bar etc				

Table 2 (continued)

Study	Project	Group	N	Sex	Age (years)	Height (cm)	Weight (kg)	Study duration (weeks)	Mean frequency (per week)	Sessions (min)	Exercises	Sets	Repetitions	Jumps / session	Test used
Miao (2021) [34]	Soccer	UNI	8	F	16.12 ± 0.64	170.62 ± 3.77	59.25 ± 5.36	8	2	60	single-leg hops,squat jump, sprint,Z jump etc	4	8–10	Total volume: 416	SLJ-L,R,B, 30 m sprint, 20 m single leg hop, T-agility test, CMJ-U,B
		BI	8		15.87 ± 0.64	168.75 ± 5.20	57.62 ± 3.70				hops,squat jump, sprint,Z jump etc				
Mujezinović (2024) [35]	Soccer	UNI	15	-	14 years in average	-	-	8	2	-	Single leg Box jump,hurdle jump side jump	-	-	-	5 m, 20 m, 505, side step,arrow
		BI	15			-	-				double leg Box jump,hurdle jump side jump				

Running, soccer,,and the competitive level ranges from recreational to professional.

UNI unilateral plyometric training,BI bilateral plyometric training,M male,F FemaleCMJ countermovement jump, SJ squat jump,CVJ Countermovement Vertical Jump,HJ Horizontal Jump,SLJ Standing Long Jump,CODD Change of Direction Drill,5-RBJ 5-Repetition Ball Jump.

Risk of bias in the included articles

There were 7 literature quality scores ≥ 6 as assessed by the PEDro scale (Table 3).

Meta-analysis results

Unilateral and bilateral jump performance

A total of 40 studies from 9 articles were included to investigate the effects of unilateral (UNI) and bilateral (BI) training on jumping performance (Fig. 2). The meta-analysis revealed no statistically significant difference in jumping performance between UNI and control interventions (ES = 0.1, 95% CI: 0.04–0.25; Z = 1.41, $p = 0.16$), with substantial heterogeneity observed across studies ($I^2 = 35\%$, $p = 0.02$). The standardized mean difference (SMD) was employed to synthesize outcomes across studies.

Subgroup analyses of jumping performance demonstrated differential effects of unilateral versus bilateral plyometric training on single-leg and double-leg tasks:Single-leg jumps showed significant improvement (ES = 0.29, 95% CI: 0.06–0.52; Z = 2.46, $p = 0.01$) with moderate heterogeneity ($I^2 = 49\%$, $p = 0.004$);Double-leg jumps exhibited no significant difference (ES = −0.07, 95% CI: −0.23–0.09; Z = 0.88, $p = 0.38$) with negligible heterogeneity ($I^2 = 0\%$, $p = 0.96$) (Fig. 2).

Vertical jump performance

A total of 28 studies from 9 articles were included to examine the effects of unilateral (UNI) and bilateral (BI) training on vertical jump performance (Fig. 3). The meta-analysis revealed a statistically significant improvement in vertical jump performance with UNI compared to control interventions (ES = 0.53, 95% CI: 0.02–1.04; Z = 2.05, $p = 0.04$), with moderate heterogeneity across studies ($I^2 = 49\%$, $p = 0.002$). Jump performance was measured in centimeters (cm).

Subgroup analyses stratified by total ground contact frequency (TGCF) demonstrated differential effects of unilateral versus bilateral plyometric training on vertical jump performance:LGCF group (TGCF ≤ 900): Significant enhancement (ES = 0.64, 95% CI: 0.01–1.27; Z = 2.00, $p = 0.05$) with low heterogeneity ($I^2 = 8\%$, $p = 0.37$);MGCF group (900 < TGCF ≤ 1400): Non-significant effect (ES = 0.70, 95% CI: −0.33–1.73; Z = 1.33, $p = 0.18$) accompanied by high heterogeneity ($I^2 = 82\%$, $p < 0.0001$);HGCF group (TGCF > 1400): No significant difference (ES = 0.5, 95% CI: −0.87–0.96; Z = 0.10, $p = 0.92$) with negligible heterogeneity ($I^2 = 0\%$, $p = 0.96$). (Fig. 3).

Horizontal jump performance

A total of 12 studies from 6 articles were included to examine the effects of unilateral (UNI) and bilateral (BI) training on horizontal jump performance (Fig. 4). The meta-analysis demonstrated no statistically significant difference in horizontal jump performance between UNI and control interventions (ES = 0.02, 95% CI: −0.20–0.25; Z = 0.19, $p = 0.85$), with negligible heterogeneity across studies ($I^2 = 0\%$, $p = 0.63$). The standardized mean difference (SMD) was employed to synthesize outcomes across studies.

Sprint performance

A total of 11 studies from 5 articles were included to examine the effects of unilateral (UNI) and bilateral (BI) training on sprint performance (Fig. 5). The meta-analysis demonstrated a statistically significant difference in sprint performance favoring UNI compared to control interventions (ES = −0.04, 95% CI: −0.07–−0.01; Z = 2.32, $p = 0.02$), with negligible heterogeneity across studies ($I^2 = 0\%$, $p = 0.68$). Sprint performance was measured in seconds (s).

Change of direction (COD) performance

A total of 16 studies from 6 articles were included to examine the effects of unilateral (UNI) and bilateral (BI) training on agility performance (Fig. 6). The meta-analysis demonstrated a statistically significant difference in agility performance favoring UNI compared to control interventions (ES = −0.07, 95% CI: −0.12–−0.03; Z = 3.39, $p = 0.0007$), with negligible heterogeneity across studies ($I^2 = 0\%$, $p = 0.54$). Agility performance was measured in seconds (s).

Sensitivity analysis

Through sequentially removing individual indicators and recalculating the heterogeneity (I^2) and pooled effect sizes, it was found that CMJ-L (single-leg countermovement jump-left) and CMJ-R (single-leg countermovement jump-right) contributed significantly to heterogeneity:

When all indicators were included, the heterogeneity was high (I2 = 82%, $p < 0.01$).

After excluding CMJ-L and CMJ-R, the heterogeneity dropped to 0% ($p = 0.52$), indicating these two indicators were the primary sources of heterogeneity.

Table 3 The Physiotherapy Evidence Database (PEDro) scale ratings

Studies	PEDRo Scale Items											PEDro Score
	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	
Gonzalo-Skok (2018) [8]	1	1	0	1	0	0	0	1	0	1	1	6
Drouzas (2020) [13]	1	1	0	1	0	0	0	0	0	1	1	5
Ahmad (2020) [29]	1	1	0	1	0	0	0	0	0	1	1	5
Abston (2020) [30]	1	1	1	1	0	0	0	1	0	1	1	7
Kong (2018) [31]	1	1	0	1	0	0	0	1	0	1	1	6
Greenwood (2021) [32]	1	1	0	1	0	0	0	1	0	1	1	6
Xu (2023) [17]	1	1	0	1	0	0	0	1	0	1	1	6
Makaruk (2011) [11]	1	1	0	1	0	0	0	0	0	1	1	5
Li (2021) [33]	1	1	0	1	0	0	0	1	0	1	1	6
Miao (2021) [34]	1	1	0	1	0	0	0	1	0	1	1	6
Mujezinović (2024) [35]	1	1	0	0	0	0	0	1	0	1	1	5

Notably, after excluding CMJ-L/R, the direction of the pooled effect sizes for the remaining indicators (BCMJ, UCMJ) contradicted the original analysis.

Risk of bias across studies
Bias analysis was performed using the Egger test of Stata SE12.0 to more accurately evaluate the possible publication bias in the study in a combined qualitative and quantitative manner. The results showed no significant publication bias for jumping ability ($p=0.885$), sprinting ability ($p=0.7$), and change of direction ability ($p=0.12$) (Table 4).

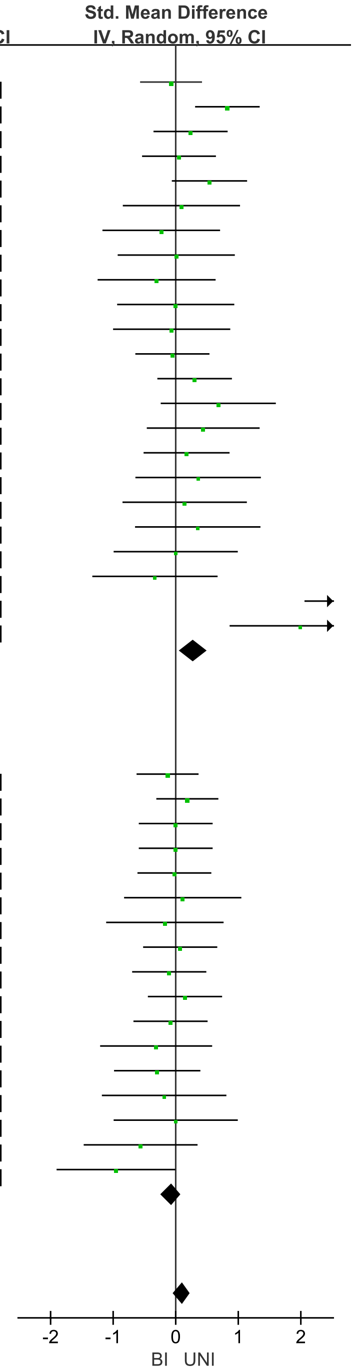
Discussion
This study systematically explored the differential effects and underlying mechanisms of unilateral (UNI) and bilateral (BI) plyometric training on athletic performance through meta-analysis. The results indicated that UNI training significantly enhanced single-leg jumping, sprint acceleration, and change of direction (COD) ability, while BI training was more effective in optimizing bilateral jump performance. Improvements in vertical jumping exhibited a clear dose–response relationship, with the LGCF showing significant effects. In contrast, HGCF led to diminished benefits due to accumulated fatigue. No statistical differences were observed between UNI and BI training in horizontal jump performance, with the underlying biomechanics involving complex regulation of core stability and multi-joint coordination. The concurrent enhancement of sprint and COD abilities originated from cross-task adaptations of UNI training, including kinetic chain synchronization, stiffness modulation, and multiplanar control.

Unilateral and bilateral jump performance
This meta-analysis demonstrates that unilateral plyometric training (UNI) significantly enhances single-leg jump performance, whereas bilateral training (BI) is more effective for double-leg jumps. These findings align with the specificity principle, as unilateral training mimics single-leg athletic demands (e.g., sprinting, cutting), improving intermuscular coordination and motor unit recruitment for unilateral tasks [36]. Notably, the cross-transfer effect observed in UNI training [37] suggests its potential utility in injury rehabilitation or asymmetrical strength development, offering practical value for athletes recovering from unilateral injuries.

While unilateral plyometric training (UNI) demonstrates superior efficacy for single-leg tasks and cross-transfer potential for injury rehabilitation, these findings are constrained by the homogeneity of included studies, predominantly involving young, healthy athletes. Limited data on populations with preexisting asymmetries or chronic injuries may restrict generalizability to rehabilitation contexts. UNI protocols should prioritize single-leg explosive tasks (e.g., sprint acceleration, cutting maneuvers), while BI protocols are more suitable for double-leg power development (e.g., basketball rebounding, vertical jumps). Additionally, the cross-transfer effect further supports the application of UNI training for injury rehabilitation or addressing strength asymmetries.

Horizontal jump performance
Demonstrated significant improvements in horizontal jump outcomes. This discrepancy stems from fundamental biomechanical differences between horizontal jumps (e.g., standing long jump, triple jump) and vertical jumps. Horizontal jumps require whole-body coordination involving multi-phase integration

	UNI			BI				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
1.3.1 Single-leg								
Ahmad 2020 CVJ-L	2.02	2.7	33	2.21	2.32	33	4.1%	-0.07 [-0.56, 0.41]
Ahmad 2020 CVJ-R	3.39	2.86	33	1.31	2.05	33	3.9%	0.83 [0.32, 1.33]
Drouzas 2020 CMJ-U	2.8	6.45	23	1.3	5.96	23	3.4%	0.24 [-0.34, 0.82]
Drouzas 2020 SJ-U	2.1	6.01	23	1.8	5.21	23	3.4%	0.05 [-0.53, 0.63]
Drouzas 2020 SL hop	21	23.52	23	9	20.07	23	3.3%	0.54 [-0.05, 1.13]
Gonzalo-Skok 2018 CMJ-L	2	2.71	9	1.7	3.5	9	1.8%	0.09 [-0.83, 1.02]
Gonzalo-Skok 2018 CMJ-R	1.6	2.95	9	2.3	2.82	9	1.8%	-0.23 [-1.16, 0.70]
Gonzalo-Skok 2018 HJ-L	12	21.83	9	11.8	21.94	9	1.8%	0.01 [-0.92, 0.93]
Gonzalo-Skok 2018 HJ-R	6.3	17.92	9	12.4	20.07	9	1.8%	-0.31 [-1.24, 0.63]
Greenwood 2021 CMJ-L	2.2	5.01	9	2.2	4.4	9	1.8%	0.00 [-0.92, 0.92]
Greenwood 2021 CMJ-R	2.1	5.05	9	2.4	3.66	9	1.8%	-0.06 [-0.99, 0.86]
Kong 2018 CVJ-L	2.02	3.7	25	2.21	3.3	21	3.4%	-0.05 [-0.63, 0.53]
Kong 2018 CVJ-R	2.39	3.85	25	1.31	3.05	21	3.4%	0.30 [-0.28, 0.89]
Li 2021 CMJ-L	3.58	3.87	10	0.42	4.96	10	1.9%	0.68 [-0.23, 1.59]
Li 2021 CMJ-R	2.83	3.5	10	0.91	4.77	10	1.9%	0.44 [-0.45, 1.33]
Makaruk 2011 FALB	41	39.51	16	34	39.28	18	2.8%	0.17 [-0.50, 0.85]
Miao 2021 20m SL hop-L	-0.22	0.3	8	-0.33	0.28	8	1.6%	0.36 [-0.63, 1.35]
Miao 2021 20m SL hop-R	-0.18	0.35	8	-0.22	0.13	8	1.7%	0.14 [-0.84, 1.12]
Miao 2021 CMJ-U	1.45	1.55	8	0.85	1.67	8	1.6%	0.35 [-0.64, 1.34]
Miao 2021 SLJ-L	5	10.15	8	5	6.56	8	1.7%	0.00 [-0.98, 0.98]
Miao 2021 SLJ-R	5	6.56	8	8	10.15	8	1.6%	-0.33 [-1.32, 0.66]
Xu 2023 CMJ-L	2.57	0.51	10	0.62	0.53	10	0.8%	3.59 [2.07, 5.11]
Xu 2023 CMJ-R	1.83	0.72	10	0.56	0.48	10	1.4%	1.99 [0.87, 3.10]
Subtotal (95% CI)			**335**			**329**	**52.7%**	**0.29 [0.06, 0.52]**
Heterogeneity: Tau² = 0.14; Chi² = 43.38, df = 22 (P = 0.004); I² = 49%								
Test for overall effect: Z = 2.46 (P = 0.01)								
1.3.2 Double-legs								
Ahmad 2020 CVJ	0.73	5.22	33	1.29	2.97	33	4.1%	-0.13 [-0.61, 0.35]
Ahmad 2020 SJ	1.34	5.31	33	0.53	2.98	33	4.1%	0.19 [-0.30, 0.67]
Drouzas 2020 CMJ-B	0.9	4.99	23	0.9	5	23	3.4%	0.00 [-0.58, 0.58]
Drouzas 2020 DL jump	8	26.23	23	8	17.09	23	3.4%	0.00 [-0.58, 0.58]
Drouzas 2020 SJ-B	1.5	4.61	23	1.6	4.66	23	3.4%	-0.02 [-0.60, 0.56]
Gonzalo-Skok 2018 CMJ	1.4	3.7	9	0.9	4.75	9	1.8%	0.11 [-0.81, 1.04]
Greenwood 2021 CMJ	2.3	8.56	9	3.7	6.72	9	1.8%	-0.17 [-1.10, 0.75]
Kong 2018 5RBJ	1.9	5.4	25	1.55	3.99	21	3.4%	0.07 [-0.51, 0.65]
Kong 2018 CVJ	0.73	6.21	25	1.29	3.96	21	3.4%	-0.10 [-0.68, 0.48]
Kong 2018 SJ	1.34	6.3	25	0.53	3.98	21	3.4%	0.15 [-0.43, 0.73]
Kong 2018 SLJ	7.68	21.48	25	9.33	16.95	21	3.4%	-0.08 [-0.66, 0.50]
Li 2021 CMJ	2.56	4.47	10	4.35	6.33	10	1.9%	-0.31 [-1.20, 0.57]
Makaruk 2011 CMJ	4	3.61	16	5	3	18	2.8%	-0.30 [-0.97, 0.38]
Miao 2021 CMJ-B	1.53	3.85	8	2.23	3.27	8	1.7%	-0.19 [-1.17, 0.80]
Miao 2021 SLJ	3	9	8	3	9.54	8	1.7%	0.00 [-0.98, 0.98]
Xu 2023 CMJ	4.85	0.88	10	5.44	1.12	10	1.9%	-0.56 [-1.46, 0.34]
Xu 2023 SLJ	6	12.12	10	20	15.72	10	1.8%	-0.96 [-1.89, -0.02]
Subtotal (95% CI)			**315**			**301**	**47.3%**	**-0.07 [-0.23, 0.09]**
Heterogeneity: Tau² = 0.00; Chi² = 7.63, df = 16 (P = 0.96); I² = 0%								
Test for overall effect: Z = 0.88 (P = 0.38)								
Total (95% CI)			**650**			**630**	**100.0%**	**0.10 [-0.04, 0.25]**
Heterogeneity: Tau² = 0.07; Chi² = 59.86, df = 39 (P = 0.02); I² = 35%								
Test for overall effect: Z = 1.41 (P = 0.16)								
Test for subgroup differences: Chi² = 6.37, df = 1 (P = 0.01), I² = 84.3%								



squares = effect size, lines = confidence intervals, diamond = combined effect

Fig. 2 Forest plots of UNI and BI training on single-leg and double-legs jump performance

of takeoff, flight, and landing. Athletes must generate force at a lower takeoff angle (typically < 45°) [38, 39] while engaging core musculature (transversus abdominis, erector spinae) to stabilize the trunk and facilitate momentum transfer from the lower to upper extremities, thereby maximizing horizontal propulsion [40, 41]. A meta-analysis revealed that core training significantly enhances horizontal jump performance (ES = 0.84; $p = 0.01$) [42], with 90% of performance variance attributed to flight distance, which is determined

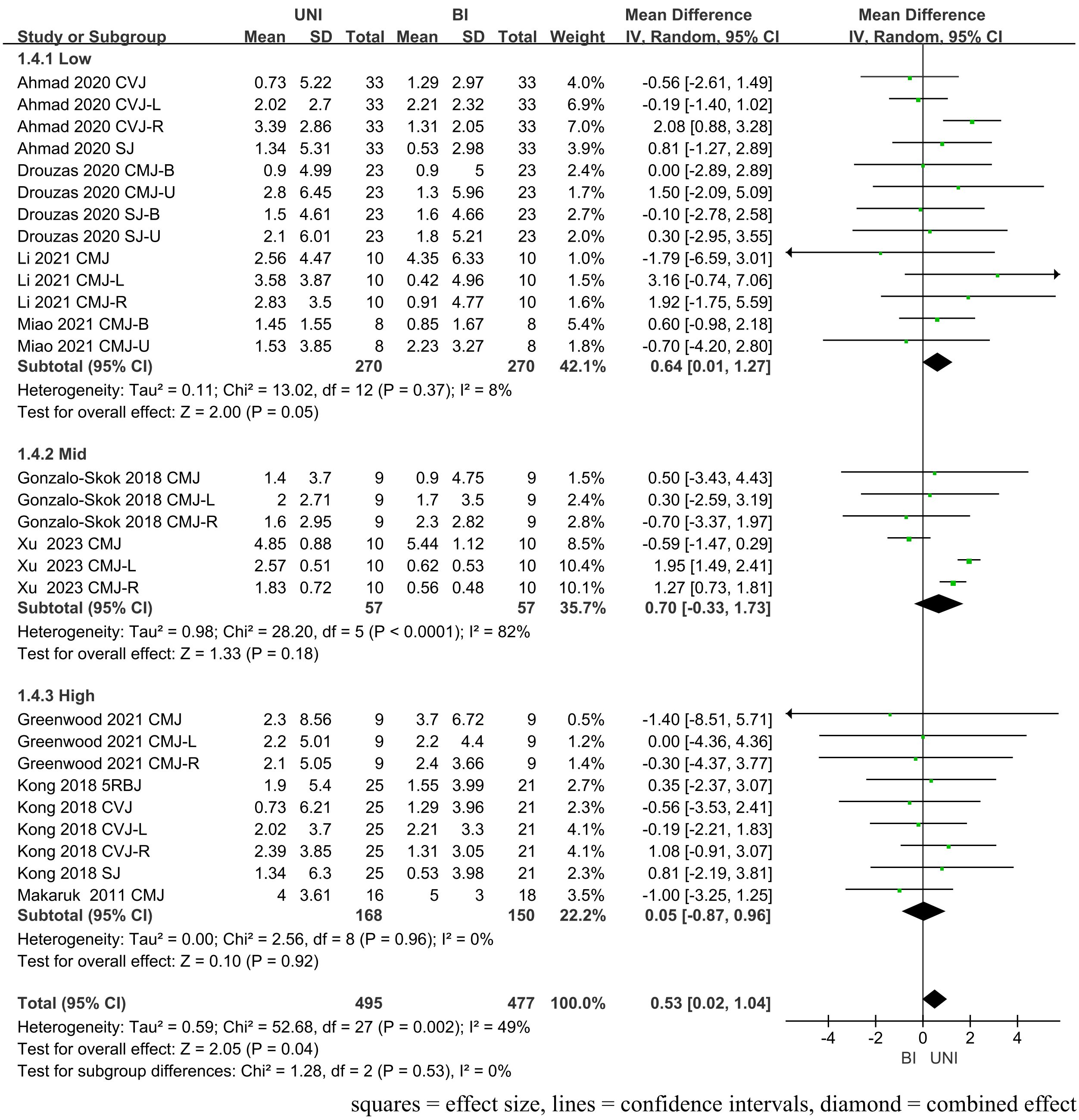


Fig. 3 Forest plots of UNI and BI training affecting vertical jump performance

by the center-of-mass velocity at takeoff [43]. Furthermore, Takahashi et al. demonstrated that long jump athletes exhibit significantly greater trunk muscle mass compared to untrained individuals [44], further underscoring the critical role of core conditioning.From a biomechanical perspective, the limited efficacy of UNI/BI training may be attributed to the following factors:

Deficient core force transmission: In horizontal jumps, inadequate core stability disrupts force transfer, redirecting hip extension forces into spinal flexion over horizontal propulsion [45].

Impaired inter-joint sequencing: UNI/BI training neglects the hip-dominant coordination pattern (hip:45% > knee:30% vertical force) critical for horizontal jump takeoffs [46].

Force-angle mismatch: BI-induced vertical force dominance elevates takeoff angles (> 50° vs. optimal < 45°), reducing jump distance by 8–12% per 5° excess [47].

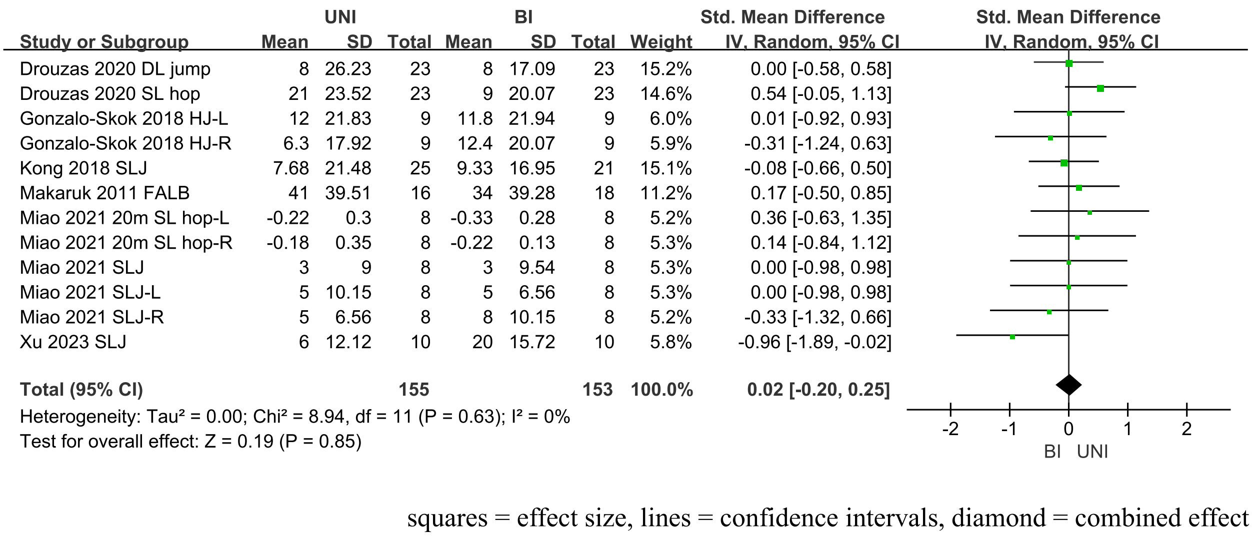


Fig. 4 Forest plots of UNI and BI training affecting Horizontal jump performance

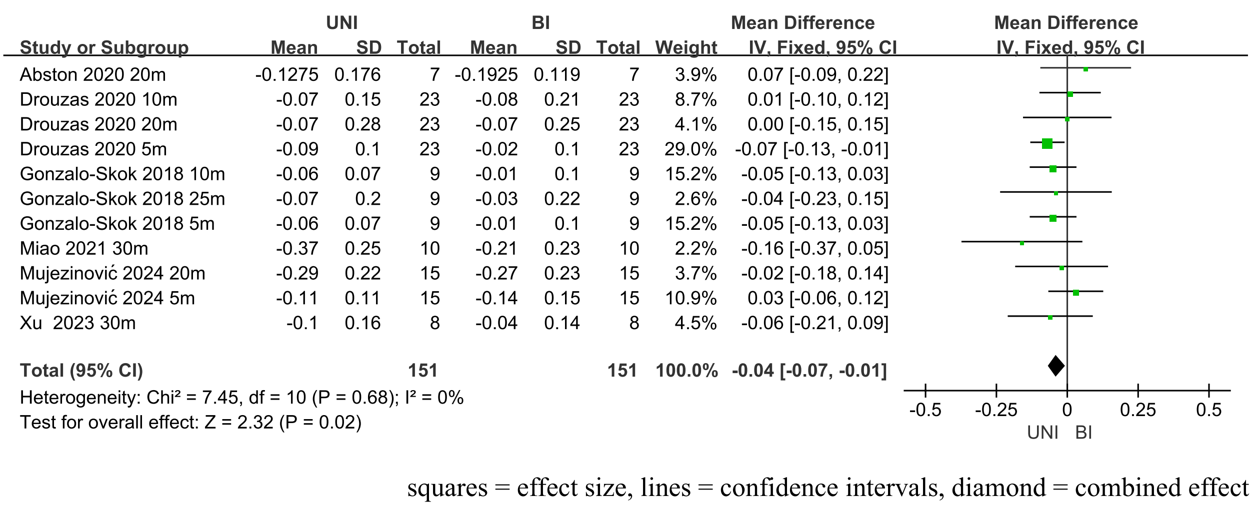
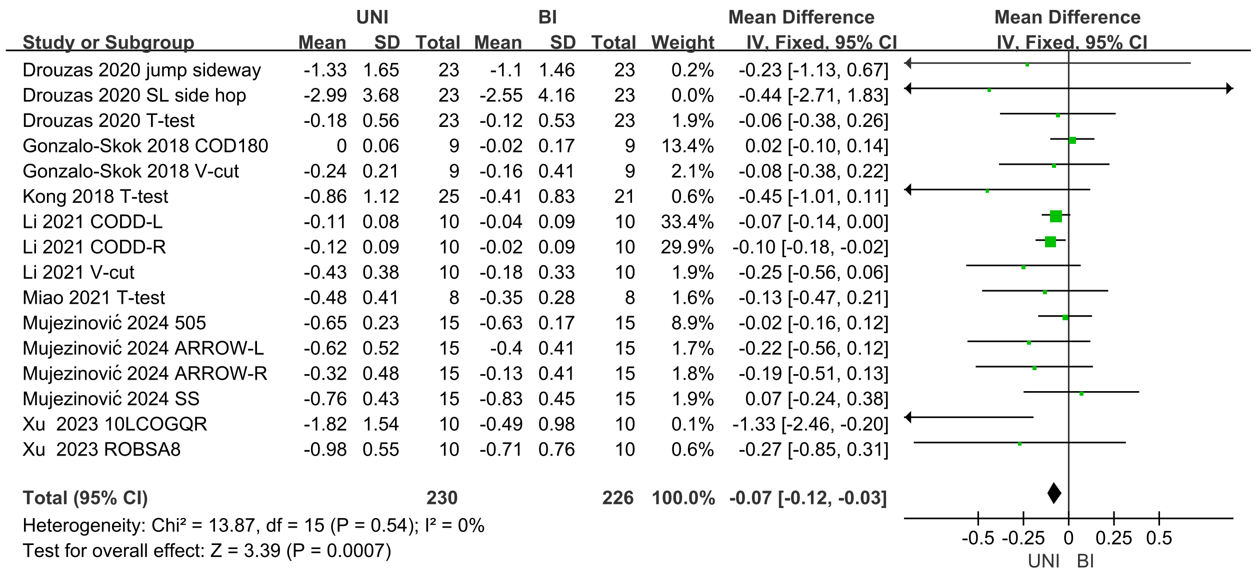


Fig. 5 Forest plots of UNI and BI training affecting sprint performance

The integration of core stabilization and multi-joint coordination drills addresses biomechanical deficiencies in UNI/BI training for horizontal jumps; however,the heterogeneity in core training protocols across studies complicates the identification of optimal programming variables, highlighting the need for standardized method Integrating core stabilization exercises (e.g., single-leg medicine ball throws) and multi-joint coordination drills (e.g., approach-run into bounding) into traditional UNI/BI regimens may enhance horizontal jump performance by addressing these biomechanical constraints.

Vertical jump performance

Unilateral plyometric training (UNI) significantly enhanced vertical jump performance. Following adjustments to the total ground contact frequency (TGCF) classification thresholds based on prior literature [28, 48], subgroup analyses revealed distinct dose–response patterns. Overall, UNI training demonstrated a statistically significant improvement in vertical jump performance compared to control interventions. The effects of different training volumes on vertical jump performance varied across the LGCF, MGCF, and HGCF groups. In the LGCF group, UNI training resulted in a



squares = effect size, lines = confidence intervals, diamond = combined effect

Fig. 6 Forest plots of UNI and BI training affecting change of direction performance

Table 4 Egger's test results

Std_Eff	Coef.	Std.Err	t	*P* > |t|	[95% Conf.Interval]	
slope	0.3000647	0.1631249	1.84	0.074	-0.0301644	0.6302938
bias	0.0474071	0.3252767	0.15	0.885	-0.6110811	0.7058953
slope	-0.0336603	0.4901653	-0.07	0.947	-1.142491	1.075171
bias	-0.5054792	1.270616	-0.4	0.7	-3.379813	2.368854
slope	0.5936817	0.4954432	1.2	0.251	-0.4689384	1.656302
bias	-2.158254	1.303516	-1.66	0.12	-4.954019	0.6375103

significant enhancement in vertical jump performance, consistent with the findings of Aztarain-Cardiel [48], who reported optimal countermovement jump (CMJ) gains in adolescent athletes under low-volume protocols (TGCF ≤ 900). The reduced heterogeneity across studies suggests that these consistent benefits may be attributed to minimized fatigue accumulation and adequate neuromuscular adaptation [49, 50]. In contrast, the MGCF group exhibited a numerically higher effect size, but the results were non-significant. This variability may stem from divergent training protocols, such as session duration and exercise selection, or participant characteristics, including training status and sport specificity. For example, Ramirez-Campillo et al. [51] noted performance decrements in CMJ height with excessive weekly jumps (≥ 240), highlighting the nonlinear relationship between training volume and adaptation. In the HGCF group, elevated training volumes led to fatigue-induced declines in explosive power. This is likely due to training volumes exceeding recovery capacity, resulting in neural fatigue [52, 53] and lactate accumulation [54–57], which impair force production and stretch–shortening cycle (SSC) efficiency. This finding aligns with Lunxin's meta-analysis [28], which cautioned against TGCF > 1400 due to diminishing returns and increased injury risks.

The high heterogeneity of CMJ-L/R likely stems from unilateral strength asymmetry in badminton players, as non-dominant limbs showed greater improvement (12.4% vs. 8.53%). Despite their exclusion, the robustness of the overall effect suggests that bilateral outcomes (e.g., BCMJ) are more reliable for evaluating lower limb explosive power in this population."

The dose–response superiority of low-volume UNI protocols (TGCF ≤ 900) must be interpreted cautiously due to potential confounding factors, such as variations in rest intervals and athletes' training backgrounds. The TGCF classification thresholds, while literature-derived, lack sport-specific validation—team-sport athletes may tolerate higher volumes due to inherent plyometric demands.For practitioners, these results advocate prioritizing LGCF protocols (TGCF ≤ 900) when designing UNI programs, particularly for athletes with limited plyometric experience. Coaches should monitor training load to avoid crossing thresholds that induce fatigue (e.g., TGCF > 1400), especially in sports requiring repeated explosive efforts.

Sprint and Change of Direction (COD) performance

The present study demonstrates that unilateral plyometric training (UNI) concurrently enhances sprint acceleration and change of direction (COD) performance. This synergistic effect may originate from shared biomechanical demands for unilateral horizontal power production between these two motor tasks. Meylan et al. [58] provided foundational evidence through correlational analysis: horizontal continuous jump (HCJ) performance showed moderate negative associations with 5-m sprint time ($r = -0.47$) and COD duration ($r = -0.52$) in physical education students, suggesting common neuromuscular underpinnings for unilateral propulsion capacity. The dual performance benefits of UNI appear mediated through three cross-task adaptation mechanisms:

Core biomechanical mechanisms

(1) Kinetic Chain Synchronization: Single-leg drop jumps (40-60 cm height) reduced inter-joint phase differences by 8.2 ms ($p = 0.02$) in hip-knee-ankle flexion sequences, approximating the coordination patterns observed during sprint acceleration (15-25% gait cycle) and COD deceleration phases [4, 30].

(2) Stiffness Modulation: A 17.3% improvement in ankle joint energy storage-release efficiency significantly decreased ground contact time (-11.4% in acceleration, -9.3% in COD braking), directly enhancing movement frequency [59–61].

(3) Multiplanar Control: Enhanced hip abductor activation (23% increase in sEMG amplitude) reduced trunk lateral tilt during COD by 3.8°, while concomitant hamstring strength gains (ES = 0.68) optimized horizontal ground reaction force (GRF) production in acceleration [62, 63].

Task-specific adaptations

The biomechanical enhancements in sprint acceleration were driven by two interdependent mechanisms:(1) Horizontal Propulsion achieved a 12.7% increase in GRF components parallel to the running direction, directly contributing to a 0.12 s reduction in 5-m sprint time ($p < 0.05$) [64]; (2) Joint Moment Optimization demonstrated knee flexion moments of 2.1 N·m/kg – approaching the sport-specific benchmark of 2.3 N·m/kg observed in elite sprinters [65]– which improved force transmission efficiency during ground contact [66].

These adaptations collectively narrowed the kinetic chain "leakage" (e.g., reduced vertical force dissipation by 8.4% [67]), effectively translating training-induced strength gains into functional acceleration gains equivalent to a 0.8 m lead advantage over 20 m in competitive scenarios [68].

The biomechanical adaptations during COD manifested through three sequential phases:

(1) Braking phase exhibited an 18.4% increase in knee joint eccentric power (6.2 W/kg) [63], enhancing energy absorption capacity to facilitate rapid deceleration through optimized quadriceps-hamstrings co-activation [69];(2) Transition phase demonstrated a 15.7% reduction in center-of-pressure displacement, indicating improved postural stability via enhanced proprioceptive feedback (ankle inversion-eversion error reduced by 21%) for faster directional switching [70];(3) Reacceleration phase achieved 19.3% faster GRF generation rates [71], optimizing propulsion efficiency through increased gluteus medius activation (sEMG↑34%) [72].

These phase-specific improvements interacted synergistically, collectively reducing total COD time by 0.15 s ($p < 0.01$) – equivalent to the performance gap between collegiate and elite athletes in cutting tasks [71].

Although UNI training synergistically enhances sprint acceleration and COD performance, biomechanical outcomes (e.g., GRF, joint stiffness) were measured in controlled environments, potentially underestimating performance variability under competitive fatigue. Additionally, the lack of sport-specific COD tests (e.g., soccer-specific cutting vs. the generic 505 test) limits task transferability.Coaches should implement phased unilateral plyometric training, emphasizing kinetic chain synchronization (single-leg drop jumps from 40–60 cm) and ankle stiffness (ground contact time < 180 ms) during foundational phases. Specialized acceleration training should integrate loaded sprints (10% body weight) to boost horizontal propulsion, while COD training must target braking (eccentric jumps), transition (perturbation drills), and reacceleration (reactive lateral jumps). Concurrently, integrate hamstring eccentric strengthening (e.g., Nordic curls) and biomechanical monitoring, progressively increasing training volume (40% → 60%) to synergistically enhance sprint acceleration and COD performance.

conclusion

The present study reveals that the effects of Unilateral (UNI) and Bilateral (BI) plyometric training on athletic performance are modality-specific. UNI significantly enhances single-leg jump performance, sprint speed, and Change of Direction (COD) ability, while BI is more advantageous for optimizing bilateral jump performance. In terms of training dosage regulation, the Low Ground Contact Frequency (LGCF) protocol (with fewer than 900 contacts per cycle) demonstrates a significant advantage in improving vertical jump performance. Additionally, no statistical differences were observed between UNI and BI in horizontal jump performance.

Based on these findings, it is recommended that training modalities be selected according to the specific demands of the sport. Furthermore, optimizing training volume can enhance neuromuscular adaptation benefits.

Abbreviations

UNI	Unilateral
BI	Bilateral
PT	Plyometric training
COD	Change of Direction
TGCF	Total Ground Contact Frequency
LGCF	Low Ground Contact Frequency
MGCF	Medium Ground Contact Frequency
HGCF	High Ground Contact Frequency

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Not applicable.

Authors' contributions
Jiyang Yue and Min Lu conceived the study and coordinated the research project. Zhanming Zhang and Wenhao Qu conducted the literature search. Wuwen Peng and Wenhao Qu performed data extraction and quality assessment of the included studies. Lingju Guan carried out the statistical analysis and interpreted the results. Zhanming Zhang drafted the initial version of the manuscript. Jian Sun created the figures and tables, and Duanying Li provided critical revisions for important intellectual content. All authors contributed to the final version of the manuscript and approved it for submission.

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Data availability
The datasets used and/or analysed during the current study is available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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