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Effect of resistance training on kinetic and kinematic indicators in jump athletes: a systematic review

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Abstract

Background High, long, and triple jumps are athletic jumping events. Although they differ in technique and rules, they share many similar biomechanical characteristics. Resistance training is a key method for enhancing jumping performance and has gained attention. Different resistance training methods have been shown to significantly improve jumping performance. However, current research on these events remains insufficient, particularly in systematically analysing kinetic and kinematic indicators, exploring their relationships, and summarising common characteristics, which are crucial. These gaps hinder a deeper understanding of how resistance training affects jumping performance.

Objective To explore the relationship between kinetic and kinematic indicators, examining how resistance training influences force conversion into momentum, optimises body movement coordination, and enhances take-off performance in jumping events.

Results The quality assessment results showed that four randomised controlled trials (RCTs) were evaluated using the ROB-2 tool. Among them, two studies raised concerns about bias related to the randomisation process, and one study also exhibited bias due to deviations from the intended interventions. Five non-randomised intervention studies were assessed using the ROBINS-I tool, with two studies judged to have a moderate risk of bias due to confounding factors. Overall, five studies were identified as having a moderate risk of bias or raising concerns in specific areas. Kinematic indicators (e.g., squat jump, countermovement jump, high jump height, standing long jump, and standing triple jump) showed significant improvements. Jump height significantly improved (SMD = 0.99; 95% CI = 0.56–1.41, $P < 0.0001$), and jump distance improved significantly (SMD = 1.67; 95% CI = 0.93–2.40, $P < 0.0001$).

Conclusion This review examines the significant effects of resistance training on kinetic and kinematic indicators of jumping performance, emphasizing its critical role in enhancing athletic performance. Resistance training significantly improves explosive power, take-off force, and maximal strength, particularly through exercises like squat jumps, which are closely linked to enhanced jump performance. Additionally, neuromuscular adaptations stabilize the output of antagonist muscles, further supporting performance enhancement. In terms of kinematic indicators, resistance training enhances jump height and distance, with methods such as plyometric and barbell jump training proving especially effective. These methods are beneficial for elite athletes and those with some training experience. However,

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the research highlights that gender and athletic level influence training outcomes, with females generally showing less improvement. The review also underscores the need for more high-quality randomized controlled trials (RCTs) to validate these findings further, as most current studies rely on non-randomized controlled trials (non-RCTs).

Systematic review registration https://www.crd.york.ac.uk/prospero, Identifier: CRD42025628838.

Keywords Resistance training, Kinetic indicators, Kinematic indicators, Jumping performance

Introduction

High, long and triple jumps are common athletic jumping events. Despite differences in competition rules and techniques, they share significant biomechanical characteristics and performance mechanisms, which rely on the ability to convert force into momentum quickly in various events. This characteristic results in similar responses to resistance training [1, 2]. From a training perspective, the high, long, and triple jump all involve rapid take-off movements and complex body coordination, requiring consistent resistance training interventions to enhance performance. These three events share the core goal of take-off, requiring athletes to coordinate body movements and efficiently generate force to convert ground reaction force into an ideal trajectory, optimising the distribution of the centre of mass in space [1–4], as reflected in kinetic and kinematic dimensions [4, 5]. Kinetics studies changes in mechanical properties during force application (e.g., ground reaction force Error! Reference source not found., joint torque [6]. At the same time, kinematics focuses on trajectory characteristics (e.g., the centre of mass height) [2]. These factors jointly determine an athlete's performance in jumping events. Categorising these three events for research enables a systematic summary of the effect of resistance training on jumping performance. It reveals commonalities in kinetics and kinematics, providing a broader theoretical foundation for related fields [7].

In recent years, resistance training in jumping events in track and field has received increasing attention, particularly for its significant value in improving athletes' kinetic and kinematic capabilities [8, 9]. To comprehensively evaluate the existing evidence, this study systematically reviews the intervention effects of resistance training on kinetic and kinematic indicators in athletes participating in events such as the long jump, triple jump, and high jump. The included studies include RCTs and non-RCT studies with clearly defined interventions. The forms of intervention encompass systematic resistance training programs, including free-weight training, plyometric training, and Olympic weightlifting.

High jump, long jump, and triple jump are three representative jumping events in track and field, each demonstrating significant differences in technical structure, movement patterns, and competition rules. These differences reflect diversified strategies in force production and movement coordination. Specifically, the high jump focuses on achieving vertical height, employing a single-leg take-off technique, emphasising take-off angle and aerial posture control. The approach run has a relatively moderate speed, emphasising rhythmic execution and spatial perception. In contrast, the long jump aims to maximise horizontal displacement, also utilising a single-leg take-off, but with a faster approach run. It requires athletes to efficiently convert horizontal kinetic energy into vertical impulse, with coordinated arm and swing-leg actions playing a critical role in take-off effectiveness.

The triple jump comprises three consecutive movement phases: the hop, step, and jump, each executed rapidly and requiring uninterrupted take-off and landing transitions. Complex, variable rhythmic patterns characterise this event and impose high demands on lower limb muscular endurance, movement continuity, and neuromuscular coordination [1, 10, 11]. Moreover, during repeated effects and successive take-offs, the triple jump places greater reliance on effect attenuation and the athlete's adaptability to ground reaction forces [11, 12].

Despite the technical heterogeneity among the three jumping events in terms of take-off technique, movement direction, approach rhythm, and upper limb movement patterns, they exhibit a high degree of consistency from training biomechanics and exercise physiology perspectives. Specifically, they share similar requirements for lower-limb explosive strength, rate of force development (RFD), and neuromuscular activation characteristics [13]. All three belong to skill-based sports predominantly driven by explosive power output. Their common motor core lies in the high-intensity, short-duration force exertion of major lower-limb muscle groups, particularly the extensor muscles around the ankle, knee, and hip joints, to efficiently convert ground reaction force (GRF) into centre of mass kinetic energy, thereby achieving optimal spatial displacement [7, 14, 15].

At the kinetic level, the take-off phase of these three jumping events typically demonstrates high peak ground reaction force, short ground contact time (GCT), and a high rate of power output [6, 14, 16]. In athletic training practice, these events commonly adopt similar training strategies, including heavy resistance training, plyometric training, and power-oriented resistance training. Empirical studies have widely validated these intervention methods as effective in enhancing athletes' neuromuscular activation and improving their athletic performance [15, 17].

In summary, although high jump, long jump, and triple jump differ significantly in technical execution and competition formats, they exhibit a high degree of commonality in training adaptation mechanisms, kinetic response characteristics, and neuromuscular force production patterns. Based on this premise, clear physiological foundations and biomechanical logic support the incorporation of these events into a unified analytical framework. This integrated perspective offers research value for exploring the coupling mechanisms among kinetics, kinematics, and athletic performance in jumping events. Moreover, it facilitates the extraction of universally applicable training intervention strategies, provides theoretical support for performance enhancement, and expands the scientific application pathways of resistance training in competitive jumping disciplines.

Although high, long, and triple jumps are often discussed in resistance training research, systematic analyses of their shared biomechanical characteristics remain insufficient. Studies on kinetics and kinematics are key determinants of jumping ability and for optimising technical movements [16]. Kinetic analysis reveals how athletes convert force into momentum, while kinematics provides the theoretical basis for optimising movements [15, 17, 18]. There is a close interaction between these two fields: kinetic output influences kinematic performance, and changes in kinematic characteristics adjust kinetic demands [7, 15]. Summarising the effects of resistance training from kinetic and kinematic perspectives can provide comprehensive guidance for theoretical research and practical application.

Resistance training has become a widely recognised intervention for enhancing jumping performance, with numerous studies demonstrating its effectiveness in improving athletes'jumping abilities [15, 19]. However, several gaps remain in the current research. First, there is a lack of systematic analysis of kinetic and kinematic indicators. Second, the relationship between these indicators has not been fully explored. Lastly, the shared characteristics of high, long, and triple jump have yet to be analysed and unified. As a result, the mechanisms and interactions between kinetic and kinematic factors in resistance training for jumping events remain poorly understood. This review aims to fill these gaps by synthesising the effect of resistance training on kinetic and kinematic performance and exploring how these changes contribute to improved jumping ability. Ultimately, the goal is to provide actionable insights for optimising resistance training in jumping events and to guide future research in this area.

Methods

The research team of this study followed the guidelines outlined in the updated Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement. This protocol was registered (registration number: CRD42025628838) at the International Prospective Register of Systematic Reviews (PROSPERO).

Literature search strategy

("Explosive Resistance training" OR "strength" OR "resistance training" OR "strengthening programs" OR "progressive resistance training" OR "resistance exercise" OR "weight lifting" OR "weight exercise" OR "strength exercise" OR "weight training" OR "intensive resistance training" OR "leg press" OR "jumping") AND ("Sport* performance*"OR"Athletic performance*"OR"Physical performance*"OR"Exercise performance*"OR"Fitness performance"OR "jump performance*" OR "long jump performance*" OR "performance*" OR "Explosive" OR "strength performance" OR "Strength" OR "power" OR "force" OR "velocity" OR "muscle performance*" OR "height" OR "distance") AND ("Long jumper*" OR "jumper*" OR "jump Competitors" OR "High jumper") From PubMed (Title/Abstract), SCOPUS (Title/Abstract/Keywords), Web of science (Abstract), EBSCOhost (Abstract) on 22/12/2024. Detailed search strategies for each database are provided in Appendix 1.

Inclusion and exclusion criteria

Inclusion criteria

(1) Randomized controlled trials (RCTs) or non-randomized intervention studies with clearly defined control conditions, including longitudinal studies (i.e., studies involving repeated measurements and data collection over an extended period on the same group of participants) and quasi-experimental research (e.g., comparing athletes' performance across different competitive seasons to evaluate causal relationships); In addition to randomized controlled trials (RCTs), high-quality non-randomized controlled trials (non-RCTs), including pre-post studies and quasi-experimental designs, were also eligible for inclusion. The decision to include non-RCTs was based on two considerations: Methodological quality assessment, ensuring that studies featured clearly described interventions, systematic training protocols, and pre- and post-intervention measurements with efforts to minimize bias; Feasibility considerations specific to the study population. Given the scarcity of elite track and field

jumpers and the ethical and practical challenges of random assignment (e.g., fixed training schedules and limited sample availability), high-quality non-RCTs provided a crucial complementary source of evidence. (2) The intervention must consist of a structured and systematic resistance training program; (3) Participants must be athletes involved in track and field jumping events; (4) The study must report at least one kinetic variable (e.g., joint torque) or one kinematic variable (e.g., velocity); (5) The language of publication must be Chinese or English.

Exclusion criteria

Studies involving participants under the age of 18; (2) Studies investigating only the acute responses to a single training session or lacking a clearly defined intervention period; (3) Studies involving injured athletes, or interventions that include pharmacological agents or nutritional supplements; (4) Literature types such as unpublished manuscripts, theses or dissertations, conference abstracts, review articles, and other forms of grey literature that are not peer-reviewed; and (5) Studies that do not report any kinematic or kinetic outcomes and instead focus solely on other types of indicators (e.g., physiological or biochemical variables).

The illustration of inclusion and exclusion criteria

Participants characteristics

Participants were required to be athletes aged 18 years or older, engaged in track and field jumping events (long jump, triple jump, high jump), and possess a certain level of competitive experience (e.g., collegiate athletes, provincial/state-level athletes or above). If a study included participants under 18 but reported an average age of $\geq$ 18 years and found no significant effect of age on study outcomes, it was considered eligible. Conversely, studies were excluded if the inclusion of minors was not justified or if the majority of participants were under 18.

Intervention characteristics

This study defines resistance training as any training protocol involving external resistance to enhance muscular strength and power. Including but not limited to: (1) Resistance training with free weights or machines; (2) Plyometric training (e.g., loaded or unloaded jump exercises); (3) Olympic weightlifting movements; (4) Combined or periodised resistance training protocols; Studies involving pharmacological, nutritional, psychological, or other multimodal interventions were excluded.

Control conditions

While RCTs are considered the gold standard for evidence, practical and ethical constraints in elite sports settings often limit the availability of RCTs with high-level athletes. This review also included non-RCT designs such as longitudinal studies and quasi-experimental research to ensure comprehensiveness and practical relevance, provided they employed clearly defined interventions and reported kinetic or kinematic indicators.

Study design

Only experimental studies with defined intervention and comparison conditions were included. Observational studies, methodological papers, audio-visual instructional articles, and non-intervention designs were excluded.

Outcome measures

To be included, studies had to report at least one performance-related kinematic or kinetic variable as an outcome, such as: (1) Kinetic indicators: joint torque, ground reaction force, power, maximal strength, peak force; (2) Kinematic indicators: take-off velocity, peak velocity, displacement; (3) Studies that did not include such outcomes or reported only physiological or biochemical variables were excluded.

Study selection

The studies retrieved from six international databases and additional sources were imported into the literature management software Zotero (version 6.0.37), and duplicates were removed using the software's built-in function. The screening process adhered to pre-established inclusion and exclusion criteria. In the title screening stage, two independent reviewers (YZ and WCR) reviewed article titles to exclude studies irrelevant to the research topic. The inter-rater agreement was Cohen's kappa = 0.78, indicating substantial agreement. Another pair of independent reviewers (LC and XRZ) screened the abstracts in the abstract screening stage. The contract between them was Cohen's kappa = 0.82, indicating substantial to excellent agreement.

In the comprehensive content screening stage, YZ and WCR independently re-evaluated the full texts. Articles not meeting the eligibility criteria were excluded, and reasons for exclusion were documented. The inter-rater agreement reached Cohen's kappa = 0.87, indicating excellent agreement. Different reviewer pairs were assigned at each screening stage to balance the workload, minimise reviewer fatigue and enhance the independence and objectivity of the review process. By alternating reviewer combinations across title, abstract, and full-text screening, potential bias introduced by individual evaluators was reduced, thereby increasing the overall reliability and transparency of the study selection procedure [20, 21].

At any stage, if there was disagreement regarding the inclusion of a study, a third independent reviewer (KGS)

Table 1 Cohen's kappa values and interpretation of inter-rater reliability during study selection

Screening Stage	Cohen's Kappa	Interpretation	Reviewer Pair
Title screening	0.78	Substantial agreement	YZ & WCR
Abstract screening	0.82	Substantial to almost perfect	LC & XRZ
Full-text screeniing	0.87	Almost perfect agreement	YZ &amp WCR

was consulted to re-evaluate the article and make the final decision. The level of inter-rater agreement was assessed using Cohen's kappa coefficient in Table 1 Cohen's Kappa Values and Interpretation of Inter-Rater Reliability During Study Selection [22]. The kappa values were interpreted according to the following scale: values below 0 indicate poor agreement, values between 0.01 and 0.20 reflect slight agreement, values between 0.21 and 0.40 suggest fair agreement, values between 0.41 and 0.60 denote moderate agreement, values between 0.61 and 0.80 represent substantial agreement, and values between 0.81 and 1.00 indicate almost perfect agreement [22].

Title and abstract screening

A total of 1,297 articles were initially identified. After removing 231 duplicates and grey literature ($n=22$), 1,044 records remained. During the title screening phase, 255 articles were excluded due to irrelevant interventions (non-resistance training), and 176 articles were excluded for not reporting kinetic or kinematic outcome measures. This left 613 articles for abstract screening. Based on abstracts, 93 studies involving injured or clinical populations, 89 studies unrelated to jumping events, 57 animal studies, 69 studies involving resistance training combined with pharmacological or nutritional interventions, and 79 studies with complex multi-component interventions (where resistance training effects could not be isolated) were excluded, leaving 226 articles.

Full text screening

Full-text reviews led to the exclusion of 31 methodological studies focused on measurement tools, 102 studies that only analyzed correlations between variables without intervention, and 36 articles related to audiovisual teaching content. Exclude 32 non-English and Chinese studies. 16 studies examined only the acute responses to a single training session. Finally, nine studies met all inclusion criteria and were included. See Fig. 1.

Data extraction and quality assessment

The risk of bias for each selected RCT was carefully assessed using the revised Cochrane risk of bias tool for randomised trials (RoB-2) [23]. This tool provides a comprehensive framework for evaluating potential biases in various aspects of trial design and execution. The assessment was conducted using the Risk of Bias in Non-randomised Studies of Interventions (ROBINS-I) tool [24] for non-RCTs. ROBINS-I is specifically designed to evaluate the risk of bias in studies that do not employ randomisation, addressing factors such as confounding, selection bias, and measurement bias. Both tools ensure a comprehensive evaluation of the studies, enhancing the reliability of the overall analysis.

Statistical methods for effect size estimation

Review Manager 5.3 was used to analyse the outcome measures of the included studies. Given that the outcome measures were continuous variables, we chose the standardised mean difference (SMD) as the effect size metric for statistical analysis. We used the SMD statistic to evaluate effect size, where $\text{SMD}<0.2$: trivial; $0.2\leq\text{SMD}<0.6$: small; $0.6\leq\text{SMD}<1.2$: moderate; $1.2\leq\text{SMD}<2.0$: large; $2.0\leq\text{SMD}<4.0$: very large; $\text{SMD}\geq4.0$: extremely large [25]. We employed the I^2 statistic to test for heterogeneity, with $I^2<40\%$ indicating low heterogeneity, $40\%\leq I^2\leq70\%$ indicating moderate heterogeneity, and $I^2>70\%$ indicating high heterogeneity. We applied fixed-effect models for analyses with no or low heterogeneity and random-effect models for analyses with moderate to high heterogeneity [26]. Four of the included studies provided complete effect size computation data (i.e., means, standard deviations, and sample sizes) for both experimental and control groups [1, 6, 27, 28].

The effect sizes for four studies were directly calculated using the reported means and standard deviations [1, 6, 27, 28]. For the five studies without control groups but with pre- and post-test data [3, 29–32], within-group effect sizes (Cohen's d) were calculated using the mean difference between post- and pre-intervention scores divided by the pre-test standard deviation. Effect sizes were further adjusted using a standardized method for repeated measures designs to address the dependency between measurements, incorporating the correlation between pre- and post-test scores [33]. A conservative estimate of $r=0.5$ was assumed when a correlation coefficient was not reported, as commonly practiced in previous meta-analyses. The formulas for the within-group effect size and its adjustment are presented as follows:

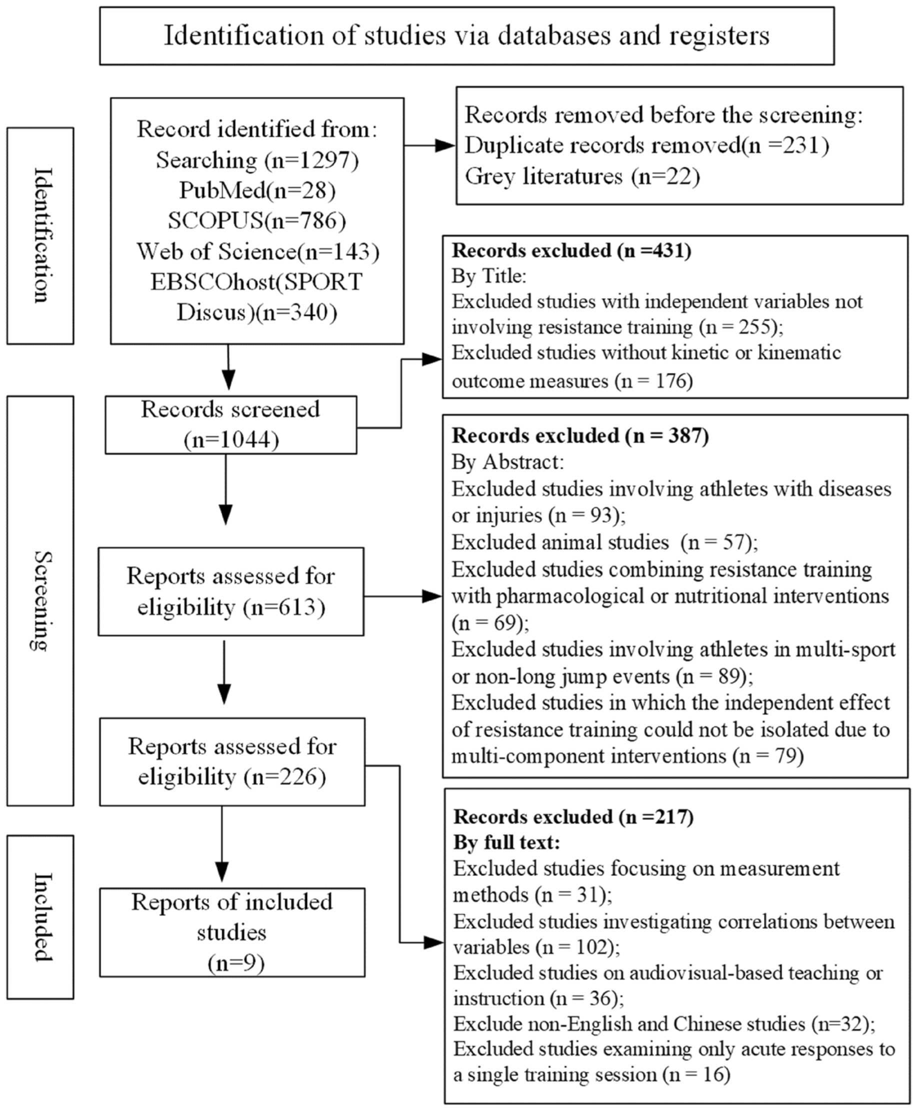

Fig. 1 Flow diagram of the study selection

$$d = \frac{M_{\text{post}} - M_{\text{pre}}}{SD_{\text{pre}}}$$

$$d_{\text{corr}} = \frac{d}{\sqrt{1 - r^2}}$$

where "d_{corr}" represents the corrected effect size, "d" is the unadjusted effect size, and r denotes the correlation coefficient between pre- and post-test scores.

In this systematic review, we evaluated the effect of intensity training on athletic performance by calculating the effect sizes of each included study. The effect size was calculated using Cohen's d, a standardised indicator for measuring the differences between the two groups. The specific calculation formula is as follows:

$$d = \frac{\text{M1} - \text{M2}}{\text{SDpooled}}$$

$$SD_{\text{pooled}} = \sqrt{\frac{(n_1 - 1) \cdot SD_1^2 + (n_2 - 1) \cdot SD_2^2}{n_1 + n_2 - 2}}$$

Among them, M1-M2 is the mean of the experimental group and the control group, respectively, SD pooled is the combined standard deviation of the two groups, and the calculation formula is:

$$d = \frac{M_{\text{diff}}}{SD_{\text{diff}}}$$

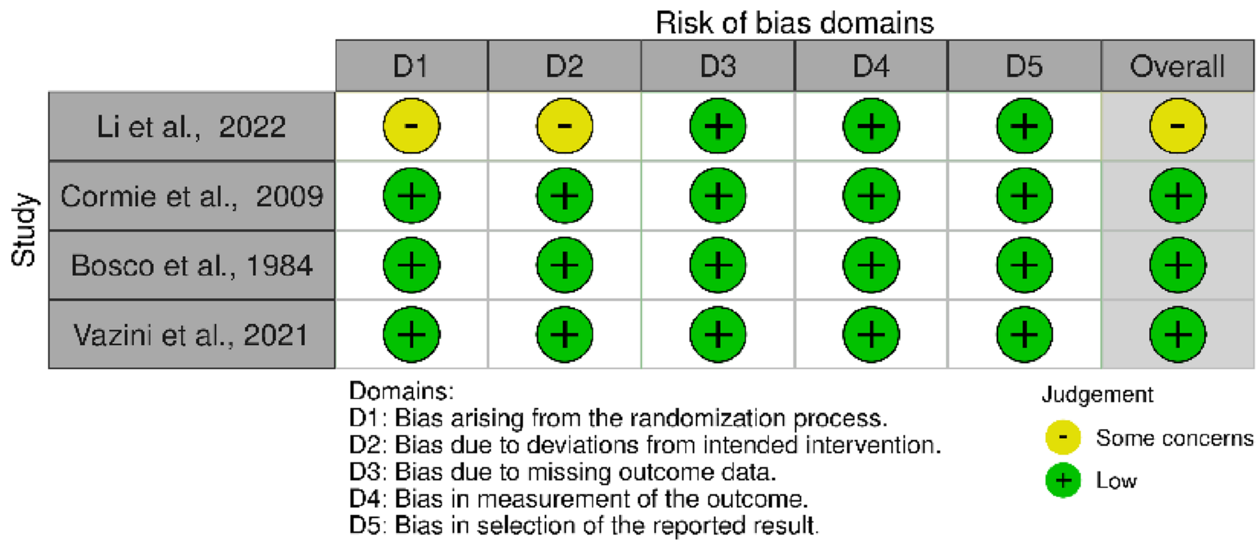

Fig. 2 ROB-2 assessment results

Among them, n1 and n2 are the sample sizes of the experimental and control groups, respectively, and SD1 and SD2 are the standard deviations of the two groups. Cohen's d calculation formula:

Results

Study quality assessment

The ROB-2 tool was applied to assess four RCTS [1, 6, 26, 27], while the ROBINS-I tool was used for five non-RCTs [3, 29–32]. Among these studies, five were rated as having a moderate overall risk of bias or some concerns, as illustrated in Figs. 2 and 3. Figure 2 ROB-2 Assessment Results shows the ROB-2 assessment results. Two studies were rated as having some concerns due to issues related to bias arising from the randomization process, and one of these studies also showed some concerns in the domain of bias due to deviations from intended interventions. Figure 3 ROBINS-I Assessment Results shows the ROBINS-I assessment results. Three non-RCTs were judged to have a moderate risk of bias

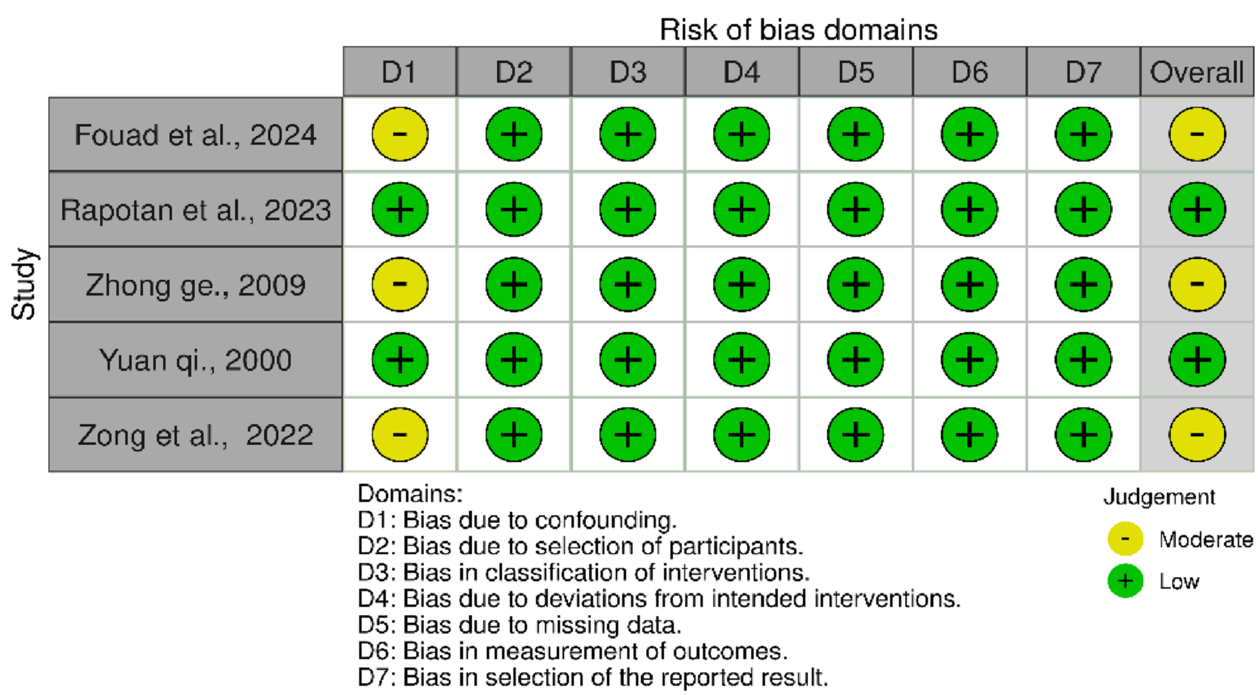

Fig. 3 ROBINS-I assessment results

due to concerns in the domain of bias due to confounding [29, 31, 32].

The results are summarised as percentage changes for the following variables: Kinetic indicators in this study include pushing force, peak torque and peak power. Kinematic indicators include approach speed, cruising angle, long jump, flight time (bilateral CMJ action), flight height, standing long jump, standing triple jump, maximal voluntary contraction, squat jump (bilateral), and peak concentric and eccentric force.

Participant characteristics

The characteristics of the participants in the ten studies included in this review are summarised as follows. A total of 61 male and nine female participants were involved. Two studies included mixed-gender samples [3, 32]. Among them, one study reported the gender distribution in detail (five males and two females), which was included in the overall gender count [3]. Additionally, one study did not specify the participants' gender, and thus, its 20 participants were not included in the gender statistics [28]. Regarding event types, 81 participants were from long jump, 11 from high jump, seven from triple jump, and seven from studies involving mixed jump events. See Table 2 for detailed Characteristics of the studies examined in the present review.

Among the included studies, seven studies reported the participants'ages [1, 3, 6, 27–30], with the minimum age being 18.6 years [3], the maximum age being 23.9 years [1], and the average age being 20.98 years. Two studies did not report age (31, 30). One study reported a squat 1RM to body mass ratio of 1.9 ± 0.2 [27], and one study reported resistance training experience as 6.6 ± 2 years. Two studies did not report the participants'level or related information [29, 32]. Five studies reported the athletes'competitive level [1, 3, 28, 30, 31]. The lowest level was second-tier athletes [3], four studies of the highest level were professional athletes participating in national or international top-level athletics events [1, 28, 30, 31].

Study design

Except for one study [3], which lasted 48 weeks, the remaining studies lasted 4–12 weeks [1, 6, 27, 28, 31]. One study did not mention the duration [6], as it involved adding isokinetic resistance training to the athletes'base training weeks [6]. Four studies included a control group [1, 6, 27, 28]. Five studies included only an experimental group [3, 29–32].

Training programs

Among the included studies, resistance training methods aimed at enhancing jump-specific performance could be classified into four main categories: (1) pure weight training, (2) barbell resistance training combined with jump training, (3) bodyweight jump training (i.e., plyometric training), and (4) jump training combined with sprint training.

Pure weight training

Pure weight training typically consists of traditional weightlifting or machine-based exercises, with the primary goal of improving maximal strength of the lower limbs. Jumping movements are excluded from this training modality. Some studies employed isokinetic training devices to perform ten repetitions of knee extension and flexion at angular velocities of 60°/s and 120°/s, with each set consisting of either 5 or 10 repetitions, respectively [6]. Other studies increased training load by using weighted vests adjusted to 10–13% of the subject's body weight. Participants wore the vests during daily physical activities and resistance exercises, training three times a week for 10 weeks [32]. This type of training emphasizes the foundational development of muscular strength.

Barbell weight training combined with jump training

One study employed a hypergravity training method, in which participants wore a weighted vest equivalent to 13% of their body weight throughout the day, in conjunction with 150–180 min of jump training. This approach aimed to simulate a constant external load condition and simultaneously stimulate physical loading and sport-specific jump performance. The weighted vest was worn 6–7 times per week over a training period of 3–4 weeks [1].

Bodyweight jump training (Plyometric Training)

In this study, plyometric training is defined as a specific form of jump-based training that utilizes the stretch–shortening cycle (SSC) mechanism, enhancing neuromuscular function through rapid eccentric-concentric contractions. Jump training is generally used as an umbrella term for various jumping movements. This study proposes that, when jump training incorporates SSC characteristics and explosive demands, basic jump training (particularly bodyweight-based jump training) can be considered a form of plyometric training. Therefore, in this review, such jump training is classified under plyometric training, aiming to provide a more systematic framework for summarizing intervention strategies and facilitating outcome comparisons. Some studies use various jumping exercises, including basic movements e.g., two-leg hurdle jumps, squat jumps, and step jumps) and advanced variations (e.g., single-leg jumps and bounding). The training duration in one study lasted 48 weeks [3]. Another study implemented nine sets of six

Table 2 Characteristics of the studies examined in the present review

Author	Participant characteristics			Intervention characteristics				Outcome measures (Experimental group)
	n	Characteristic	Type	EG	CG	ID (weeks)	Frequency	
Fouad et al., 2024 [29]	Male *n* = 8	Age: 20 ± 1.3; Height 190 ± 3.5 cm; Weight: 85 ± 5.2 kg	Long jumpers	Sprint + Jump	N/A	10	3/week	Explosive Power↑*; Approach speed↑*; Cruising Angle↑*; Long jump, pushing force↑*;
Zong 2022 [32]	Mixed gender *n* = 20	Age, height: Not reported Have a certain training period	Long jumpers	Weighted squats	N/A	12	3/week	Standing long jump ↑*; Standing triple jump↑*; Long jump↑*;
Li 2022 [6]	Male *n* = 10	Age: 19.3 ± 3; Height: 187.9 ± 5.5 cm; Weight: 76.9 ± 7.3 kg; Training years 6.6 ± 2;	Hight jumpers	Isokinetic resistance training	Basic resistance training	Integrated into daily training, no separate cycle		Peak torque of ankle flexor↑*; Peak torque of knee flexor →;
Rapotan et al., 2023 [30]	Female *n* = 7	Age:22.4 ± 6.5; Weight: 59.1 ± 3.6 kg; Height: 171.9 ± 3.2 cm; Quasi-professional level	Triple jumpers	Single, double jumps, weighted half-squat jumps	N/A	5	5/week	Squat jump↑*; Countermovement jump↑*; Flight Time↑;
Vazini et al., 2021 [28]	Gender unknown *n* = 20	Age: 22.5 ± 4.2; Height: 178.4 ± 9.8 cm; Weight: 70.3 ± 7.6 kg; Professional	Long jump	Plyometric training (horizontal jumps) + (vertical jumps) 60%–80% best effort	Standard training	8	N/A	Vertical jump height↑* Horizontal velocity at take-off↑* Standing long jump↑*
Zhong., 2009 [31]	Male *n* = 1	The world's best level high jumper	Hight jumper	Resistance training + bouncing exercises + speed exercises	N/A	3–4	6/week	High jump height
Cormie 2009 [27]	Male *n* = 26	Age:20.2 ± 2.9; Height: 175.8 4.5 cm; Weight: 85.5 ± 24.0 kg; squat1RM to body mass1.9 ± 0.2	Long jumpers	Peak power output with squat jumps for trained	Peak power output squat jumps for Untrained	12	2–3/week	Peak Power ↑*; RFD↑ Peak Force ↑*; Peak Velocity ↑* CMJ Displacement ↑*
Yuan qi 2000 [3]	*n* = 7 female = 2 male = 5	Age:18.6 ± 3.8; At the second-level and first-level elite athlete level	Long jumpers	Depth jump/hurdle jump/single-leg hop/step jump	N/A	48	N/A	Speed↑*; Running and jumping to touch hight↑*; Five jumps↑*; Timed single foot jump↑*
Bosco et al., 1984 [1]	Male *n* = 11	Age: 23.9 ± 3.05 Height: 183.15 ± 6.9 cm; Weight:77.6 ± 10.55 kg; International jumpers	Jumping items are mixed	Daily barbell training and jumping drills with a weighted vest	Barbell weight training and jumping training	4	6–7/week	Center of Mass Height↑*

EG Experimental Group, *CG* Control Group, *ID* Intervention Duration, "*"Represents a significant change;"↑"represents before and after the experiment, and"→"represents the results have not changed maximal-effort jumps with 3-min rest intervals between sets, focusing on maximizing peak power output under light-load conditions. This protocol was performed 2–3 times per week for 12 weeks [27].

Other studies further classified jump exercises into sport-specific forms such as approach jumps, five-step approach jumps, and single-leg jumps. These studies emphasized the coordination of horizontal and vertical force application during the jumping process. Accordingly, horizontal and vertical jumps were integrated into the training sessions at 60% to 80% of each athlete's maximum capability. Each session involved 6 to 12 repetitions, with active rest of 3 min between sets and 40–90 s between repetitions) over an 8-week period [28].

One study employed jump training as the core intervention, introducing additional external load via handheld weighted discs (2–5 kg), and training was conducted 6 times per week for 3–4 weeks. Each session included 5 sets of 10 repetitions, with 1–2 min of rest between sets [30]. Another study incorporated jump training within a single training unit, along with exercises such as high pulls, power cleans, weighted squats, and lunges; however, the exact load and number of sets were not reported [31].

Jump training combined with sprint training

Some studies combined plyometric training with sprint training, utilizing 30-m and 50-m sprints performed at 90–100% of maximal sprinting effort, alongside jump-based exercises such as hurdle sprints and standing jumps. This represents a model that combines discrete and continuous high-intensity resistance training. The purpose of this approach is to enhance athletes' mechanical output and neuromuscular control through explosive sprinting and jumping stimuli. The training frequency was three sessions per week, with each session lasting 50–60 min, over a total duration of 10 weeks [29].

The results of kinetic indicators

Kinetic indicators emphasise intrinsic aspects of the movement process, including force, power, and velocity. Existing literature has extensively examined the effects of resistance training on kinetic and mechanical performance metrics in jump athletes. Scholars indicate that the following indicators are crucial for improving performance in jumping events:Error! Reference source not found. peak force [27], peak power, and rate of force development, although the improvement in RFD was not statistically significant [27]. Research has also investigated maximal torque at specific joints, particularly the ankle and knee flexors [6]. No significant changes were observed in the maximal torque of the antagonist muscles involved in jumping, particularly the knee flexors [6]. Thrust performance and peak power have also been identified as key indicators, demonstrating significant improvements [27]. The indicators above collectively represent essential kinetic parameters that contribute to improved jump performance, reflecting the neuromuscular and mechanical adaptations elicited by resistance training. However, the maximal torque of antagonist muscles, or relatively non-primary movers, does not show significant improvement [34, 35]. This outcome may be explained by the fact that resistance training primarily enhances thrust and power output through improvements in neuromuscular transmission, optimisation of muscular coordination and increased neural activation of the primary movers. In contrast, antagonist muscles may maintain a relatively stable output level due to adaptations in neuromuscular regulatory mechanisms [36–38].

One study included in this review reported that a combination of sprint and jump training enhanced the explosive power of long jump athletes after 10 weeks. This study adopted a within-subject pre–post experimental design. The results demonstrated marked improvements in both upper and lower limb explosive power following the intervention, with upper limb performance showing a moderate increase and lower limb performance exhibiting a more substantial enhancement. Statistically significant differences were observed within the group before and after the training period [29].

In this review, the combination of sprint and jump training was found to enhance pushing force, with a significant within-group improvement observed in post-intervention, particularly during the take-off phase in long jump athletes after 10 weeks [29]. One study included in this review demonstrated that peak force in long jump athletes was significantly enhanced (12.6%) through squat jump training with peak power output training after 12 weeks. Additionally, peak power was also significantly increased (21.6%) [27]. The correlation coefficients between peak force and both average and peak power in squat-related jump tests ranged from 0.78 to 0.84, indicating a strong positive correlation. One study reported that peak power increases significantly at 120°/s, particularly in the knee flexors and extensors, which play a crucial role in enhancing high jump performance [6]. One study reported an improvement in RFD following peak power output training in long jump athletes, although this change did not reach statistical significance.

The results of kinematic indicators

Kinematic indicators emphasise parameters such as position, velocity, and acceleration during the movement process, which primarily describe the performance and Kinetics of the movement, rather than directly involving the generation of force or power [39, 40]. Kinematic indicators infer an athlete's movement abilities by analysing their temporal and spatial trajectories, as well as the kinematic characteristics of the movement, particularly in explosive actions like jumping and running. These indicators typically do not rely on direct external force measurements but reflect an athlete's explosive power, movement technique, and performance through characteristics such as movement trajectory, velocity changes, and height. They provide direct insight into an athlete's skill performance and movement efficiency [41–43]. The kinematic indicators discussed in this review for the long jump include approach speed, cruising angle, long jump, standing long jump, standing triple jump, vertical jump height, horizontal velocity at take-off, CMJ displacement, speed, running and jumping to touch height, five jumps, and timed single-foot jump [3, 27–29, 32]. Kinematic indicators for the high jump include high jump height [31], while those for the triple jump include squat jump, countermovement jump, and flight time [30]. In mixed studies, kinematic indicators include the centre of mass height [1].

Five studies evaluated jump height using parameters such as the squat jump [30], countermovement jumps [30], running jump to touch height [3], centre of mass height [1], vertical jump height [28], and high jump [31]. The studies reported significant improvements in these parameters after resistance training, ranging from 7 to 13% (SMD = 0.99; 95% CI = 0.56–1.41, $P < 0.0001$), ($I^2 = 0\%$, $P = 0.46$). The effect size (SMD = 0.99) is considered small.

This study included five studies on the effects of resistance training on jump height, consisting of two RCTs [1, 28] and three non-RCT studies [3, 30, 31]. According to the RoB-2 and ROBINS-I tools, all four studies were assessed as having a low risk [1, 3, 28, 30]. The overall findings of these studies reported statistically significant positive effects, with 95% confidence intervals not crossing zero (SMD of 1.67 [0.40, 2.95] [1], 1.52 [0.55, 2.49] [3] and 1.12 [0.04, 2.20]) [3], indicating that resistance training, including plyometric training [3, 28, 30] and barbell-loaded jumps [1] can significantly enhance jump height. In contrast, the non-RCT study [30] and the RCT study [28], while high-quality studies, show that the confidence intervals for the effect size cross zero (SMD = 0.39; 95% CI = −0.67–1.45) [30], (SMD = 0.42; 95% CI = −0.65–1.48) [30], and (SMD = 0.92; 95% CI = −0.01–1.85) [28], with only one study, which including female participants, whose 95% confidence interval lower bound was the lowest compared to other studies [30].

After a 10-week intervention combining sprint and jump training, a revised Cohen's d of approximately 1.76 was observed [29]. Additionally, seven eligible studies were included to examine the effects of resistance training on jump height. The methodological quality of these studies ranged from moderate to low risk, and the study designs included non-RCTs and RCTs. Among them, studies reporting larger effect sizes were all classified as moderate-risk non-RCTs, including (SMD = 4.91; 95% CI = 1.88, 7.94) [32], (SMD = 2.31; 95% CI = 0.52–4.11] [32], (SMD = 2.19; 95% CI = 0.88–3.50) [29], and (SMD = 1.90; 95% CI = 0.26–3.53) [32]. Most of these studies involved male or mixed-gender participants. All reported statistically significant effects. However, this also indicates that the primary conclusions rely considerably on non-RCTs with moderate methodological quality and relatively weaker study designs.

Four studies assessed jump distance using parameters such as the standing long jump, standing triple jump, long jump, broad jump, and five jumps [3, 28, 29, 32]. These studies found significant improvements in jump distance after resistance training, with enhancements ranging from 4 to 15% (SMD = 1.67; 95% CI = 0.93–2.40, $P < 0.0001$), ($I^2 = 38\%$, $P = 0.13$). The effect size (SMD = 1.67) is considered moderate, indicating that resistance training has a significant promoting effect on improving horizontal jump distance, with low heterogeneity. One low-risk RCT study reported a statistically significant effect (SMD = 1.57; 95% CI = 0.54–2.60). However, the effect size was notably smaller than that observed in most moderate-quality non-RCT studies [28].

Discussion

Discussion on resistance training for kinetic indicators

Explosive power refers to generating maximal force in the shortest possible time [44]. Previous research has shown that lower limb explosive power is significantly correlated with jump height or distance [45], This research finding is also validated in the present review, where resistance training significantly enhanced both explosive power and long jump distance [29]. Furthermore, some studies have indicated that short-distance sprint training combined with multiple jumps can effectively stimulate the neuromuscular system, improving muscle explosive capacity and increasing athletes'muscle force output levels [16]. This finding suggests that incorporating sprinting and jumping elements into training can activate different lower limb muscle groups from multiple angles, thereby enhancing overall explosive performance.

In addition, pushing force is actively exerted by muscles against an external object (e.g., the ground or equipment) through voluntary contraction. Its primary function is to enable acceleration, displacement, or stabilisation of the body or external objects. The applied pushing force's magnitude, direction, and timing influence athletic performance and training effectiveness [7, 15, 46]. Previous research has investigated the influence of kinetic parameters on vertical jump performance, revealing that combining short sprint training with jump training can enhance lower limb muscle force output during rapid movements, thereby providing greater propulsion during the take-off phase. The study further indicated that complex training contributes to the improvement of the elastic storage and release capacity of the muscle–tendon complex, a mechanism that plays a significant role in facilitating force transmission during take-off [16].

Experimental evidence indicates that during the rapid stretch–shortening cycle, muscle spindles and Golgi tendon organs provide critical proprioceptive feedback, regulating motor neuron excitability and the timing of muscle activation, thereby optimizing the storage and release of elastic energy in tendons [47, 48]. Ultrasonographic observations have shown that the Achilles tendon stores elastic energy during the eccentric phase of jumping and rapidly releases this energy during the concentric phase to enhance explosive force output [49]. Furthermore, electrophysiological studies demonstrate that increased stretch reflex sensitivity and pre-activation of the agonist muscles help improve the efficiency of tendon elasticity utilization, preparing the muscle–tendon unit for rapid force transmission. This neuromuscular coordination mechanism not only reduces electromechanical delay but also maximizes explosive force production, highlighting the crucial role of tendons as biological springs in dynamic movements [47].

Peak force refers to the maximum force output produced by an athlete during a specific movement [50]. It measures the most significant muscular force that can be generated instantaneously, typically assessed at a critical moment of the movement, such as the initial phase of a jump or the lowest point of a squat [19]. Increasing peak force markedly enhances athletes'jumping ability. The peak force is a key to jumping performance [51]. The findings of this study are consistent with previous research, which has reported a significant correlation between peak power output and peak force in jump-based resistance training.

The correlation coefficients between peak force and both average and peak power in squat-related jump tests ranged from 0.78 to 0.84, which suggests that, during the squat jump, as the instantaneous maximum force (peak force) generated by the muscles increases, the power output (peak power output) also increases accordingly[52]. A scholar reported that combining strength and plyometric training enhances explosive strength and jumping performance, especially in short and vertical sprints [16]. Scholar found that peak force improvements are strongly linked to coordination. Scholars have observed that peak force correlates with ground reaction forces during jumping, ultimately enhancing performance in experimental settings [53]. This review concludes that resistance training increases peak force, enabling greater thrust at take-off and improving jump height or distance. Multiple lines of experimental evidence have revealed the specific neuromuscular mechanisms by which neural coordination influences peak force. In athletic movements, neuromuscular coordination is reflected in the effective synchronous activation of motor units, the sequencing of activation, and the modulation of firing frequency, all of which jointly determine the magnitude of peak force output [54–56]. Electromyographic studies have indicated that rapid neural transmission and pre-activation of muscles reduce electromechanical delay and increase contraction velocity, thereby contributing to the production of higher peak force [57, 58].

Moreover, training enhances coordination between agonist and antagonist muscles, minimizes unnecessary antagonistic interference, and improves net force output. These neuromuscular adaptations enable athletes to utilize muscular strength more efficiently, improving explosive power and overall athletic performance. Empirical studies further support that targeted neuromuscular coordination training can significantly enhance peak force and related performance indicators. Thus, neuromuscular coordination is a key mechanism underlying improvements in peak force and plays a critical role in understanding how resistance training contributes to enhanced athletic performance [59–61].

Peak torque refers to the maximum torque (moment of force) that a muscle or joint can generate during a specific movement or motion [62]. Multiple studies have demonstrated that increased peak torque is closely associated with enhanced explosive power and neuromuscular coordination during jumping tasks. Study reported that peak torque measured at 120°/s was significantly correlated ($r = 0.82$, $p < 0.01$) with vertical jump height, indicating that faster muscle contraction speeds promote neural adaptations that enhance strength output [6]. Compared to 60°/s, 120°/s velocity induces faster muscle contraction, which improves explosive power by enabling more effective utilization of stored elastic energy during jumps [63]. This mechanism relies on better control of movement trajectories during complex athletic tasks [64].

Isokinetic resistance training enhances muscle strength and coordination by increasing peak torque, thereby improving high jump performance. For instance, a randomized controlled trial showed a significant increase in peak torque and vertical jump height ($p < 0.05$) [65]. Neural adaptations also play a crucial role; studies using electromyography (EMG) have documented increased muscle activation levels following isokinetic training protocols, alongside morphological changes such as muscle hypertrophy and fiber-type transitions [66]. Additionally, later-stage neural adaptations, including improved motor unit recruitment and synchronization, have been observed, which are critical for optimizing explosive power and coordination in complex movements like high jumping [67, 68]. Collectively, these findings provide robust evidence that isokinetic resistance training-induced increases in peak torque are underpinned by both mechanical and neural adaptations, which together enhance athletic explosive performance.

The rate of force development refers to the speed at which force is produced within a unit of time, reflecting the rate of change in the muscle's ability to generate force from the onset of exertion to the attainment of peak force. It is typically expressed in newtons per second (N/s). It represents the neuromuscular system's ability to produce force rapidly over a short period, serving as an essential indicator for assessing explosive strength characteristics [41]. The study suggested that although the athletes altered their jumping technique by increasing the amplitude of the eccentric phase, this adjustment did not result in a significant enhancement of RFD during the concentric phase [27]. Previous research has discussed the negative correlation between the eccentric utilisation ratio and RFD during countermovement jumps. This suggests that although athletes may attempt to enhance power output through technical adjustments, such as increasing the amplitude of the eccentric phase, these modifications do not necessarily result in significant improvements in concentric RFD. This conclusion is consistent with the study mentioned above, which reported a trend towards increased RFD following peak power training in long jump athletes, yet without achieving statistical significance, suggesting that the technical changes during the eccentric phase were not effectively transferred to force production during the concentric phase [69].

This review examines the effect of power and speed-related indicators on jumping performance. Peak power and peak velocity are key indicators of athletic performance in sports physiology and training. Researchers have indicated that peak power is the maximum value of the product of force and velocity at a specific moment during the entire movement, which directly enhances athletes'performance in explosive movements [7, 14]. Increasing peak power enables athletes to generate greater explosive force quickly, which is crucial for jumping events [19]. A combined training approach that integrates strength, explosive power, and speed training is the optimal strategy for increasing peak power. Research shows that combined training improves an athlete's strength, speed, and explosive power simultaneously, maximising peak power [15, 45]. Combined training can effectively utilize the post-activation potentiation (PAP) effect to enhance muscle strength and contraction speed, thereby increasing power output. The underlying mechanism is that after high-intensity resistance training, the neuromuscular system enters a highly excited state, improving motor unit recruitment efficiency, particularly enhancing the activation capacity of fast-twitch muscle fibers.

Meanwhile, the sensitivity of muscle fibers to calcium ions increases, facilitating a stronger muscular contraction response. In addition, the heightened excitability of the central nervous system contributes to faster muscle contraction and improved movement coordination. Through this series of physiological regulatory processes, combined training significantly enhances both force and velocity output in explosive movements, thereby effectively improving overall power performance [27, 45, 70, 71].

Additionally, research indicates a significant positive correlation between peak power and jump performance [72]. During a jump, athletes must generate sufficient force quickly to overcome gravity and complete the leap effectively. Increasing peak power is key to achieving this [63]. Therefore, improving an athlete's maximal strength and contraction speed through resistance training increases power output, significantly enhancing jump explosiveness and effectiveness. Other speed-related indicators, such as approach speed and timed single-foot jumps, also improve with resistance training interventions. Increasing speed helps athletes generate more momentum during the approach phase, resulting in a more decisive thrust at takeoff. This has been verified, particularly in the long and triple jump [15, 19, 32].

Discussion on resistance training for kinematic indicators

Five studies evaluated jump height and reported significant improvements following resistance training, indicating that resistance training has a pronounced effect on enhancing jump performance [1, 3, 27, 29, 30]. The heterogeneity among these studies was low. The absence of heterogeneity ($I^2 = 0\%$) further strengthens the reliability and consistency of this finding across the included studies. These consistent results across diverse contexts not only support the generalizability of the findings but also underscore the foundational role of resistance training in sports performance enhancement programs designed to improve vertical power. This study included five studies on the effects of resistance training on jump height, consisting of two RCTs [1, 28] and three non-RCT studies [3, 30, 31]. According to the RoB-2 and ROBINS-I tools, all four studies were assessed as having a low risk [1, 3, 28, 30]. The overall findings of these studies reported statistically significant positive effects, with 95% confidence intervals not crossing zero (SMD of 1.67 [0.40, 2.95] [1], 1.52 [0.55, 2.49] [3] and 1.12 [0.04, 2.20] [3], indicating that resistance training, including plyometric training

[3, 28, 30] and barbell-loaded jumps [1] can significantly enhance jump height. Thus, the primary conclusion of this study on jump height largely relies on the evidence provided by high-quality studies, which strengthens the conclusion's robustness and reliability. Previous research has found that plyometric training has significantly improved strength, power, and jump performance [65].

Furthermore, the study pointed out that plyometric jump training protocols can effectively improve vertical jump height [73], further confirming the effectiveness of plyometric training in improving jump performance. As a form of resistance training, barbell-loaded jumps apply additional load during the jump, increasing the external resistance that athletes must overcome during actual work. Research showed that when load centralisation is effectively performed during weighted jumps, peak jump power can be improved within a specific load range, increasing vertical jump height [74].

Moreover, the dual stimulation of muscle fibres and the nervous system from weighted jump training can promote simultaneous improvements in the agility and strength of muscles to counter external weight during long-term training [74]. In contrast, although both the non-RCT study [30] and the RCT study [28] are of high quality, their effect size confidence intervals cross zero. Notably, only one study [30], which included female participants, had the lowest lower bound of the 95% confidence interval compared to all other studies. This may be related to the participants'gender, as research has indicated that the improvement in jump performance after resistance training is lower in females than in males [75]. Overall, RCTs provide high-confidence causal inferences, while non-RCTs reflect the broad applicability and diversity of real-world intervention effects. All studies were rated as low risk, which enhances the credibility of the findings, with a consistent and significant positive effect forming a stable foundation for the conclusion.

Furthermore, this study identified that among resistance training modalities aimed at improving jump height, barbell jump training exhibited a larger effect size than traditional plyometric training. Specifically, the maximum effect size for plyometric training was 1.52, whereas that for barbell jump training reached 1.67 [1]. Both interventions were associated with substantial improvements in jump performance.

From a mechanistic perspective, plyometric training primarily enhances explosive strength and neuromuscular coordination by stimulating the stretch–shortening cycle (SSC). During the rapid transition from eccentric (lengthening) to concentric (shortening) contraction, the elastic energy stored in muscles and tendons can be released. The effective utilization of the SSC improves the efficiency and speed of muscle contraction. In addition, SSC-based training can increase the excitability of α-motor neurons and enhance the responsiveness of motor units, thereby optimizing the synchronization and coordination of muscle contractions [76, 77].

Barbell jump training, on the other hand, combines SSC activation with external loading, thereby increasing muscle tension and the recruitment level of motor units. Studies have shown that external resistance can significantly enhance the activation rate of high-threshold motor units, particularly fast-twitch fibers, and improve the nervous system's control over muscular force output. Compared with traditional plyometric training, barbell jumps provide a more potent stimulus to neural drive, effectively improving the overall output efficiency of the neuromuscular system [78, 79]. Therefore, barbell jump training can elicit a stronger neural drive, that is, faster and more intense signaling from the central nervous system to the muscles, and more effectively convert strength into speed, producing more significant improvements in explosive, high-velocity, lower-limb coordination tasks, such as jumping movements [80].

It is essential to note that one study included in this review involved an international-level high jumper [31]. Due to its limited generalizability, it was classified as a case study. Furthermore, as the mean and standard deviation could not be computed from a single competition, this study was excluded from the effect size synthesis. In this case, the training approach primarily included strength and hopping exercises, supplemented by hurdle drills, resulting in an average jump height of 2.23 m and average placements within the top two across eight international competitions.

Four studies assessed jump distance using parameters such as the standing long jump, standing triple jump, long jump, broad jump, and five-bound jump. The effect size (SMD = 1.67) was considered moderate, indicating that resistance training had a significant promoting effect on improving horizontal jump distance, with low heterogeneity observed. The absence of heterogeneity ($I^2 = 38\%$) further strengthens the reliability and consistency of this finding across the included studies [3, 28, 29, 32]. The studies included in this analysis encompassed diverse athletic backgrounds and varying resistance training interventions. Despite such variability, a consistently positive effect was observed. An I^2 value of 38% indicates low heterogeneity among the included studies, remaining within an acceptable range and thus reflecting the robustness of the pooled results. This relatively low heterogeneity further enhances the credibility of the findings, suggesting that resistance training consistently yields beneficial outcomes across different participant populations and intervention designs. Moreover, jump distance is a key indicator of lower-limb explosive strength and technical coordination. The observed improvements in this parameter suggest that resistance training effectively enhances athletes' horizontal propulsion capabilities and overall performance, particularly in disciplines such as long jump, triple jump, and composite physical fitness assessments. Taken together, these results reinforce the fundamental role of resistance training in enhancing athletic performance and provide solid evidence to inform the development of evidence-based training programmes.

Furthermore, this study identified that among three resistance training modalities aimed at improving jump distance, plyometric training was less effective than both barbell jump training and sprint-integrated jump training. Specifically, the maximum effect size for plyometric training was 1.83, slightly lower than that for sprint-integrated jump training (1.87), and markedly lower than the maximum effect size observed for loaded deep squat training (4.91) [1]. All three modalities made meaningful contributions to performance enhancement.

From a mechanistic perspective, plyometric training enhances neuromuscular reactivity and explosive strength by activating the stretch–shortening cycle. The SSC mechanism improves the efficiency of the transition from eccentric to concentric muscle contraction, thereby enhancing muscle reactivity and the utilization of elastic potential energy, which in turn improves jumping performance. However, due to the lack of significant external load stimulation, plyometric training has relatively limited effects on the improvement of maximal strength and lower-limb rate of force development. Therefore, although plyometric training effectively improves movement speed and reactive explosiveness, its contribution to the development of foundational strength and the efficiency of strength transfer is relatively weak [60, 81–83].

Combining sprint-jump training on this basis can further enhance running speed during the approach phase and optimize the transfer of strength at take-off, particularly by improving the recruitment efficiency of lower-limb type II muscle fibres and strengthening the nervous system's adaptability to high-speed contractions. Studies have shown that sprint-jump training helps strengthen the synergistic force production of the lower-limb neuromuscular system, improve motor unit synchronization and reaction speed, and effectively enhance horizontal propulsion capability, which plays a significant role in improving performance in horizontal jumping events [84, 85].

In contrast, loaded squat training, through sustained high-intensity external load stimulation, significantly enhances the muscular strength and neural drive capacity of lower-limb extensors (such as the quadriceps, gluteus maximus, and hamstrings). This training method can activate high-threshold motor units, improve the recruitment capacity of the neuromuscular system, and increase the frequency of action potentials, thereby contributing to the enhancement of lower-limb maximal strength and explosive strength. Moreover, long-term squat training can induce adaptive structural changes in muscles (e.g., hypertrophy), providing a solid foundation for force output during jumping movements and demonstrating its excellent training effects in improving jump distance [86–88].

In summary, although plyometric training and sprint-jump training each have unique value in improving movement speed, reactivity, and technical execution, loaded squat training, as a high-load resistance training method, shows more significant effects in enhancing athletes'foundational strength, neuromuscular control, and force output capacity. These findings underscore the pivotal role of foundational strength development in enhancing horizontal jumping performance, suggesting that it should form a key foundation in designing training programs for jumping events.

Additionally, three studies investigated speed-related parameters: approach speed, timed single-foot jump, and peak velocity [3, 28, 29]. All results showed significant improvements after resistance training. One study reported a substantial increase in cruising angle [29]. The cruising angle: It is the angle confined between the intersection of the straight line connecting the center of gravity of the body at the moment of leaving the board with the horizontal line parallel to the ground and towards the front. It is measured in degrees [29]. Previous studies have shown that this angle is a critical determinant of performance, as it reflects the balance between vertical lift and horizontal velocity during take-off [89, 90]. An optimal cruising angle enables efficient conversion of approach speed into flight distance, maximizing horizontal displacement while minimizing excessive vertical motion [90]. Seven eligible studies were included to examine the effects of resistance training on jump height, which involved male or mixed-gender participants. All reported statistically significant effects. However, this also indicates that the primary conclusions rely considerably on non-RCTs with moderate methodological quality and relatively weaker study designs [29, 32].

The effect size of one low-risk RCT study [28] was notably smaller than that observed in most moderate-quality non-RCT studies. It is worth noting that the participants in this study were elite athletes with experience competing internationally. Previous studies have suggested that elite athletes, due to their performance levels approaching the ceiling of training potential, have limited room for improvement and, thus, may exhibit smaller training responses than amateur or semi-professional participants. This finding indirectly highlights the important moderating role of athletic level in the effectiveness of training interventions [91]. In addition, two non-significant results were obtained in one study [3], which employed the five-bound jump as the testing method. This test differs from the standing long jump, long jump, and triple jump tests used in other studies. The five-bound jump demands greater coordination and rhythmic movement, which may limit its sensitivity in detecting improvements in pure strength or explosive power [92, 93]. Therefore, the lack of statistical significance in these results may not entirely reflect the ineffectiveness of training interventions, but rather the misalignment between the testing method and the targeted training outcomes. Previous studies have indicated that the five-bound jump test is a skill that highly depends on overall coordination and rhythm control. Its performance is influenced by direct factors such as muscular strength, explosive power, and indirect variables including stride consistency, movement coordination, and technical execution [94, 95].

In contrast to assessments like the standing long jump or vertical jump, which focus on measuring pure muscular strength or explosive capacity, the five-bound jump consists of a more extended movement sequence and requires multiple consecutive take-offs. Therefore, its performance is more strongly associated with the athlete's ability to control complex motor patterns [96]. This implies that although training interventions may significantly enhance instantaneous muscular force output and explosive performance, the five-bound jump test may not fully capture such improvements. The test's emphasis on technical execution and rhythm increases the threshold for detecting improvements limited to strength or power capacities [94, 96].

In summary, although numerous studies support the positive effect of resistance training on jump performance, the current body of evidence remains derived mainly from studies with moderate methodological quality and relatively limited experimental rigour. Furthermore, the effectiveness of interventions may be affected by multiple variables, such as participant sex distribution, training experience, and the specific performance assessment tools utilised. Therefore, future research should aim to improve methodological quality, reduce sample heterogeneity, and refine measurement protocols. Special attention should also be given to the training responses of high-performance athletes, whose adaptations may differ due to limited room for improvement. These improvements would strengthen the robustness and external validity of research conclusions.

Differences in the adaptability of different resistance training methods

According to this review, pure resistance training, weight training combined with jump trainingbodyweight jump training, and jump training combined with sprint training have become the primary training methods for improving jumping events in track and field sports. In jump-specific training, different approaches have distinct characteristics and varying effects on strength, explosive power, and performance optimisation. However, each method has certain limitations, making it essential to consider their advantages and drawbacks when designing a comprehensive training program. Pure resistance training has significantly improved lower limb maximal strength and relative strength, effectively increasing muscle cross-sectional area and laying the foundation for explosive power development, as well as enhancing movement efficiency [7, 97, 98]. However, pure resistance training alone has limited direct benefits for speed-strength conversion and lacks sport specificity, making it more suitable for beginners who require fundamental strength development [28, 69].

Resistance training combined with other training methods can optimise the conversion effect. For example, combining resistance training with jump training can simultaneously enhance maximum strength and explosive power, thereby improving jump height and distance. It also optimises neuromuscular adaptations, increasing motor unit recruitment efficiency and making this training approach more specific to jumping events [99, 100]. Bodyweight jump training can directly improve take-off speed and movement efficiency, enhance jumping ability, and optimise speed, coordination, and rhythm control, making it suitable for beginners or athletes aiming to refine their jumping technique [29, 101]. However, this method lacks an external load stimulus, has limited effects on maximal strength development, and provides only minor improvements for athletes with a strong foundation in strength [100, 102]. Jump training combined with sprint training can improve speed-strength conversion, optimise approach run quality, and enhance the fast-twitch fibres recruitment of the lower limbs, making it particularly beneficial for long jump and triple jump athletes [103, 104]. However, this training method requires a solid technical foundation; if an athlete's technique is underdeveloped, it may lead to compensatory movements or an increased risk of injury [105]. Table 3 Comparison of Training Methods: Utility, Benefits, Limitations, and Recommendations presents a comparison of various training methods, highlighting their utility, benefits, limitations, and the recommended athlete profiles for each approach.

Table 3 Comparison of Training Methods: Utility, Benefits, Limitations, and Recommendations

Training Method	Utility	Benefits	Limitations	Recommended For
Pure Resistance Training	Develop fundamental strength	Increases maximal and relative strength; enhances muscle cross-sectional area	Limited speed-strength conversion; low sport specificity	Beginners; off-season base building
Resistance + Jump Training	Strength-power integration	Enhances both maximal strength and explosive power; improves neuromuscular efficiency	Requires careful load management	Intermediate to advanced athletes; preseason preparation
Bodyweight Jump Training	Technique refinement and coordination	Improves take-off speed, movement efficiency, coordination, and rhythm control	Limited maximal strength development; less effective for advanced athletes	Beginners; technique-focused phases
Jump + Sprint Training	Speed-strength conversion for event specificity	Optimizes approach run; enhances fast-twitch fiber recruitment	Requires strong technical foundation; risk of compensatory movement or injury	Elite athletes; in-season fine-tuning

Conclusions

This review consolidates the significant effects of resistance training on kinetic and kinematic indicators of jump performance, highlighting its critical role in enhancing athlete performance.

In terms of kinetic indicators, resistance training significantly improves athletes'explosive power, take-off force, and maximal strength. Studies have shown that combining sprinting and jumping training can increase lower limb muscle strength, promote explosive power, and thus improve jump height and distance. Notably, resistance training is crucial for increasing maximal strength, particularly in exercises like squat jumps, where improvements in maximal strength are closely associated with enhanced jump performance. Furthermore, due to adaptations in neuromuscular regulation mechanisms, the output of antagonist muscles remains relatively stable, further supporting the improvement in athletic performance.

In terms of kinematic indicators, resistance training significantly enhances jump height and distance. Research indicates that training methods such as plyometric training and barbell jump training are particularly effective in improving vertical jump height. Plyometric training boosts explosive power, while barbell jump training increases muscle strength, promotes higher power output, and improves kinematic performance. These findings provide strong evidence supporting the effectiveness of these training methods, especially for elite athletes and those with some training experience.

However, the research also indicates that gender and athletic level are essential factors influencing training outcomes, with females generally showing less improvement in jump performance compared to males. The review further notes that most existing studies are based on non-randomized controlled trials (non-RCTs). Although these non-RCT studies involved highly trained athletes, future research should incorporate more high-quality randomised controlled trials (RCTs) to validate the current conclusions further.

Research limitations

Although this study identified over 1,200 relevant articles, only 9 met the predetermined inclusion criteria and were included in the analysis. This relatively small number of included studies reflects the stringent selection criteria applied during the literature screening process. The requirements were designed to ensure that the included studies were experimental research with clear intervention plans, with systematic resistance training as the intervention, aimed at enhancing the neuromuscular power of athletes in track and field jumping events, and requiring the reporting of at least one kinematic or kinetic indicator. While this process improved the internal validity of the studies and reduced methodological heterogeneity, it also somewhat limited the generalizability of the findings, specifically excluding studies involving minors, those with additional pharmacological or nutritional interventions, studies lacking a clear intervention period, or those that did not report relevant performance indicators resulted in a final sample composed mainly of adult competitive-level athletes, with training content primarily focusing on standardized resistance training. Therefore, caution is advised when generalizing the findings to other populations (such as adolescent athletes), different training strategies, or broader training practices. Future reviews should consider expanding the range of populations and intervention types to enhance the external validity and practical applicability of the conclusions. The number of studies included in this review was relatively small ($n=9$), which somewhat limits the robustness and generalizability of the findings.

Although the strict selection criteria ensured the quality of the included studies, the limitation in sample size meant that we were unable to conduct a more extensive analysis or draw more representative conclusions. Therefore, the small sample size may have influenced the results, causing them to be affected by random factors, which in turn affect their applicability to a broader population.

The heterogeneity in training protocols and outcome measures across the included studies had a significant impact on the synthesis of the research findings. Specifically, there were differences in the design of the training interventions, primarily in terms of the training methods used. These factors directly influenced the assessment of intervention effects, leading to substantial variability among the study results. Regarding the outcome measures, the studies included in this review used different measurement conditions, categorized as either competition conditions or experimental conditions. The differences in these conditions introduced additional heterogeneity into the results, which may affect our comprehensive understanding of the intervention effects. Results measured under different conditions may differ due to contextual factors, further increasing the variability between studies. Therefore, future research should consider conducting more intervention studies under actual competition conditions to enhance the external validity of the findings and should also explore ways to narrow the gap between laboratory-based results and performance in real-world competition settings.

Another notable limitation is the small number of female participants in the included studies, which limits the ability to assess gender-specific responses to strength training interventions accurately. Given the known physiological and biomechanical differences between men and women, this underrepresentation may affect the generalizability of the findings. However, this also points to a clear direction for future research. As more high-quality studies incorporate adequate samples of both genders, the evidence will become more comprehensive and representative.

In this review, the quality of the included studies was assessed using the ROB-2 and ROBINS-I tools. The results showed that one RCT study and three non-RCT studies were of moderate quality. For the RCT studies, the primary limitation of the moderate-quality studies was the imperfect randomization process and the potential deviation from the intended intervention, which could lead to bias in the results and affect the accuracy of the conclusions. For the non-RCT studies, the primary limitation was bias due to confounding factors. As non-RCT studies lack randomization, their results are more susceptible to interference from other potential variables, which can influence the internal validity of the research.

Additionally, this study only included Chinese and English literature, which helps improve the controllability of literature quality and research reproducibility [106]. However, this may still lead to language bias [107]. Previous study has highlighted that excluding non-English literature may overestimate the intervention effect or overlook research evidence from specific regions, thereby affecting the representativeness and external applicability of the results [108]. Therefore, future systematic reviews, resources permitting, are encouraged to expand the language scope, particularly by including research from other representative languages, to enhance the robustness and universality of the conclusions.

Despite the limitations of this review, it still makes a significant academic contribution to the current body of research in the field. Firstly, although the number of studies included is relatively small, this is due to our strict adherence to clearly defined criteria during the literature selection process, which ensured that the included studies had high-quality experimental designs and intervention plans. While this stringent selection limited the number of studies included, it ensured the scientific integrity and internal validity of the analysis, making the conclusions of this review more credible. Additionally, despite the heterogeneity in training protocols, sample sizes, and measurement environments, these differences underscore the complexity of research in this field and provide clear directions for future studies. For example, the heterogeneity between different training protocols and outcome measures highlights the need for more unified standards and consistent evaluation methods in future research, thereby improving the consistency and comparability of studies.

This review employed standardized methods to calculate effect sizes in non-RCT studies, accounting for pre- and post-measurement correlations. However, there are some limitations. Firstly, without a control group in non-RCT studies, baseline differences between groups cannot be directly compared, which may affect the effect sizes, especially if there are significant baseline differences. While standardized effect sizes were used to minimize this, caution is needed when interpreting the results. Secondly, despite standardization, baseline imbalances and confounding factors could still influence the results. Future studies could use methods like ANCOVA to control for these factors. Finally, the variety of non-RCT designs, such as pre-post comparisons and quasi-experimental designs, may lead to differences in effect size estimates. Readers should consider these design differences when interpreting the results.

In conclusion, despite the limitations of this review, stemming primarily from the stringent selection criteria and existing constraints in the field, it still provides a clear overview of the research, highlighting the potential and direction for future studies. This review provides strong theoretical support and practical guidance for future research in this area, enabling researchers to identify key issues and gaps that still require attention, thereby laying the groundwork for further academic exploration.

Research and application

Based on the results of this study, resistance training, particularly plyometric and barbell-loaded jump training, holds significant applied value in enhancing the kinetic and kinematic performance of jump athletes. The findings reveal that resistance training substantially improved key performance metrics, including peak force, peak power, rate of force development, and both jump height and distance. Notably, these improvements were most evident in the thrust and power output during the jump propulsion phase, critical factors in overall jump performance enhancement. Specifically, plyometric and barbell-loaded jump training were particularly effective in increasing vertical jump height, demonstrating that such training methods significantly enhance explosive strength and jump performance. Therefore, training programs aimed at improving jump performance should prioritize these types of training, carefully considering load and intensity adjustments to optimize the athletes'training outcomes, particularly in vertical jump development.

Moreover, the study found that resistance training led to significant improvements in the thrust and power output of primary driving muscles (such as the quadriceps and calf push muscles). However, no significant change was observed in the maximum torque of antagonist muscles (such as the knee flexors). This suggests that the neural adaptations from resistance training primarily target the primary driving muscles. As such, training interventions should focus on enhancing the force output of these muscles, with less emphasis on the antagonist muscles. The study also highlighted that gender differences significantly improve jump performance, with female athletes showing a generally smaller performance increase than male athletes. This finding suggests that training programs should consider gender specific physiological differences, adjusting load and intensity accordingly to achieve optimal training outcomes. Based on these unique findings, future research should investigate how fine-tuned load management and targeted training can further enhance training effects for athletes of different genders and muscle group types, enabling more personalized training strategies to achieve the best possible results.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13102-025-01249-5.

Appendix 1.

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Authors' contributions
WCR drafted this systematic review and completed the literature search and collation. The development of literature inclusion and exclusion criteria, methodological assessment, and article screening were done by XZW and XRZ and SS subsequently determined in discussion with KGS. LC and YZ analysed and interpreted the data, which was ultimately checked and revised by KGS. All authors approved the final version.

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Data availability
The datasets generated and analysed during the current study are provided in Appendix 1. No additional data are available.

Declarations

Ethics approval and consent to participate
Not applicable.

Statement of human ethics and consent participation
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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References

1. Bosco C, Zanon S, Rusko H, Dal Monte A, Bellotti P, Latteri F, et al. The influence of extra load on the mechanical behavior of skeletal muscle. Europ J Appl Physiol. 1984;53:149–54.
2. Zushi K, Kariyama Y, Ogata M. Longitudinal changes in the rate of force development during single-leg press and sports performance for jumpers. Tairyoku Kagaku. 2020;69:383–92.
3. Guo Y. Research on means of power training in long jumpers. J Beijing Sports Univ. 2000;02:252–3.
4. MacKenzie SJ, Lavers RJ, Wallace BB. A biomechanical comparison of the vertical jump, power clean, and jump squat. J Sports Sci. 2014;32:1576–85.
5. Sperlich PF, Behringer M, Mester J. The effects of resistance training interventions on vertical jump performance in basketball players: a meta-analysis. J Sports Med Phys Fitness. 2016;56:874–83.
6. Li Z, Xu J, Ou S. Isokinetic kneel muscle strength characteristics in high jump athletes. Rev Bras Med Esporte. 2023;29: e2022_0276.
7. Alfaroby MI, Nurhidayat N, Denata GY. The relationship between agility; eye-foot coordination; leg muscles strength and soccer dribbling skills of football school (SSB) players. JCSS. 2022;1:6–12.
8. Zhu Z, Wu H, Li L, Jia M, Li D. Effects of diverse resistance training modalities on performance measures in athletes: a network meta-analysis. Front Physiol. 2024;15: 1302610.
9. Morris SJ, Oliver JL, Pedley JS, Haff GG, Lloyd RS. Comparison of weightlifting, traditional resistance training and plyometrics on strength, power and speed: a systematic review with meta-analysis. Sports Med. 2022;52:1533–54.

10. Domire ZJ, Challis JH. Maximum height and minimum time vertical jumping. J Biomech. 2015;48:2865–70.
11. Hoseini AS, Ghasemi F, Valizadeh F, Nayeri ND, Toulabi T, Hasanvand S. Improving the quality of clinical training in maternal and neonatal health in undergraduate nursing students: a participatory action research. BMC Nurs. 2024;23:647.
12. Perttunen JO, Kyröläinen H, Komi PV, Heinonen A. Biomechanical loading in the triple jump. J Sports Sci. 2000;18:363–70.
13. Alkjaer T, Meyland J, Raffalt PC, Lundbye-Jensen J, Simonsen EB. Neuromuscular adaptations to 4 weeks of intensive drop jump training in well-trained athletes. Physiol Rep. 2013;1:1.
14. Dani A, Sudiadharma S, Hakim H, Arimbi A, Hudain MA. The effect of half squat jump and hurdle jump training on short distance running of 60 meters in class IX students of SMP Negeri 11 Makassar. Compet J Pendidik Kepelatihan Olahraga. 2024;16:27.
15. Santos EJAM, Janeira MAAS. The effects of resistance training on explosive strength indicators in adolescent basketball players. J Strength Cond Res. 2012;26:2641–7.
16. Dal Pupo J, Detanico D, Dos Santos SG. Parâmetros cinéticos determinantes do desempenho nos saltos verticais. Rev Bras Cineantropom Desempenho Hum. 2012;14:41–51.
17. Komi PV. Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. J Biomech. 2000;33:1197–206.
18. McMahon J, Rej S, Comfort P. Sex differences in countermovement jump phase characteristics. Sports. 2017;5: 8.
19. Loturco I, D'Angelo RA, Fernandes V, Gil S, Kobal R, Cal Abad CC, et al. Relationship between sprint ability and loaded/unloaded jump tests in elite sprinters. J Strength Cond Res. 2015;29:758–64.
20. Holmes O, Lopiano G, Hall E. A review of compensatory strategies to mitigate bias. PAD. 2019;5:5.
21. Liberati A, Altman DG, Tetzlaff J, Mulrow C, Gotzsche PC, Ioannidis JPA, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate healthcare interventions: explanation and elaboration. BMJ. 2009;339 jul21 1:b2700–b2700.
22. Landis JR, Koch GG. An application of hierarchical Kappa-type statistics in the assessment of majority agreement among multiple observers. Biometrics. 1977;33:363.
23. Flemyng E, Moore TH, Boutron I, Higgins JP, Hróbjartsson A, Nejstgaard CH, et al. Using risk of bias 2 to assess results from randomised controlled trials: guidance from Cochrane. BMJ EBM. 2023;28:260–6.
24. Sterne JA, Hernán MA, Reeves BC, Savović J, Berkman ND, Viswanathan M, et al. ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. BMJ. 2016;355:i4919.
25. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. Med Sci Sports Exerc. 2009;41:3–12.
26. Higgins JPT. Measuring inconsistency in meta-analyses. BMJ. 2003;327:557–60.
27. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. J Strength Cond Res. 2009;23:177–86.
28. Vazini Taher A, Pavlović R, Ahanjan S, Skrypchenko I, Joksimović M. Effects of vertical and horizontal plyometric exercises on explosive capacity and kinetic variables in professional long jump athletes. Pedagogy of Physical Culture and Sports. 2021;25:108–13.
29. Fouad A. The effect of intermittent and continuous instantaneous strength training on biomechanical ability, technical performance and long jump success in athletics. International Journal of Disabilities Sports and Health Sciences. 2024;7:168–77.
30. Rapotan A. The impact of Optojump training on the power of lower limbs in female triple jumpers. JPES. 2023;23:555–63.
31. Zhong-ge Z. A study on pre-competition special strength training of elite man high jumper———taking the high jump champion of the10th National Games Zhang Shufeng as a case. Journal of Beijing Sport University. 2009;32:126–9.
32. Zong P. Strength training of long jump athletes. Rev Bras Med Esporte. 2023;29: e2022_0278.
33. Morris SB, DeShon RP. Combining effect size estimates in meta-analysis with repeated measures and independent-groups designs. Psychol Methods. 2002;7:105–25.
34. Reeves ND, Maganaris CN, Narici MV. Plasticity of dynamic muscle performance with strength training in elderly humans. Muscle Nerve. 2005;31:355–64.
35. Dal Maso F, Longcamp M, Amarantini D. Training-related decrease in antagonist muscles activation is associated with increased motor cortex activation: evidence of central mechanisms for control of antagonist muscles. Exp Brain Res. 2012;220:287–95.
36. Izquierdo M, Häkkinen K, Gonzalez-Badillo JJ, Ibáñez J, Gorostiaga EM. Effects of long-term training specificity on maximal strength and power of the upper and lower extremities in athletes from different sports. Eur J Appl Physiol. 2002;87:264–71.
37. Lu W, Du Z, Zhou A. Fast and medium tempo resistance training with a low number of repetitions in trained men: effects on maximal strength and power output. J Hum Kinet. 2023;87:157–65.
38. Griffin L, Cafarelli E. Resistance training: cortical, spinal, and motor unit adaptations. Can J Appl Physiol. 2005;30:328–40.
39. Wang L, Hao L, Zhang B. Kinematic diagnosis of throwing motion of the Chinese elite female discus athletes who are preparing for the tokyo olympic games. J Environ Public Health. 2022;2022: 3334225.
40. Horst F, Janssen D, Beckmann H, Schöllhorn WI. Can individual movement characteristics across different throwing disciplines be identified in high-performance decathletes? Front Psychol. 2020;11: 2262.
41. Rodríguez-Rosell D, Pareja-Blanco F, Aagaard P, González-Badillo JJ. Physiological and methodological aspects of rate of force development assessment in human skeletal muscle. Clin Physio Funct Imaging. 2018;38:743–62.
42. Kyröläinen H, Avela J, McBride JM, Koskinen S, Andersen JL, Sipilä S, et al. Effects of power training on muscle structure and neuromuscular performance. Scandinavian Med Sci Sports. 2005;15:58–64.
43. Castillo-Domínguez A, García-Romero JC, Páez-Moguer J, Ponce-García T, Medina-Alcántara M, Alvero-Cruz JR. Relationship between running spatiotemporal kinematics and muscle performance in well-trained youth female athletes. a cross-sectional study. IJERPH. 2021;18:8869.
44. Cui J, Liu Y, He F, Bu Y. Systematic review and meta-analysis on the effect of plyometric vs. resistance training on lower limb explosive power and speed. J Sports Med Phys Fitness. 2024;65:65.
45. Haff GG, Nimphius S. Training principles for power. Strength & Conditioning Journal. 2012;34:2–12.
46. Molla RY, Fatahi A, Khezri D, Ceylan HI, Nobari H. Relationship between impulse and kinetic variables during jumping and landing in volleyball players. BMC Musculoskelet Disord. 2023;24:619.
47. Tillin NA, Pain MTG, Folland JP. Contraction speed and type influences rapid utilisation of available muscle force: neural and contractile mechanisms. J Exp Biol. 2018;2:jeb.193367.
48. Muramatsu T, Muraoka T, Takeshita D, Kawakami Y, Hirano Y, Fukunaga T. Mechanical properties of tendon and aponeurosis of human gastrocnemius muscle in vivo. J Appl Physiol. 2001;90:1671–8.
49. Lichtwark GA, Wilson AM. *In vivo* mechanical properties of the human Achilles tendon during one-legged hopping. J Exp Biol. 2005;208:4715–25.
50. Job TDW, Cross MR, Cronin JB. Shoulder internal and external rotation strength assessment in baseball pitchers: normative data and reliability. J Strength Cond Res. 2025;39:e634–8.
51. Barker LA, Harry JR, Mercer JA. Relationships between countermovement jump ground reaction forces and jump height, reactive strength index, and jump time. J Strength Cond Res. 2018;32:248–54.
52. Sleivert G, Taingahue M. The relationship between maximal jump-squat power and sprint acceleration in athletes. Eur J Appl Physiol. 2004;91:46–52.
53. Kipp K, Kiely MT, Geiser CF. Reactive strength index modified is a valid measure of explosiveness in collegiate female volleyball players. J Strength Cond Res. 2016;30:1341–7.
54. Dideriksen JL, Del Vecchio A, Farina D. Neural and muscular determinants of maximal rate of force development. J Neurophysiol. 2020;123:149–57.
55. Haugen ME, Vårvik FT, Grgic J, Studsrud H, Austheim E, Zimmermann EM, et al. Effect of isolated and combined ingestion of caffeine and citrulline malate on resistance exercise and jumping performance: a randomized double-blind placebo-controlled crossover study. Eur J Nutr. 2023;62:2963–75.

56. Del Vecchio A, Casolo A, Negro F, Scorcelletti M, Bazzucchi I, Enoka R, et al. The increase in muscle force after 4 weeks of strength training is mediated by adaptations in motor unit recruitment and rate coding. J Physiol. 2019;597:1873–87.
57. Stefanovic F, Ramanarayanan S, Karkera NU, Mujumdar R, Sivaswaamy Mohana P, Hostler D. Rate of change in longitudinal EMG indicates time course of an individual's neuromuscular adaptation in resistance-based muscle training. Front Rehabilit Sci. 2022;3: 981990.
58. Farina D, Merletti R, Enoka RM. The extraction of neural strategies from the surface EMG: an update. J Appl Physiol. 2014;117:1215–30.
59. Wan B, Shan G. Biomechanical modeling as a practical tool for predicting injury risk related to repetitive muscle lengthening during learning and training of human complex motor skills. Springerplus. 2016;5:441.
60. Saliba CM, Rainbow MJ, Selbie WS, Deluzio KJ, Scott SH. Co-contraction uses dual control of agonist-antagonist muscles to improve motor performance. 2020.
61. Lee SSM, De Boef Miara M, Arnold AS, Biewener AA, Wakeling JM. Recruitment of faster motor units is associated with greater rates of fascicle strain and rapid changes in muscle force during locomotion. J Exp Biol. 2013;216(Pt 2):198–207. https://doi.org/10.1242/jeb.072637.
62. Coletta F, Cesanelli L, Kamandulis S, Conte D. Comparative analysis of elbow flexor morphology, physiology, and performance between arm wrestlers and strength-trained athletes. J Strength Cond Res. 2025;39:579–86.
63. González-Parada A, Lozano-García JM, Ibarra-Manzano MA. Digital pole control for speed and torque variation in an axial flux motor with permanent magnets. Electronics. 2022;11: 482.
64. Heuzé T, Rech J, Dumont F, Leblond J, Bergheau J. Two experimental set-ups designed for investigation of friction stir spot welding process. Sci Technol Weld Joining. 2011;16:735–44.
65. Iranpour AR, Hemmatinafar M, Nemati J, Salesi M, Esmaeili H, Imanian B. The effects of plyometric training with speed and weight overloads on volleyball players' strength, power, and jumping performance. PLoS One. 2025;20: e0316477.
66. Haider Khan HMM, Masood T. Knee biomechanics and physical performance: an ACL-reconstructed athlete before and after isokinetic strength training. TPMJ. 2017;24:1921–6.
67. Maffiuletti NA, Zory R, Miotti D, Pellegrino MA, Jubeau M, Bottinelli R. Neuromuscular adaptations to electrostimulation resistance training. Am J Phys Med Rehabil. 2006;85:167–75.
68. Escamilla RF, Ionno M, deMahy MS, Fleisig GS, Wilk KE, Yamashiro K, et al. Comparison of three baseball-specific 6-week training programs on throwing velocity in high school baseball players. J Strength Cond Res. 2012;26:1767–81.
69. Kozinc Ž, Žitnik J, Smajla D, Šarabon N. The difference between squat jump and countermovement jump in 770 male and female participants from different sports. Eur J Sport Sci. 2022;22:985–93.
70. Peng A. Resistance training combined with athletic training. Rev Bras Med Esporte. 2023;29: e2022_0525.
71. Tsimachidis C, Patikas D, Galazoulas C, Bassa E, Kotzamanidis C. The post-activation potentiation effect on sprint performance after combined resistance/sprint training in junior basketball players. J Sports Sci. 2013;31:1117–24.
72. Nuzzo JL, McBride JM, Cormie P, McCaulley GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. J Strength Cond Res. 2008;22:699–707.
73. Balasas DG, Kellis S, Christoulas K, Bampouras TM. An off-season plyometric and resistance training programme to improve vertical jump height in adolescent female volleyball players. J Sci Sport Exerc. 2022;4:213–20.
74. Tredrea MSJ, Middleton KJ, Bourne MN, Carey DL, Scanlan AT, Dascombe BJ. Load centralization does not affect the kinetic and kinematic output of countermovement jumps. J Strength Cond Res. 2022;36:1084–9.
75. Karatrantou K, Gerodimos V, Voutselas V, Manouras N, Famisis K, Ioakimidis P. Can sport-specific training affect vertical jumping ability-during puberty? Biology of sport. 2019;36:217–24.
76. Porrati-Paladino G, Cuesta-Barriuso R. Effectiveness of plyometric and eccentric exercise for jumping and stability in female soccer players—a single-blind, randomized controlled pilot study. IJERPH. 2021;18:294.
77. Shimizu T, Tsuchiya Y, Ueda H, Izumi S, Ochi E. Eight-week flywheel training enhances jump performance and stretch-shortening cycle function in collegiate basketball players. Eur J Sport Sci. 2025;25: e12257.
78. Holzer D, Hahn D, Schwirtz A, Siebert T, Seiberl W. Decoupling of muscle-tendon unit and fascicle velocity contributes to the in vivo stretch-shortening cycle effect in the male human triceps surae muscle. Physiol Rep. 2024;12: e70131.
79. Ramirez-Campillo R, Thapa RK, Afonso J, Perez-Castilla A, Bishop C, Byrne PJ, et al. Effects of plyometric jump training on the reactive strength index in healthy individuals across the lifespan: a systematic review with meta-analysis. Sports Med. 2023;53:1029–53.
80. Booth MA, Orr R. Effects of plyometric training on sports performance. Strength & Conditioning Journal. 2016;38:30–7.
81. Krishnan C, Williams GN. Sex differences in quadriceps and hamstrings EMG-moment relationships. Med Sci Sports Exerc. 2009;41:1652–61.
82. Taitano RI, Yakovenko S, Gritsenko V. Neuromechanical coupling is reflected in the spatial organization of the spinal motoneuron pools. 2022.
83. Van De Hoef PA, Brauers JJ, Van Smeden M, Backx FJG, Brink MS. The effects of lower-extremity plyometric training on soccer-specific outcomes in adult male soccer players: a systematic review and meta-analysis. Int J Sports Physiol Perform. 2020;15:3–17.
84. Garcia T, Pupo JD, Knihs DA, Furlaneto Rodrigues OA, Zimmermann HB, Padulo J. Single- versus multi-joint isometric protocols to induce a post activation potentiation effect on squat jump performance. Hum Mov. 2020;21:71–80.
85. Santana EE, Medeiros MFD, Almeida Neto PFD, Rocha MDL, Dantas PMS, Cabral BGDAT. Effect of plyometric and sprint training on repeated sprint and vertical jump capacities in volleyball players aged 11 to 14 years: a longitudinal study. RSD. 2024;13: e8313244923.
86. Häkkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, et al. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. Eur J Appl Physiol. 2003;89:42–52.
87. Rong W, Geok SK, Samsudin S, Zhao Y, Ma H, Zhang X. Effects of strength training on neuromuscular adaptations in the development of maximal strength: a systematic review and meta-analysis. Sci Rep. 2025;15:19315.
88. Sáez Sáez De Villarreal E, Izquierdo M, Gonzalez-Badillo JJ. Enhancing jump performance after combined vs. maximal power, heavy-resistance, and plyometric training alone. Journal of Strength and Conditioning Research. 2011;25:3274–81.
89. Kamnardsiria T, Janchaia W, Khuwuthyakorna P, Suwansrikhama P, Klaphajoneb J, Suriyachanc P. Knowledge-based system framework for training long jump athletes using action recognition. JAIT. 2015;6(4):182–93.
90. Linthorne NP, Guzman MS, Bridgett LA. Optimum take-off angle in the long jump. J Sports Sci. 2005;23:703–12.
91. Berriel GP, Cardoso AS, Costa RR, Rosa RG, Oliveira HB, Kruel LFM, et al. Does complex training enhance vertical jump performance and muscle power in elite male volleyball players? Int J Sports Physiol Perform. 2022;17:586–93.
92. Stošić D, Uzunović S, Pantelić S, Veličković S, Đurović M, Piršl D. Effects of an exercise program on the coordination and explosive power of university dance students. FU Phys Ed Sport. 2020;17(3):579–589.
93. Gherghel A, Badau D, Badau A, Moraru L, Manolache GM, Oancea BM, et al. Optimizing the explosive force of the elite level football-tennis players through plyometric and specific exercises. IJERPH. 2021;18: 8228.
94. Meylan C, Malatesta D. Effects of in-season plyometric training within soccer practice on explosive actions of young players. J Strength Cond Res. 2009;23:2605–13.
95. Leirdal S, Roeleveld K, Ettema G. Coordination specificity in strength and power training. Int J Sports Med. 2008;29:225–31.
96. Brini S, Boullosa D, Calleja-González J, Ramirez-Campillo R, Nobari H, Castagna C, et al. Neuromuscular and balance adaptations following basketball-specific training programs based on combined drop jump and multidirectional repeated sprint versus multidirectional plyometric training. PLoS One. 2023;18: e0283026.
97. Anousaki E, Zaras N, Stasinaki A-N, Panidi I, Terzis G, Karampatsos G. Effects of a 25-week periodized training macrocycle on muscle strength, power, muscle architecture, and performance in well-trained track and field throwers. J Strength Cond Res. 2021;35:2728–36.
98. Litao G, Jintian Y, Xutao L. Influence of lower limb resistance training on the explosive quality of athletes. Rev Bras Med Esporte. 2023;29: e2023_0015.

99. Polakovičová M, Vavák M, Ollé R, Lehnert M, Sigmund M. Vertical jump development in elite adolescent volleyball players: effects of sex and age. Acta Gymnica. 2018;48:115–20.
100. McLellan CP, Lovell DI, Gass GC. The role of rate of force development on vertical jump performance. J Strength Cond Res. 2011;25:379–85.
101. Lorenzetti S, Ammann F, Windmüller S, Häberle R, Müller S, Gross M, et al. Conditioning exercises in ski jumping: biomechanical relationship of squat jumps, imitation jumps, and hill jumps. Sports Biomechanics. 2019;18:63–74.
102. Makaruk H, Winchester JB, Czaplicki A, Sacewicz T, Zieliński J, Sadowski J. Effects of assisted and traditional drop jumps on jumping performance. Int J Sports Sci Coach. 2014;9:1217–25.
103. Ketterer J, Gollhofer A, Lauber B. Biomechanical agreement between different imitation jumps and hill jumps in ski jumping. Scandinavian Med Sci Sports. 2021;31:115–23.
104. Zhang M, Li D, He J, Liang X, Li D, Song W, et al. Effects of velocity-based versus percentage-based resistance training on explosive neuromuscular adaptations and anaerobic power in sport-college female basketball players. Healthcare (Basel). 2023;11:11.
105. Makaruk H, Sacewicz T, Czaplicki A, Sadowski J. Effect of additional load on power output during drop jump training. J Hum Kinet. 2010;26:31–7.
106. Moher D, Liberati A, Tetzlaff J, Altman DG. The PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 2009;6:e1000097.
107. Jüni P, Holenstein F, Sterne J, Bartlett C, Egger M. Direction and impact of language bias in meta-analyses of controlled trials: empirical study. Int J Epidemiol. 2002;31:115–23.
108. Morrison A, Polisena J, Husereau D, Moulton K, Clark M, Fiander M, et al. The effect of English-language restriction on systematic review-based meta-analyses: a systematic review of empirical studies. Int J Technol Assess Health Care. 2012;28:138–44.

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