

Comparison of Variable Resistance and Free Weight Training on Long-Term and Acute Effects on Different Assessments of Strength: A Systematic Review and Meta-Analysis

Jie Li,¹ Zongwei Chen,² Kai Xu,³ Yifan Wang,¹ and Mingjun Gong^{1,*}

¹School of Sports Training, Tianjin University of Sport, Tianjin, China; ²Department of Physical Education and Sport, Faculty of Sport Sciences, University of Granada, Granada, Spain; and ³School of Athletic Performance, Shanghai University of Sport, Shanghai, China

Abstract

Li, J, Chen, Z, Xu, K, Wang, Y, and Gong, M. Comparison of variable resistance and free weight training on long-term and acute effects on different assessments of strength: a systematic review and meta-analysis. *J Strength Cond Res* XX(X): 000–000, 2025—Variable resistance training (VRT) addresses biomechanical disadvantages of free weight training (FWT), but its long-term and acute effects on strength remain underexplored. This study aimed to compare the effects of VRT and FWT on the following variables—maximal strength, velocity, power output, and jump distance—under both long-term and acute interventions. The study used cluster analysis to define variable resistance load proportion (VRLP) groups. Pairwise meta-analysis assessed long-term outcomes, subgroup analyses by VRLP, VRT equipment (elastic bands or chains), and number of VRT exercises (single or multiple). Acute interventions were evaluated using network meta-analysis across VRLP and FWT groups. Effect sizes were reported as standardized mean differences (SMD). For long-term effects, VRT outperformed FWT in maximal strength (repetition maximum or force output) and jump distance (vertical or horizontal) ($0.28 \leq \text{SMD} \leq 0.37$). Specifically, chain-based loading and VRLP $\leq 20\%$ showed advantages across both outcomes ($0.39 \leq \text{SMD} \leq 0.51$). Multiple-exercise VRT improved maximal strength ($\text{SMD} = 0.27$), whereas single-exercise VRT improved jump distance ($\text{SMD} = 0.46$). For acute effects, VRLP $>20\%$ showed superior maximal strength (force output) ($0.46 \leq \text{SMD} \leq 0.79$), VRLP $>37\%$ resulted in lower maximal velocity (movement velocity) and power output ($\text{SMD} \leq -1.31$) compared with FWT. Thus, long-term VRT surpasses FWT in maximal strength and jump distance, with chain-based or VRLP $\leq 20\%$ of VRT optimal; multiple exercises benefit maximal strength, and single exercise improves maximal jump distance. Acutely, VRLP of 21–37% VRT results in greater mechanical output in a variety of exercises.

Key Words: accommodating resistance training, constant resistance training, chain resistance, elastic resistance, exercise prescription, strength and conditioning

Introduction

Resistance training is a well-established strategy for enhancing various measures of strength. Among its modalities, free weight training (FWT), which does not rely on fixed trajectory machine and typically involves multi-joint movements, elicits greater activation across a broader range of muscle groups and engages multiple physiological systems compared with machine-based resistance training, thereby facilitating more comprehensive improvements in strength (58,59,61,62). However, FWT still presents biomechanical disadvantages. Torque does not appropriately match the actual resistance throughout the movement range, making it difficult to effectively overcome the load. Therefore, when the external load is relatively heavy (e.g., $>70\%$ of 1 repetition maximum [1RM]), sticking points may occur near joint limits or at specific angles (38,39,56). Sticking points can lead to unnecessary energy expenditure, increased fatigue, and

disrupted movement rhythm, potentially hindering the completion of repetitions (39,56).

Variable resistance training (VRT), a derivative of FWT, integrates variable resistance into free-weight exercises. By modifying the VRT equipment type (chains or elastic bands), the number of VRT exercises (single exercise: using only one VRT exercise in the VRT protocol; multiple exercises: incorporating more than one VRT exercise in the VRT protocol), and the variable resistance load proportion (VRLP), which refers to the percentage of total resistance contributed by the variable resistance (from chains or elastic bands), VRT allows for diverse adaptations (1,32,52,66). In contrast to FWT, VRT adjusts torque based on joint angle and moment arm, providing appropriate resistance throughout the range of motion and helping subjects overcome sticking points (38,39,56).

Building on these biomechanical advantages, long-term VRT improves strength adaptations across the range of motion while acutely enhancing motor unit recruitment (6,32,52,66). It is theorized to produce superior adaptations in maximal strength (commonly expressed as a RM or as maximal force output), maximal velocity (commonly expressed as the maximal movement velocity of the person or object), and explosiveness (maximal power output and jump distance) (66,67). Notably, findings

*Address correspondence to Mingjun Gong, gongsimon@tj.us.edu.cn.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (<http://journals.lww.com/nsca-jscr>).

Journal of Strength and Conditioning Research 00(00)/1–13

© 2025 National Strength and Conditioning Association

are inconsistent—some studies report no difference between VRT compared with FWT (2,49,52), whereas others show clear benefits of VRT (32,67,78). The optimal VRT setup remains unclear and VRT protocols vary notably across studies in VRT equipment type, number of VRT exercises, and VRLP settings (1,32,52,66). These methodological discrepancies, particularly in VRLP design, preclude the development of clear guidelines for identifying the most effective VRT approach (6,56,76).

Although previous meta-analyses have explored the effects of VRT on strength outcomes such as maximal strength (4,43,46,68,71), there are still several issues that remain unaddressed. For example, in a meta-analysis of long-term interventions (≥ 3 weeks), previous researchers reported no significant differences in maximal strength between VRT and conventional resistance training (4). Yet many included studies used single-joint or machine-based exercises rather than direct comparisons between VRT and FWT. Key VRT variables—such as VRT equipment, number of VRT exercises, and VRLP—were also seldom analyzed. Furthermore, other strength outcomes lack detailed investigation (52,66). In contrast, acute intervention meta-analyses—which assess strength during the intervention—found that higher VRT loads reduced maximal velocity compared with FWT, whereas elastic bands improved maximal force output and higher VRLP configurations enhanced maximal power output (65). However, these analyses lack comparisons between different VRLP within VRT protocols and the effects of specific VRLP ranges remain unclear.

Overall, comparisons between VRT and FWT should focus on the following aspects: (a) greater emphasis on multi-joint exercises; (b) in long-term interventions, inclusion of strength outcome beyond maximal strength and investigation of whether different VRT protocols; (c) in acute interventions, analysis of whether different VRLP-based VRT protocols yield distinct effects, both among themselves and FWT. In long-term VRT interventions, VRT is typically based on a single specific VRLP, resulting in pairwise comparisons (6,7,9,66,70). In contrast, acute studies often involve multiple VRT protocols based on VRLPs, forming network of interventions (20,21,65,67). Because of potential structural gaps in long-term data, a network meta-analyses may introduce bias, making a pairwise meta-analysis a more suitable approach for evaluating long-term VRT versus FWT effects.

Therefore, this study will compare VRT and FWT from both long-term and acute effects. For the long-term effects, a pairwise meta-analysis was used to directly assess the effects of VRT versus FWT on maximal strength, maximal velocity, and explosiveness (maximal power output and jump distance) after long-term interventions, with subgroup analyses conducted across different VRT equipment, number of VRT exercises, and VRLP-based intervention designs. For acute interventions, a network meta-analysis was used to compare the effects of different VRT based on VRLP design with FWT on maximal strength (force output), maximal velocity, and explosiveness (maximal power output). We make the following hypotheses: (a) for long-term effects, VRT would lead to superior improvements in the aforementioned measures of strength, with these effects being influenced by different VRT designs; (b) for acute effects, varying VRLP strategies would differentially influence strength outcomes (51,67). In addition, explosiveness—conceptualized as the combined expression of maximal strength and velocity—was operationally defined using 2 indicators: (a) maximal power output and (b) maximal jump distances (vertical or horizontal) (73).

Methods

Experimental Approach to the Problem

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and was registered in the PROSPERO database (registration number: CRD42024550030; date: 16 Mar 2025). All steps were independently completed by 2 authors (Li, J and Chen, Z), with discrepancies resolved by other authors (Xu, K, Wang, Y, and Gong, M) and final consensus among all authors.

Search Strategy

The literature search for this study was conducted up until March 2025 across 6 databases: PubMed, Embase, Scopus, Web of Science, SPORTDiscus, and Cochrane Library. A comprehensive search strategy was designed using Boolean operators (AND/OR) and relevant keywords. The search query for PubMed was used as the primary reference, and the Polyglot Search Translator Tool (41) was used to adapt the query for other databases. The PubMed search query was: (“variable resistance” OR “accommodating resistance” OR “resistance training” OR “strength training” OR “constant resistance training” OR “free weight” OR “back squat” OR “bench press” OR “deadlift” OR “weightlifting”) AND (“acute effects” OR “long term effects” OR “kinetic” OR “kinematic” OR “force” OR “power” OR “velocity” OR “acceleration” OR “RM” OR “repetitions maximum” OR “strength” OR “maximal strength” OR “RFD” OR “rate of force development” OR “jump” OR “CMJ” OR “counter movement jump” OR “vertical jump” OR “standing long jump” OR “jump height” OR “jump distance”) AND (“band” OR “elastic band” OR “rubber band” OR “rubber tube” OR “elastic tube” OR “chain” OR “thera-band”). The detailed search strategies for each database are provided in Supplemental Digital Content (see Table S1, <http://links.lww.com/JSCR/A764>).

In addition, this study applied backward citation tracking by examining reference lists in existing systematic reviews of VRT and reached out directly to researchers by ResearchGate to obtain articles not indexed by conventional databases. All identified records were then systematically organized and managed in EndNote 21.4.

Inclusion and Exclusion Criteria

Inclusion and exclusion criteria were based on commonly used VRT and FWT protocols reported in previous studies, following the PICOS framework (4,15,65,73). Studies with a modified PEDro score ≤ 4 were excluded to ensure methodological quality (10,13). Detailed criteria are presented in Table 1.

Risk of Bias and Study Quality Assessment

This study will assess the risk of bias in the included studies using the second edition of the Cochrane Risk-of-Bias Tool for Randomized Trials (RoB-2) (72), implemented in Review Manager 5.4. The quality of the included studies will be assessed using the modified PEDro scale (13,35), which consists of 8 items.

Baseline Data Extraction

Baseline data were extracted using Microsoft Excel (2019), including author, publication year, subject characteristics,

Table 1
Inclusion and exclusion criteria for studies.*

Population	Intervention	Comparison	Outcome	Study design
Inclusion criteria				
Age more than 18 y old and less than 60 y old	VRT based on free weights	VRT group was compared with the FWT group	Outcome data are available for each group	Original study
For human studies	Long-term intervention lasts for at least 3 wk	The training load was equal between the VRT group and the FWT group	Test results of acute intervention need to be obtained during the intervention period	Publish in English
No history of sports injuries or other medical conditions	Training involves multiple joint involvement		Includes following key variables: maximal strength, velocity, and explosiveness (maximal power output and jump vertical or horizontal distance)	Modified PEDro score ≥ 4
	Training was carried out under the stable plane		VRLP used in VRT must be specified	
	Use elastic bands or chains for resistance or assistance		Missing data can be obtained by contacting the authors or by software extraction	
	Training in a nonspecial environment			
	Fixed trajectory instrument not used			
	No using blood flow restriction bands for training			
	No other medications or supplements were taken during the training			
Exclusion criteria				
Age less than 18 y or more than 60 y old	Only use elastic bands or chains for VRT without using free weights	VRT was not compared with FWT	Outcome data were not available in each group	Observational study
Nonhuman studies	Duration of the long-term intervention was less than 3 wk	The training load was unequal between the VRT group and the FWT group	Test results of acute intervention were not obtained during the intervention	Systematic review or meta-analysis
History of sports injuries and other medical conditions	Single-joint training		Key variables: maximal strength, velocity and explosiveness (maximal power output and jump vertical or horizontal distance) were not measured	Conference
	Training was carried out under the unstable plane		VRLP used in VRT not be specified	Not publish in English
	Use elastic straps to hang weights from the barbell		Missing data could not have been obtained by contacting the authors or by software extraction	Modified PEDro score < 4
	Fixed trajectory instrument was used			
	Training in a special environment			
	Using blood flow restriction bands for training			
	Taking medications or other supplements during training			

*FWT = free weight training; VRT = variable resistance training; VRLP = variable resistance load proportion.

intervention protocols, outcome measurement methods, and intervention duration (only long-term intervention) for studies. For duplicate datasets published in multiple articles, data were extracted from the most comprehensive source. When data were not available in tables or text, WebPlotDigitizer (17) was used to extract values from figures, or the corresponding authors were contacted directly.

For the VRLP in VRT during long-term interventions, if different VRLP protocols were applied across weeks, the VRLP for each week (Per week VRLP) was calculated as a Weighted VRLP based on the number of VRT sessions per week (Frequency of VRT) (48). The formula used for this calculation is as follows:

$$\text{Weighted VRLP} = \frac{\sum (\text{Per week VRLP} \times \text{Frequency of VRT})}{\sum (\text{Frequency of VRT})}$$

Effect Size Calculation

Because the study involves outcomes with various units, the standardized mean difference (SMD) (27) was used as the effect size metric for analysis. The SMD was categorized as follows: $\text{SMD} < 0.2$ (trivial), $0.2 \leq \text{SMD} < 0.5$ (small), $0.5 \leq \text{SMD} < 0.8$ (moderate), and $\text{SMD} \geq 0.8$ (large).

In long-term interventions, SMD was calculated using pre-post change scores (Change mean and Change *SD*) to compare differences in strength outcomes between VRT and FWT. The change mean was obtained by subtracting the pre-intervention mean (Pre mean) from the post-intervention mean (Post mean). The change *SD* (Change *SD*) was calculated using the pre-intervention and post-intervention *SDs* (Pre *SD* and Post *SD*) according to the following formula:

In the formula above, r represents the correlation coefficient between the pre-intervention and post-intervention data. According to the Cochrane Handbook, r is assumed to be 0.5 (14,47).

$$\text{Change } SD = \sqrt{\text{Pre } SD^2 + \text{Post } SD^2 - (2 \times r \times \text{Pre } SD \times \text{Post } SD)}.$$

For acute interventions, SMD was calculated using the data measured during the intervention sessions. Specifically, strength variables such as maximal force output, velocity, and power output were recorded in real time under both VRT and FWT conditions. The mean values and SDs of these measures were then compared to evaluate the immediate effects of the 2 training modalities (67,74,78).

Cluster Analysis

To further classify the VRT protocols based on VRLP, all reported VRLP values were first compiled. Outliers within each VRLP dataset were identified and removed using boxplot analysis in IBM SPSS Statistics 27. The cleaned data were then subjected to k-mean clustering (number of clusters = 2) using the cluster package in R version 4.4.3. The average silhouette coefficient was used to evaluate clustering quality. Based on the clustering results, the included VRT interventions were grouped according to their VRLP characteristics (19,28,45).

Pairwise Meta-analysis and Publication Bias Assessment

For studies involving long-term interventions, pairwise meta-analysis conducted using a random-effects model in STATA 16. Following strength outcomes—maximal strength, maximal velocity and explosiveness (maximal power output and jump distance)—were analyzed to compare the effects of VRT and FWT. For each outcome, subgroup analyses were conducted based on: (a) the VRT equipment (chains or elastic bands); (b) the number of VRT exercises of VRT (single exercise or multiple exercises); and (c) the VRLP-based VRT grouping obtained from clustering analysis. Standardized mean differences were calculated with 95% confidence intervals (CIs), and p -values were used to determine statistical significance ($p < 0.05$ considered significant) (42). In addition, meta-regression analyses were performed for each strength outcome to explore potential moderating effects of subject age, intervention duration, and weekly VRT frequency (75). To assess publication bias, funnel plots and Egger's test were applied to comparisons involving 10 or more studies in the pairwise meta-analysis (18).

Network Meta-analysis

In the acute intervention analysis, studies were grouped based on VRLP for VRT. A Bayesian network meta-analysis was conducted for maximal strength, velocity, and power output outcomes using the network package in STATA 16 and the *gemtc* package in R version 4.4.3. The Bayesian framework used the Markov chain Monte Carlo method, with the model type set to “consistency” (consistency model), running with 4 chains. The likelihood function for the data was assumed to follow a normal distribution, and the identity link function was used. The model was run using the *mtc.run*

function, with an initial 20,000 iterations for adaptation to adjust parameters, followed by 50,000 iterations in total. Each sample of the iteration was retained without thinning. Convergence of each

Markov chain in the network meta-analysis was evaluated using trace and density plots, the Gelman–Rubin diagnostic, and calculation of the potential scale reduction factor (PSRF). Global inconsistency was assessed by comparing consistency and inconsistency models by the deviance information criterion (DIC), with a DIC difference >5 indicating significant inconsistency. For the comparisons of each outcome, the relative effects of each intervention were ranked using stacked rank plots and cumulative ranking results (15,55). Specifically, when the probability of an intervention method approached 100%, it indicated that the method was more effective in enhancing the respective strength outcome, resulting in a higher ranking compared with the other interventions. Conversely, a lower probability suggested that the method was less effective, corresponding to a lower ranking. In addition, network meta-analysis results were reported as SMD with 95% credible interval (CrI). If the 95% CrI included zero, the result was considered not statistically significant because CrI reflects the probability of the parameter value given the data and prior, whereas traditional CI in the pairwise meta-analysis, based on frequentist methods, do not incorporate prior information. The network meta-analysis, conducted under the Bayesian framework, uses CrI to express uncertainty from both data and prior information (15,23,42).

Assessment of Heterogeneity and Sensitivity Analysis

Heterogeneity in each comparison of both the pairwise and network meta-analyses was evaluated using the I^2 statistic (26). For comparisons showing high heterogeneity ($I^2 > 75\%$) or apparent publication bias (in pairwise meta-analysis only), sensitivity analyses were conducted to detect potential outliers. If outliers were identified, they were removed one by one, and the analyses was repeated to assess the robustness and stability of the results (24).

Certainty of Evidence Assessment

Certainty of evidence for each outcome comparison in both the pairwise and network meta-analyses was evaluated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) approach (60). According to GRADE, the certainty of evidence is classified into 4 levels: very low (very uncertain about the estimated result), low (limited confidence in the estimate result; the true result may be substantially different), moderate (the result is likely close to the true estimate, but some uncertainty remains), and high (high confidence that the result estimate is close to the true result).

Results

Search Results

This systematic review and meta-analysis identified a total of 5,899 studies, with the detailed search process outlined in the

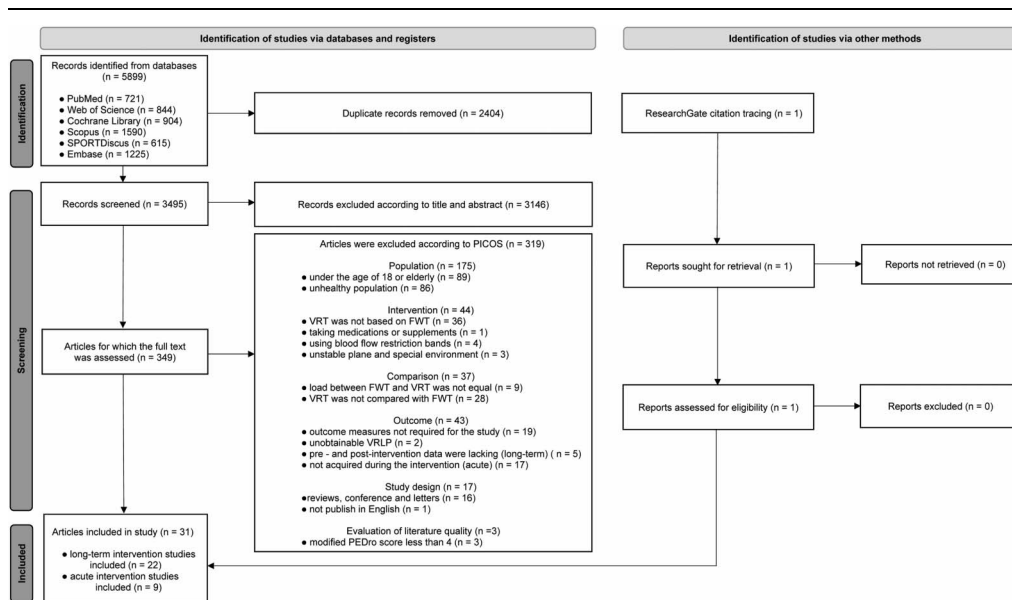


Figure 1. PRISMA flow diagram. PRISMA = Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

Figure 1. Finally, 31 studies were included in this systematic review and meta-analysis, with 22 studies involving long-term interventions included in the paired meta-analysis (1,6–9,11,12,22,31,32,34,36,44,49,52,53,57,64,66,69,70,77) and 9 studies involving acute interventions included in the network meta-analysis (2,3,20,21,30,40,67,74,76).

Risk of Bias and Study Quality

Among the 31 studies assessed for risk of bias (long-term: 22; acute: 9), 9.7% (long-term: 2; acute: 1) were rated as having a high overall risk of bias. The remaining 90.3% (20 long-term; 8 acute) were rated as having an unclear overall risk of bias. None found to have a low overall risk of bias. A detailed summary of the risk of bias assessment is presented in Figure 2.

The quality of the 31 included studies (long-term: 22; acute: 9) was assessed using the modified PEDro scale. Scores ranged from 4 to 7 (long-term: 4–7; acute: 4–5), with an overall mean score of 5.12 ± 0.76 (long-term: 5.27 ± 0.83 ; acute: 4.77 ± 0.44). Detailed quality assessment results are shown in the Supplemental Digital Content (see Table S2, <http://links.lww.com/JSCR/A764>).

Subjects and Intervention Characteristics

Among the 31 studies included in this review, 22 involved long-term interventions, comprising a total of 572 subjects (VRT = 304; FWT = 268). Regarding sex distribution, 422 were male and 150 were female. In training background, 4 studies included untrained subjects ($n = 124$), whereas the remaining subjects ($n = 448$) had at least 6 months of training experience. Two studies (32,49) ($n = 42$) did not mention the use of randomized controlled trials in their interventions. Detailed subject and intervention characteristics for the long-term intervention studies are provided in the Supplemental Digital Content (see Table S3–S4, <http://links.lww.com/JSCR/A764>).

In the 9 studies involving acute interventions, a total of 126 subjects were included. All subjects were male and had at least 6 months

of training experience. One study (30) ($n = 10$) did not mention the use of randomized controlled trials in their interventions. A detailed summary of subjects and intervention characteristics for the acute intervention studies is provided in the online Supplemental Digital Content (see Table S5–S6, <http://links.lww.com/JSCR/A764>).

Definition and Classification of Outcome Measures

Based on the outcome variables reported in the included studies, this review extracted and categorized 3 primary strength outcomes for meta-analysis: maximal strength, maximal velocity, and explosiveness. These outcomes were further classified according to the type of intervention (long-term or acute) and the specific assessment methods used. Detailed classifications of outcome types and their corresponding assessment methods are presented in Table 2.

For explosiveness, 2 subtypes were analyzed: (a) maximal power output; (b) maximal jump distances. Maximal power output was examined under both long-term and acute intervention conditions, whereas jump distance were analyzed only within long-term intervention studies to compare the effects between VRT and FWT (73).

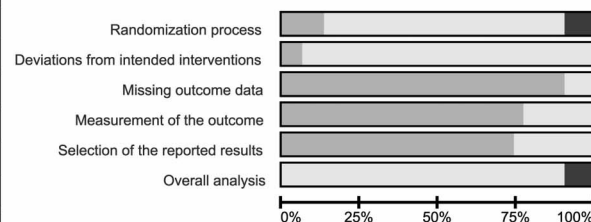
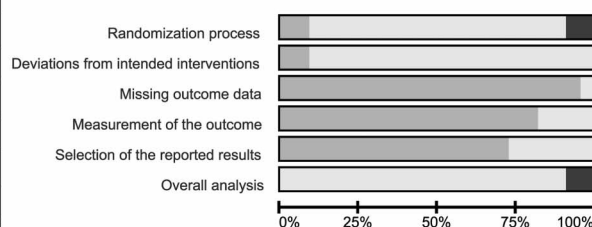
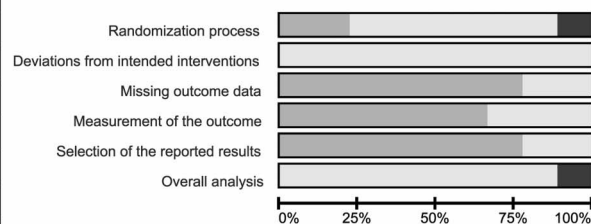
Cluster Analysis Results

Boxplots were used to identify outliers in the 47 VRLPs (long-term: 24; acute: 23) included in the studies. The VRLP in all studies ranged from 5 to 80% (long-term: 5–80%; acute: 15–41%). After excluding one outlier VRLP based on the boxplot (28,45), k-means clustering was performed on the VRLP data. The results showed that the cluster centers of VRLP were 20.03 and 37.40, with an average silhouette coefficient of 0.67, which is close to 1, indicating a good clustering outcome.

Based on the clustering results and previous literature (1,11,32,52,67), the 2 authors (Li, J and Chen, Z) reached a consensus to classify VRLP into 3 categories. The VRT with $0\% < \text{VRLP} \leq 20\%$ was defined as the low variable resistance load proportion (LVRLP) group, VRT with $20\% < \text{VRLP} \leq 37\%$ was defined as the moderate variable resistance

A Total studies risk of bias assessment details for each item

	Randomization Process	Deviations from Intended Interventions	Missing Outcome Data	Measurement of the Outcome	Selection of the Reported Results	Overall analysis
Andersen et al., 2008 (long)	?	?	+	+	+	?
Andersen et al., 2015 (long)	+	?	+	+	+	?
Andersen et al., 2019 (acute)	+	?	+	+	+	?
Andersen et al., 2020 (acute)	?	?	+	?	+	?
Arazi et al., 2020 (long)	?	+	+	+	+	?
Arazi et al., 2022 (long)	?	?	+	?	?	?
Ataee et al., 2014 (long)	?	?	+	?	+	?
Bellar et al., 2011 (long)	?	?	+	+	+	?
Burnham et al., 2010 (long)	?	?	+	?	+	?
Galpin et al., 2015 (acute)	?	?	+	+	?	?
García-López et al., 2016 (acute)	?	?	+	+	+	?
Ghigiarrelli et al., 2009 (long)	?	?	+	+	+	?
Israel et al., 2010 (acute)	●	?	?	+	?	●
Izadi et al., 2020 (long)	?	?	+	+	+	?
Joy et al., 2016 (long)	●	+	+	+	+	●
Kashiani et al., 2020 (long)	?	?	+	+	?	?
Katushabe et al., 2020 (long)	?	?	+	+	+	?
Kubo et al., 2018 (acute)	?	?	+	?	+	?
Liu et al., 2024 (long)	?	?	+	+	+	?
McCurdy et al., 2009 (long)	●	?	+	+	+	●
Parten et al., 2023 (long)	+	?	+	+	+	?
Rhea et al., 2009 (long)	?	?	+	?	?	?
Sawyer et al., 2021 (long)	?	?	+	+	+	?
Scott et al., 2023 (long)	?	?	+	+	+	?
Shi et al., 2022 (long)	?	?	?	+	+	?
Shi et al., 2024 (acute)	+	?	+	+	+	?
Shoepe et al., 2011 (long)	?	?	+	+	?	?
Somak et al., 2020 (long)	?	?	+	+	?	?
Swinton et al., 2011 (acute)	?	?	+	?	+	?
van den Tillaar et al., 2022 (acute)	?	?	?	+	+	?
Vojinovic et al., 2023 (long)	?	?	+	+	?	?

B Total studies risk of bias assessment**C Long-term intervention studies risk of bias assessment****D Acute intervention studies risk of bias assessment****Figure 2.** Risk of bias assessment diagram. Long = long-term intervention; acute = acute intervention.

load proportion (MVRLP) group, and VRT with VRLP >37% was defined as the high variable resistance load proportion (HVRLP) group. Detailed VRLP values and their cluster analysis results are provided in the Supplemental Digital Content (see Figure S1, <http://links.lww.com/JSCR/A764>).

Pairwise Meta-analysis of Long-Term Interventions

In the pairwise meta-analysis, detailed results of each comparison are presented in Figure 3. The results indicated that VRT elicited significantly greater improvements in maximal strength

compared with FWT (SMD = 0.28; 95% CI: 0.14–0.42; GRADE: low). Subgroup analyses further demonstrated that using chains as a form of variable resistance resulted in superior maximal strength gains compared with FWT (SMD = 0.51; 95% CI: 0.23–0.79; GRADE: low). In addition, multiple exercises VRT (SMD = 0.29; 95% CI: 0.12–0.46; GRADE: low) and LVRLP VRT (SMD = 0.39; 95% CI: 0.15–0.63; GRADE: moderate) were also more effective than FWT. No significant differences were found between VRT and FWT in maximal velocity (SMD = 0.33; 95% CI: –1.01 to 0.34; GRADE: very low). As only 3 included studies assessed this outcome, no subgroup or meta-regression analyses were conducted. Regarding maximal

Table 2**Characteristics and measurement criteria of outcome indicators.***

Strength outcome indicators	Intervention type	Measurement criteria
Maximal strength	Long-term intervention	Measure the RM (e.g., 1RM and 2RM) of a specific exercise Force obtained was measured using isokinetic maximum voluntary contraction
	Acute intervention	Measure the force exerted on the force platform during a specific exercise
Maximal velocity	Long-term intervention	Ball throwing velocity measured by infrared-based motion capture system
	Acute intervention	Barbell movement velocity measured by linear position transducer
Explosiveness (maximal power output)	Long-term intervention	Power output measured by jump testing using the established equipment Power output measured using the Wingate test
	Acute intervention	Measured based on the force-velocity relationship with the established equipment
Explosiveness (maximal jump distance)	Long-term intervention	Vertical height or horizontal distance measured by jump test

*RM = repetition maximum.

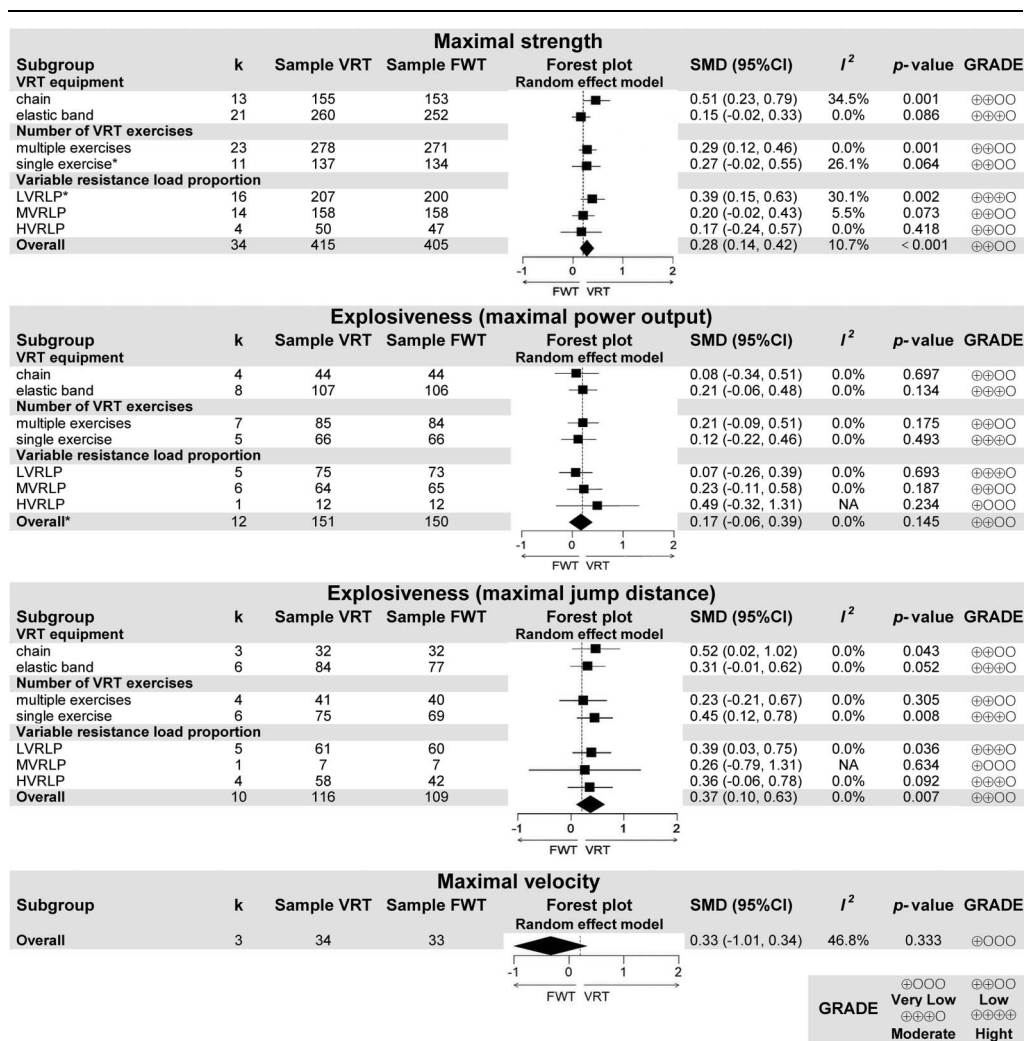


Figure 3. Pairwise meta-analysis forest plot for long-term interventions. All data were calculated based on a random effects model. FWT = free weight training; GRADE = Grading of Recommendations Assessment, Development and Evaluation; HVRLP = variable resistance training is conducted using a high variable resistance load proportion (>37%); k = number of comparisons; LVRLP = variable resistance training is conducted using a low variable resistance load proportion (0–20%); MVRLP = variable resistance training is conducted using a moderate variable resistance load proportion (21–37%); sample = sample size; SMD = standardized mean difference; VRT = variable resistance training; 95% CI = 95% confidence interval; * = publication bias existed in the comparison.

power output, no significant difference was observed between VRT and FWT ($p > 0.05$; GRADE: very low–moderate). With respect to maximal jump distance, VRT remained superior to FWT (SMD = 0.37; 95% CI: 0.10–0.63; GRADE: low). Sub-group analyses indicated that interventions using chains (SMD = 0.52; 95% CI: 0.02–1.02; GRADE: low), using a single-exercise VRT modality (SMD = 0.45; 95% CI: 0.12–0.78; GRADE: moderate), and applying LVRLP (SMD = 0.39; 95% CI: 0.03–0.75; GRADE: moderate), all demonstrated more favorable outcomes than FWT.

None of the long-term intervention comparisons showed high heterogeneity ($I^2 < 75\%$). Publication bias was assessed for comparisons involving 10 or more studies, and sensitivity analysis was subsequently performed based on the results of publication bias assessment. No potential outliers were identified, supporting the robustness of the findings. Detailed publication bias test and sensitivity analysis results can be found in the Supplemental Digital Content (see Table S7–S10, Figure S2–S3, <http://links.lww.com/JSCR/A764>). In addition, meta-regression analysis did not show any moderating effects of subjects' age, intervention duration, or weekly VRT frequency on the differences in intervention effects between VRT and FWT ($p > 0.05$). Detailed meta-regression results can be found in the Supplemental Digital Content (see Table S11–S13, <http://links.lww.com/JSCR/A764>).

Network Meta-analysis of Acute Interventions

All indicators in the network meta-analysis demonstrated good convergence. The trajectory plots of multiple Markov chain Monte Carlo showed that the parameter values stabilized after sufficient iterations, and the posterior distribution density plots were concentrated, indicating stable parameter estimation. In addition, the Gelman-Rubin diagnostic results for each indicator were close to 1, suggesting that the convergence across different chains was consistent. Furthermore, the DIC differences between the consistency and inconsistency models for each network were all less than 5, indicating no global inconsistency. Detailed convergence diagnostics and DIC results of the network meta-analysis are presented in Supplemental Digital Content (see Table S14–S15, Figure S4–S5, <http://links.lww.com/JSCR/A764>).

Figure 4 illustrates the network geometry for each strength outcome, and Figure 5 summarizes the network comparison results. Seven studies were included for the network analysis of maximal strength, involving 30 direct comparisons and 468 samples (referring to the number of data points in each

comparison condition, not the number of independent subjects). Network comparison indicating that under acute intervention, subjects performed better in MVRLP (SMD = 0.46; 95% CrI: 0.01–0.90; GRADE: moderate) and HVRLP (SMD = 0.79; 95% CrI: 0.32–1.24; GRADE: moderate) VRT compared with FWT, whereas HVRLP VRT outperformed LVRLP VRT (SMD = 0.58; 95% CrI: 0.09–1.06; GRADE: moderate). Comparisons between HVRLP VRT and FWT included 6 direct comparisons with 106 samples. Moderate variable resistance load proportion, variable resistance training and free weight training had 7 direct comparisons with 93 samples. High variable resistance load proportion and low variable resistance load proportion, variable resistance training were compared directly in 5 comparisons with 91 samples. For maximal velocity, 7 studies were included, with 30 direct comparisons and 497 samples. Network comparison results revealing that HVRLP VRT performed worse than FWT (SMD = -1.32 ; 95% CrI: -2.45 to -0.17 ; GRADE: moderate), involving 5 direct comparisons with 91 samples. In addition, regarding maximal power output, 5 studies were included, with 25 direct comparisons and 391 samples. Network comparison results for power output are shown with no differences found in the comparisons between intervention methods (95% CrI included zero; GRADE: very low–moderate).

The rankings for each intervention method and its corresponding outcome were derived from the probabilities obtained using stacked rank plots (i.e., a higher probability corresponds to a higher ranking, reflecting greater intervention effectiveness). For maximal strength under acute interventions, the overall rankings from highest to lowest were as follows: HVRLP (95.9%), MVRLP (63.9%), LVRLP (39.9%), and FWT (6.1%). For maximal velocity under acute VRT and FWT interventions, the overall rankings from highest to lowest were as follows: FWT (80.0%), MVRLP (79.1%), LVRLP (35.3%), and HVRLP (5.5%). In maximal power output, the overall rankings from highest to lowest were as follows: FWT (74.7%), MVRLP (68.6%), LVRLP (41.9%), and HVRLP (14.9%). The detailed ranking probabilities of various intervention methods for their corresponding strength outcomes are presented in Figure 6.

After performing sensitivity analysis on comparisons with high heterogeneity ($I^2 > 75\%$), it was found that in the acute intervention for maximal power output, the comparison between HVRLP and FWT showed outliers in 2 instances (40,67). Detailed details are provided in Supplemental Digital Content (see Table S16–S26, <http://links.lww.com/JSCR/A764>). After excluding these outliers and reconducting the network meta-

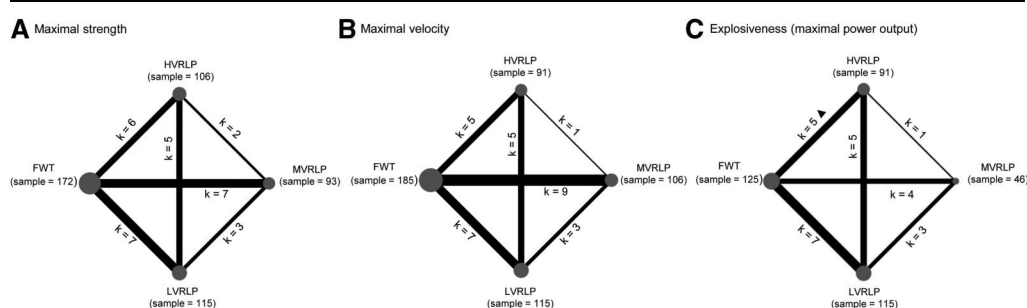


Figure 4. Network geometry for acute interventions. FWT = free weight training; HVRLP = variable resistance training is conducted using a high variable resistance load proportion (>37%); k = number of comparisons; LVRLP = variable resistance training is conducted using a low variable resistance load proportion (0–20%); MVRLP = variable resistance training is conducted using a moderate variable resistance load proportion (21–37%); VRT = variable resistance training; sample = sample size; ▲ = comparison includes outliers in the sensitivity analysis.

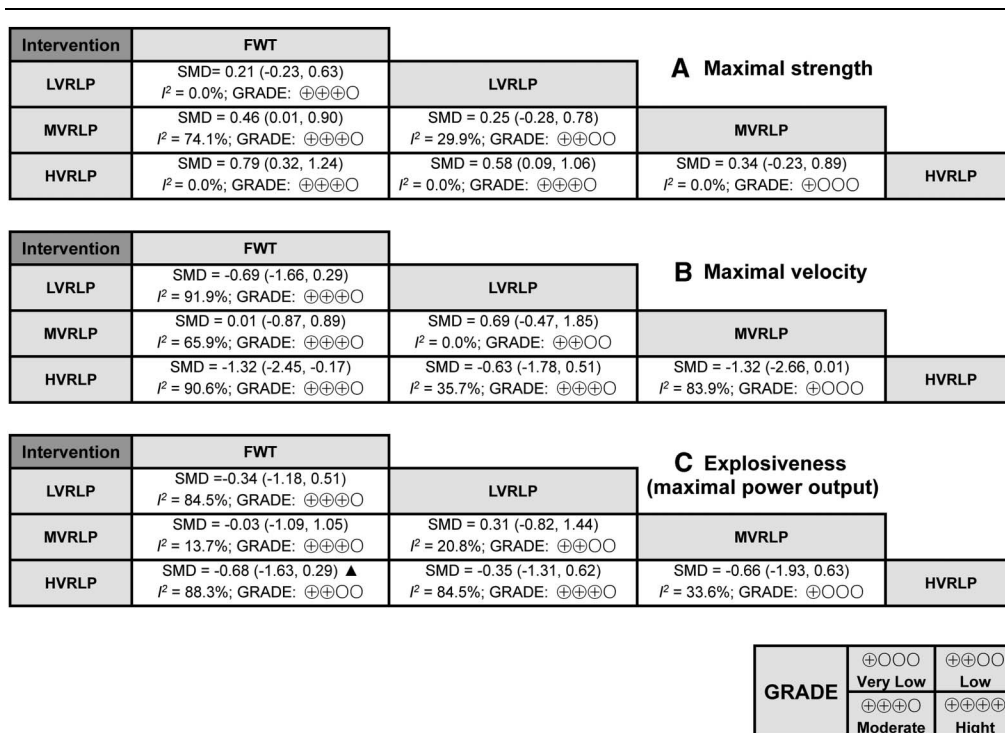


Figure 5. Network comparison results for acute interventions. All data were calculated based on a random effects model. FWT = free weight training; GRADE = Grading of Recommendations Assessment, Development and Evaluation; HVRLP = variable resistance training is conducted using a high variable resistance load proportion (>37%); LVRLP = variable resistance training is conducted using a low variable resistance load proportion (0–20%); MVRLP = variable resistance training is conducted using a moderate variable resistance load proportion (21–37%); sample = sample size; SMD = standardized mean difference; VRT = variable resistance training; ▲ = comparison includes outliers in the sensitivity analysis.

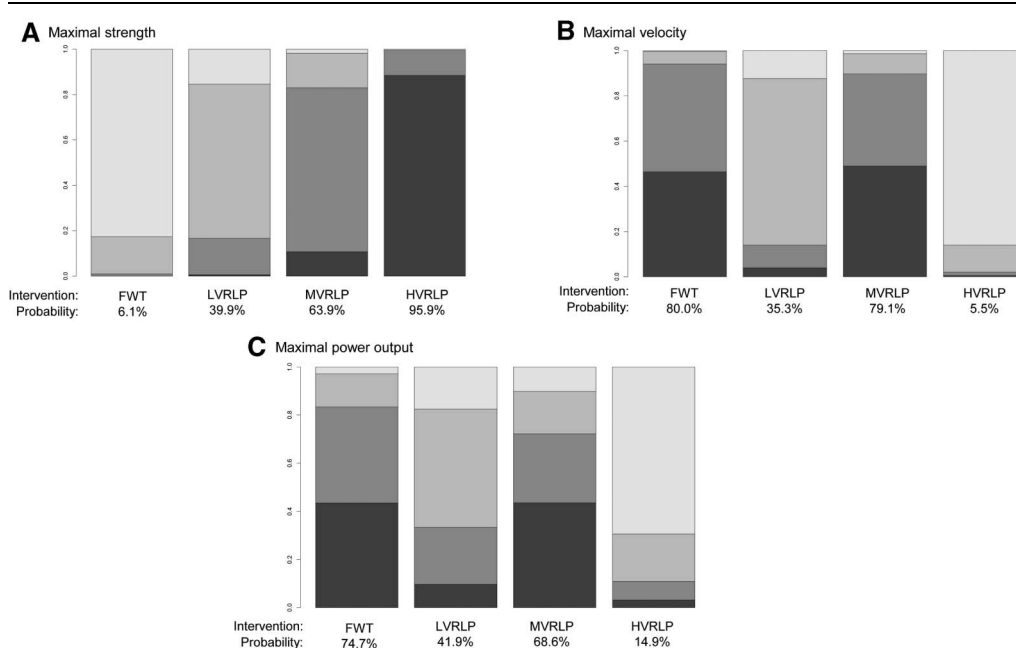


Figure 6. Ranking chart of the network meta-analysis of acute intervention. FWT = free weight training; HVRLP = variable resistance training is conducted using a high variable resistance load proportion (>37%); LVRLP = variable resistance training is conducted using a low variable resistance load proportion (0–20%); MVRLP = variable resistance training is conducted using a moderate variable resistance load proportion (21–37%); VRT = variable resistance training.

analysis for power output, the adjusted results revealed that acute maximal power output under HVRLP VRT was worse than FWT (SMD = -1.31 ; 95%: -2.41 to -0.23 ; GRADE: moderate). The VRT and FWT treatment ranking probabilities were, in descending order: FWT (76.4%), MVRLP (76.2%), LVRLP (45.1%), and HVRLP (2.4%). The adjusted network meta-analysis results of power output are provided in Supplemental Digital Content (see Figure S6–S8, <http://links.lww.com/JSCR/A764>).

Discussion

This study used pairwise and network meta-analyses to compare the effects of long-term and acute VRT versus FWT on maximal strength, maximal velocity, and explosiveness. To focus on multi-joint exercises, studies involving single-joint or fixed-path machines were excluded. In long-term interventions (≥ 3 weeks) (4), VRT led to greater improvements in maximal strength and jump distance compared with FWT—particularly with chain-based and LVRLP protocols. Notably, VRT protocols incorporating multiple exercises further enhanced maximal strength gains, whereas single-exercise protocols were more effective for improving maximal jump distance. In acute interventions, both HVRLP and MVRLP VRT produced greater maximal strength than FWT, although HVRLP impaired maximal velocity and power output.

Pairwise meta-analysis of long-term VRT showed that VRT elicited significantly greater maximal strength gains than FWT (SMD = 0.28), a finding that is consistent with Andersen et al. (6). Compared with FWT, VRT provides more biomechanically appropriate dynamic loading by reducing resistance at mechanically disadvantaged positions and increasing it where mechanical advantage is greater (4,16,38). This facilitates passage through sticking points, thereby enhancing muscle recruitment at specific joint angles and during particular phases of contraction (3,5,25). For example, during the concentric phase, muscle activation elicited by VRT squats is greater than that of FWT (67). In addition, long-term VRT has been shown to increase quadriceps activation by 15% at a 60° knee angle (1). Collectively, these findings suggest that enhanced neuromuscular recruitment underlies the superior maximal strength adaptations produced by VRT and underscore the greater potential of long-term VRT to improve muscle activation. Our analysis revealed that chain-based VRT produced larger maximal-strength gains than FWT (SMD = 0.51), further supporting the recommendations proposed by Saeterbakken et al. (56) in their research. The advantage is likely because of the resistance profile of chains, which better matches the human strength curve than elastic bands and therefore helps subjects work through the sticking point. It is likely that, compared with elastic bands, chain-based VRT more effectively enhances coordination among muscle groups (e.g., agonists, synergists, and stabilizers), improving the trainee's control of the load throughout the entire movement and, over time, leading to superior maximal strength development (38,39,56). Moreover, long-term VRT interventions using multiple exercises consistently yielded superior maximal strength improvements over FWT (SMD = 0.29), a finding that aligns with Joy et al. (32). A plausible explanation is that VRT raises the load as the lever arm shortens, producing high muscle tension throughout the lift—unlike free weights, where tension drops in the second half. That sustained tension heightens type II fiber loading and time-under-tension, accelerating hypertrophy and maximal strength;

multiple exercises VRT modes in multi-joint training amplifies the effect (32,52,73). In the context of VRLP, long-term interventions using LVRLP for VRT demonstrated superior maximal strength improvements compared with FWT (SMD = 0.39), a finding that is consistent with Pan et al. (51). In contrast, when long-term VRT uses an excessive VRLP, McCurdy et al. (49) suggested that using chains to constitute 80% of the VRLP in the bench press led to greater improvements in 1RM in the chain-resisted (barbell combined with chains) bench press. However, no significant difference was found in free-weight 1RM compared with FWT. Combined with the findings of our study, it can be concluded that using a HVRLP VRT produces excessively large fluctuations in resistance, leading to biomechanical characteristics that diverge too greatly from those in FWT. In contrast, LVRLP VRT retains a substantial proportion of free-weight loading while still introducing dynamic resistance, thereby facilitating better transfer of maximal strength gains from VRT to FWT than HVRLP VRT (6,31,67). Collectively, these findings corroborate our initial hypothesis that VRT is superior to FWT in improving maximal strength. Furthermore, different VRT design variables modulate the extent of this beneficial effect during long-term training.

However, during acute interventions, subjects generated greater maximal force output during exercise with MVRLP and HVRLP VRT compared with FWT ($0.46 \leq \text{SMD} \leq 0.79$). The differences in these results may be attributed to load variations within VRT. During acute interventions, HVRLP VRT induces larger load fluctuations than both LVRLP VRT and FWT, delivering higher muscle stimulation at specific angles and eliciting greater muscle activation. This likely activates more muscle fibers, particularly high-threshold fast-twitch fibers, resulting in higher maximal force output in a single training session (65,67). Consequently, although high load variability can enhance force output and muscle activation in acute training, prolonged exposure to excessive VRLP without integration with the biomechanical characteristics of actual movement may not enhance of long-term training adaptations.

Regarding maximal velocity, long-term VRT did not demonstrate a statistically significant advantage over FWT ($p = 0.333$) (22,77), a result that contrasts with our initial hypothesis. It has been suggested that, although overall maximal velocity gains may be comparable, VRT can confer greater enhancement at specific movement phases—e.g., after long-term VRT, concentric-phase maximal velocity during subsequent FWT may be superior (65). Rivi re et al. (54) observed that elite junior rugby players who completed 6 weeks of VRT at 20% VRLP experienced greater increases in barbell bench-press maximal velocity at both 75 and 85% 1RM compared with FWT, suggesting a potential advantage of VRT for maximal velocity development. However, there remains a paucity of research examining whether VRT can similarly enhance maximal velocity in healthy adult populations. Future investigations should therefore evaluate the effects of VRT on maximal velocity across different exercises, movement phases, and athletic disciplines in healthy adults while also probing the underlying mechanisms.

In acute interventions under equal loads, HVRLP VRT produced lower maximal velocity than FWT (SMD = -1.32). Notably, this conclusion exhibits a high level of heterogeneity ($I^2 = 90.6\%$), which can be explained by the choice of VRT equipment. Swinton et al. (74) found that when chains were used in VRT, an increase in VRLP led to a decrease in maximal velocity during training. In contrast, this negative impact on maximal velocity was not observed in other studies using elastic bands for VRT (40,67). Chains differ from elastic bands, which generate

resistance solely through elastic deformation; chains have both mass and inertia (50). Each chain link must be accelerated from rest to barbell velocity, resulting in additional momentum changes and resistance. When using chains for VRT, as VRLP increases, the inertia of the chain that the trainee must overcome also increases (56). At the same time, as the chain is lifted off the ground, it begins to swing, and the trainee may need to reduce movement velocity to maintain stability (50). The impact of the swinging chains may also increase as VRLP rises. However, there is currently a lack of acute experimental research that simultaneously investigates the effects of both VRLP and VRT equipment. Future research should further explore the potential impact of these 2 factors on various strength outcomes. Coaches should also consider the balance between strength, VRLP, and VRT equipment in training to maximize benefits.

Although long-term VRT did not produce significantly greater maximal power output improvements than FWT ($p = 0.145\text{--}0.697$), network meta-analysis of acute intervention—after excluding outliers—revealed that HVRLP VRT acutely impairs maximal power output ($SMD = -1.31$). Not only do these findings support the perspective of Wallace et al. (78), but the collective evidence from acute interventions also corroborates the hypothesis that varying VRLP strategies differentially influence strength outcomes. The reason may be that, although HVRLP VRT produces greater maximal force output, it does not fully compensate for the reduced maximal velocity and the technical deviations caused by large load fluctuations throughout the movement. Shi et al. (65) reported in their meta-regression of acute interventions that, when VRT and FWT loads were equated, VRLP positively moderated maximal power output. However, most of the data points they included fell within a 0–37% VRLP range, with only one exceeding that threshold, leaving the effects of HVRLP (>37%) underexplored. In our study, the cumulative ranking analysis showed that VRT using the MVRLP protocol ranked higher than the LVRLP protocol for maximal power output. Although no statistically significant difference emerged between the MVRLP and LVRLP protocols for acute maximal power output, the effect sizes still favored MVRLP (before outlier removal: $SMD = 0.31$; after outlier removal: $SMD = 0.39$). These observations are not contradictory to the findings by Shi et al.; rather, they suggest that the relationship between VRLP and acute maximal power output in acute interventions is not strictly linear. Taken together, existing evidence shows a positive influence of VRLP on acute maximal power output within the 0–37% range, whereas excessively high VRLP (>37%) seems to reverse this effect (20,40,65,74,78).

Long-term VRT offers greater improvements in maximal jump distance compared with FWT ($SMD = 0.37$). Subgroup analyses further demonstrated that chain-based VRT, single-exercise VRT, and LVRLP VRT each produced superior maximal jump distance gains compared with FWT ($0.39 \leq SMD \leq 0.52$), which is consistent with our initial hypothesis. This may stem from the variable resistance in VRT, which can further optimize force transmission between the limbs and the trunk—compared with FWT—thereby enhancing maximal jump distance. By mimicking the terminal take-off phase, lower limb VRT optimizes the stretch-shortening cycle, thereby enhancing the maximal force output and velocity (37,66). Regarding number of VRT exercises, targeted single-exercise VRT protocols conferred larger maximal jump distance improvements ($SMD = 0.45$), suggesting that focusing on one VRT movement alongside complementary plyometrics is most effective; incorporating too many VRT exercises may introduce unnecessary fatigue and yield diminishing returns in maximal jump distance (66,73). In VRT equipment and VRLP, the mechanism by which

chain-based VRT enhances maximal jump distance is linked to the mechanisms previously discussed for improving maximal strength and velocity (56,74). Specifically, the use of chains may enhance intermuscular coordination, whereas their inertial characteristics require subjects to overcome resistance in a way that mimics the static inertia encountered in actual jumps (50,56,74). Notably, among the studies included in the analysis of this strength outcome, those implementing chain-based VRT used a VRLP range of 12.5–20% (7,9,31). This suggests that lowering VRLP may help avoid the acute negative effects on maximal velocity while simultaneously capitalizing on the inertial properties of chains to maximize improvements in jump distance (74). Furthermore, excessively VRLP (>37%), regardless of VRT equipment type, may all disrupt maximal power output sequencing and movement stability. Collectively, these findings indicate that VRT with VRLP below 20% achieved the greatest maximal jump distance gains ($SMD = 0.39$) (29,33).

Despite comparing VRT and FWT across the dimensions of maximal strength, maximal velocity, and explosiveness, the present study did not conduct an in-depth analysis of distinct movement phases—such as the sticking point and various muscle contraction stages—and the various strength outcomes within these phases may be influenced by factors such as training method, subjects' training status, and individual anatomical characteristics (65,67). Future research should use high precision data capture technologies to explore these temporal performance patterns.

Moreover, although VRLP was clustered into discrete ranges and evaluated by paired and network meta-analyses in both acute and long-term contexts, this approach only yields relative VRLP intervals. Given that the relationship between VRLP and strength enhancements seems nonlinear and may be moderated by factors including exercise selection (5,6,56), overall training intensity, subject sex, training experience, and joint structure. Future meta-analyses should adopt multivariate random-effects model and nonlinear meta-regression models to pinpoint optimal VRT parameters across multiple strength outcome (65,75). In long-term interventions, there are currently few studies directly comparing different VRLP within VRT protocols (51). The current research remains largely focused on comparing the long-term effects of VRT versus FWT. Further investigations are needed to explore the comparative efficacy of various VRT protocols, to optimize and refine training program design. In addition, future research should compare VRT and FWT for enhancing sprint time, muscular endurance, muscle activation levels, and other relevant metrics; evaluate VRT's efficacy and implementation as a postactivation performance enhancement protocol; and explore its impact across various populations and sports. Such work will reinforce VRT's theoretical foundation and practical value in training (51,63,68,79).

Practical Applications

This study demonstrates that when coaches use VRT as a long-term intervention, subjects achieve greater gains in maximal strength and vertical jump distance compared with traditional FWT at the equal load. Improvements in maximal velocity and power output, however, are comparable between VRT and FWT. Moreover, the type of VRT equipment, the number of VRT exercises, and the VRLP all influence the long-term effectiveness of VRT. For enhancing maximal strength and jump distance, we recommend coaches prioritize chains as the source of variable resistance and combine VRT with free weights using a VRLP of $\leq 20\%$. Regarding number of VRT exercises, a multiple and diverse array of VRT exercise is

advised to develop maximal strength, whereas a single and targeted VRT exercise is preferable for targeting maximal jump distance. When VRT is applied as an acute intervention, subjects' maximal strength, velocity, and power output are all affected by VRLP. As VRLP increases, acute maximal strength during VRT gradually rises; when VRLP exceeds 20%, VRT yields higher acute maximal strength levels than FWT under equal load. Increases in VRLP within the 0–37% range positively enhance acute velocity and power output. However, when VRLP surpasses 37%, excessive load fluctuation may lead to declines in maximal velocity and power output below those achieved with FWT at equal load. This phenomenon may occur more frequently during chain-based VRT because subjects must overcome the additional challenges posed by chain inertia and swing during the movement. In contrast to excessively high VRLP, low or moderate VRLP may help avoid this negative effect. Taken together, we suggest that coaches set VRLP between 21 and 37% when using VRT for acute interventions to best support greater mechanical output.

Acknowledgments

Author contributions: J. Li came up with the research idea, wrote the article and data analysis; J. Li, Z. Chen, K. Xu, M. Gong and Y. Wang searched the literature, extracted the data, and corrected it; J. Li, Z. Chen, and M. Gong contributed to the conception of the study and helped further revise the article. All authors contributed to the article and approved the submitted version. All authors received no external financial support.

References

- Andersen V, Fimland MS, Kolnes MK, Saeterbakken AH. Elastic bands in combination with free weights in strength training: Neuromuscular effects. *J Strength Cond Res* 29: 2932–2940, 2015.
- Andersen V, Fimland MS, Mo D-A, et al. Electromyographic comparison of the barbell deadlift using constant versus variable resistance in healthy, trained men. *PLoS One* 14: e0211021, 2019.
- Andersen V, Pedersen H, Fimland MS, et al. Acute effects of elastic bands as resistance or assistance on EMG, kinetics, and kinematics during deadlift in resistance-trained men. *Front Sports Act Living* 2: 598284, 2020.
- Andersen V, Prieske O, Stien N, et al. Comparing the effects of variable and traditional resistance training on maximal strength and muscle power in healthy adults: A systematic review and meta-analysis. *J Sci Med Sport* 25: 1023–1032, 2022.
- Andersen V, Steiro Fimland M, Knutson Kolnes M, et al. Electromyographic comparison of squats using constant or variable resistance. *J Strength Cond Res* 30: 3456–3463, 2016.
- Anderson CE, Sforzo GA, Sigg JA. The effects of combining elastic and free weight resistance on strength and power in athletes. *J Strength Cond Res* 22: 567–574, 2008.
- Arazi H, Mohammadi M, Asadi A, Nunes JP, Haff GG. Comparison of traditional and accommodating resistance training with chains on muscular adaptations in young men. *J Sports Med Phys Fitness* 62: 258–264, 2022.
- Arazi H, Salek L, Nikfal E, et al. Comparable endocrine and neuromuscular adaptations to variable vs. constant gravity-dependent resistance training among young women. *J Transl Med* 18: 239, 2020.
- Ataee J, Koozehchian MS, Kreider RB, Zuo L. Effectiveness of accommodation and constant resistance training on maximal strength and power in trained athletes. *PeerJ* 2: e441, 2014.
- Baz-Valle E, Fontes-Villalba M, Santos-Concejero J. Total number of sets as a training volume quantification method for muscle hypertrophy: A systematic review. *J Strength Cond Res* 35: 870–878, 2021.
- Bellar DM, Muller MD, Barkley JE, et al. The effects of combined elastic and free-weight tension vs. free-weight tension on one-repetition maximum strength in the bench press. *J Strength Cond Res* 25: 459–463, 2011.
- Burnham TR, Ruud JD, McGowan R. Bench press training program with attached chains for female volleyball and basketball athletes. *Percept Mot Skills* 110: 61–68, 2010.
- Cashin AG, McAuley JH. Clinimetrics: Physiotherapy evidence database (PEDro) scale. *J Physiother* 66: 59, 2020.
- Cumpston M, Li T, Page MJ, et al. Updated guidance for trusted systematic reviews: A new edition of the Cochrane handbook for systematic reviews of interventions. *Cochrane Database Syst Rev* 10: ED000142, 2019.
- Currier BS, Mcleod JC, Banfield L, et al. Resistance training prescription for muscle strength and hypertrophy in healthy adults: A systematic review and Bayesian network meta-analysis. *Br J Sports Med* 57: 1211–1220, 2023.
- Dai J, Liang X, Wang H, et al. The effect of elastic band variable resistance training on the explosive power of lower limbs in college basketball athletes. *J Strength Cond Res* 39: e1003–e1009, 2025.
- Drevon D, Fursa SR, Malcolm AL. Intercoder reliability and validity of WebPlotDigitizer in extracting graphed data. *Behav Modif* 41: 323–339, 2017.
- Egger M, Davey Smith G, Schneider M, Minder C. Bias in meta-analysis detected by a simple, graphical test. *BMJ* 315: 629–634, 1997.
- Ferris J, Fiedelley LK, Kim B, et al. Systematic review and meta-analysis of disease clustering in multimorbidity: A study protocol. *BMJ Open* 13: e076496, 2023.
- Galpin AJ, Malyszczek KK, Davis KA, et al. Acute effects of elastic bands on kinetic characteristics during the deadlift at moderate and heavy loads. *J Strength Cond Res* 29: 3271–3278, 2015.
- García-López D, Hernández-Sánchez S, Martín E, et al. Free-weight augmentation with elastic bands improves bench press kinematics in professional rugby players. *J Strength Cond Res* 30: 2493–2499, 2016.
- Ghigiarelli JJ, Nagle EF, Gross FL, et al. The effects of a 7-week heavy elastic band and weight chain program on upper-body strength and upper-body power in a sample of Division 1-AA football players. *J Strength Cond Res* 23: 756–764, 2009.
- Gray K, Hampton B, Silveti-Falls T, McConnell A, Bausell C. Comparison of Bayesian credible intervals to frequentist confidence intervals. *J Mod Appl Stat Methods* 14: 43–52, 2015.
- Greenland S. Quantitative methods in the review of epidemiologic literature. *Epidemiol Rev* 9: 1–30, 1987.
- Heelas T, Theis N, Hughes JD. Muscle activation patterns during variable resistance deadlift training with and without elastic bands. *J Strength Cond Res* 35: 3006–3011, 2021.
- Higgins JPT, Thompson SG. Quantifying heterogeneity in a meta-analysis. *Stat Med* 21: 1539–1558, 2002.
- Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc* 41: 3–13, 2009.
- Huo Z, Ding Y, Liu S, Oesterreich S, Tseng G. Meta-analytic framework for sparse k-means to identify disease subtypes in multiple transcriptomic studies. *J Am Stat Assoc* 111: 27–42, 2016.
- Impellizzeri FM, McCall A, Ward P, Bornn L, Coutts AJ. Training load and its role in injury prevention, part 2: Conceptual and methodologic pitfalls. *J Athl Train* 55: 893–901, 2020.
- Israetel MA, McBride JM, Nuzzo JL, Skinner JW, Dayne AM. Kinetic and kinematic differences between squats performed with and without elastic bands. *J Strength Cond Res* 24: 190–194, 2010.
- Izadi M, Arazi H, Ramirez-Campillo R, Mirzaei M, Saidie P. In-season in-field variable resistance training: Effects on strength, power, and anthropometry of junior soccer players. *J Sports Med Phys Fitness* 60: 220–228, 2020.
- Joy JM, Lowery RP, Oliveira De Souza E, Wilson JM. Elastic bands as a component of periodized resistance training. *J Strength Cond Res* 30: 2100–2106, 2016.
- Jukic I, Castilla AP, Ramos AG, et al. The acute and chronic effects of implementing velocity loss thresholds during resistance training: A systematic review, meta-analysis, and critical evaluation of the literature. *Sports Med* 53: 177–214, 2023.
- Kashiani AB, Geok SK. Comparison between two methods of variable resistance training on body composition, muscular strength and functional capacity among untrained males. *Malaysian J Mov Health Exerc* 9: 45–66, 2020.
- Kassiano W, Nunes JP, Costa B, et al. Does varying resistance exercises promote superior muscle hypertrophy and strength gains? A systematic review. *J Strength Cond Res* 36: 1753–1762, 2022.
- Katushabe ET, Kramer M. Effects of combined power band resistance training on sprint speed, agility, vertical jump height and strength in collegiate soccer players. *Int J Exerc Sci* 13: 950–963, 2020.

37. Komi PV. Physiological and biomechanical correlates of muscle function: Effects of muscle structure and stretch-shortening cycle on force and speed. *Exerc Sport Sci Rev* 12: 81–121, 1984.
38. Kompf J, Arandjelović O. Understanding and overcoming the sticking point in resistance exercise. *Sports Med* 46: 751–762, 2016.
39. Kompf J, Arandjelović O. The sticking point in the bench press, the squat, and the deadlift: Similarities and differences, and their significance for research and practice. *Sports Med* 47: 631–640, 2017.
40. Kubo T, Hirayama K, Nakamura N, Higuchi M. Effect of accommodating elastic bands on mechanical power output during back squats. *Sports* 6: 151, 2018.
41. Kung J. Polyglot search translator. *J Can Health Libr Assoc* 43: 35–39, 2022.
42. Liang Z, Zhang M, Wang C, et al. The best exercise modality and dose to reduce glycosylated hemoglobin in patients with type 2 diabetes: A systematic review with pairwise, network, and dose–response meta-analyses. *Sports Med* 54: 2557–2570, 2024.
43. Lin Y, Xu Y, Hong F, et al. Effects of variable-resistance training versus constant-resistance training on maximum strength: A systematic review and meta-analysis. *Int J Environ Res Public Health* 19: 8559, 2022.
44. Liu Y, Huang Z, Zhou Z, et al. Effects of variable resistance training within complex training on strength and punch performance in elite amateur boxers. *Front Physiol* 15: 1472258, 2024.
45. Lixandão ME, Ugrinowitsch C, Berton R, et al. Magnitude of muscle strength and mass adaptations between high-load resistance training versus low-load resistance training associated with blood-flow restriction: A systematic review and meta-analysis. *Sports Med* 48: 361–378, 2018.
46. Lopes JSS, Machado AF, Micheletti JK, et al. Effects of training with elastic resistance versus conventional resistance on muscular strength: A systematic review and meta-analysis. *SAGE Open Med* 7: 2050312119831116, 2019.
47. Lopez P, Radaelli R, Taaffe DR, et al. Resistance training load effects on muscle hypertrophy and strength gain: Systematic review and network meta-analysis. *Med Sci Sports Exerc* 53: 1206–1216, 2021.
48. Marrier B, Le Meur Y, Leduc C, et al. Training periodization over an elite rugby sevens season: From theory to practice. *Int J Sports Physiol Perform* 14: 113–121, 2019.
49. McCurdy K, Langford G, Ernest J, Jenkerson D, Doscher M. Comparison of chain- and plate-loaded bench press training on strength, joint pain, and muscle soreness in Division II baseball players. *J Strength Cond Res* 23: 187–195, 2009.
50. McMaster DT, Cronin J, McGuigan MR. Quantification of rubber and chain-based resistance modes. *J Strength Cond Res* 24: 2056–2064, 2010.
51. Pan C, Li W, Su Y, Shi Y. Effects of variable resistance training with different load ratios on lower-limb strength and power in male college students. *J Exerc Sci Fitness* 23: 181–189, 2025.
52. Parten AL, Barker GA, O’Neal EK, Waldman HS. Seven-week accommodating resistance training improves Wingate peak power but not muscular strength or endurance in strength-trained females. *J Strength Cond Res* 37: 1789–1794, 2023.
53. Rhea MR, Kenn JG, Dermody BM. Alterations in speed of squat movement and the use of accommodated resistance among college athletes training for power. *J Strength Cond Res* 23: 2645–2650, 2009.
54. Rivière M, Louit L, Strokosch A, Seitz LB. Variable resistance training promotes greater strength and power adaptations than traditional resistance training in elite youth rugby league players. *J Strength Cond Res* 31: 947–955, 2017.
55. Rouse B, Chaimani A, Li T. Network meta-analysis: An introduction for clinicians. *Int Emerg Med* 12: 103–111, 2017.
56. Saeterbakken AH, Andersen V, van den Tillaar R. Comparison of kinematics and muscle activation in free-weight back squat with and without elastic bands. *J Strength Cond Res* 30: 945–952, 2016.
57. Sawyer J, Higgins P, Cacoliche PA, Doming T. Bilateral back squat strength is increased during a 3-week undulating resistance training program with and without variable resistance in DIII collegiate football players. *PeerJ* 9: e12189, 2021.
58. Schick EE, Coburn JW, Brown LE, et al. A comparison of muscle activation between a smith machine and free weight bench press. *J Strength Cond Res* 24: 779–784, 2010.
59. Schoenfeld BJ. The mechanisms of muscle hypertrophy and their application to resistance training. *J Strength Cond Res* 24: 2857–2872, 2010.
60. Schünemann HJ, Higgins JP, Vist GE, et al. Completing “Summary of findings” tables and grading the certainty of the evidence. *Cochrane Handbook Syst Rev Inter* 14: 375–402, 2019.
61. Schwanbeck S, Chilibeck PD, Binsted G. A comparison of free weight squat to Smith machine squat using electromyography. *J Strength Cond Res* 23: 2588–2591, 2009.
62. Schwanbeck SR, Cornish SM, Barss T, Chilibeck PD. Effects of training with free weights versus machines on muscle mass, strength, free testosterone, and free cortisol levels. *J Strength Cond Res* 34: 1851–1859, 2020.
63. Scott DJ, Ditroilo M, Marshall P. Effect of accommodating resistance on the postactivation potentiation response in rugby league players. *J Strength Cond Res* 32: 2510–2520, 2018.
64. Scott DJ, Ditroilo M, Orange ST, Marshall P. The effect of complex training on physical performance in rugby league players. *Int J Sports Physiol Perform* 18: 240–247, 2023.
65. Shi L, Cai Z, Chen S, Han D. Acute effects of variable resistance training on force, velocity, and power measures: A systematic review and meta-analysis. *PeerJ* 10: e13870, 2022.
66. Shi L, Lyons M, Duncan M, et al. Effects of variable resistance training within complex training on neuromuscular adaptations in collegiate basketball players. *J Hum Kinet* 84: 174–183, 2022.
67. Shi L, Lyons M, Duncan M, et al. Kinetics, kinematics, and muscle activity patterns during back squat with different contributions of elastic resistance. *Int J Sports Physiol Perform* 19: 921–931, 2024.
68. Shi L, Ye X, Han D, Yang C, Tu Y. Acute effects of back squat combined with different elastic band resistance on vertical jump performance in collegiate basketball players. *J Sports Sci Med* 22: 502–511, 2023.
69. Shoepe T, Ramirez D, Rovetti R, Kohler D, Almstedt H. The effects of 24 weeks of resistance training with simultaneous elastic and free weight loading on muscular performance of novice lifters. *J Hum Kinet* 29: 93–106, 2011.
70. Smoak Y. Effects of free-weight with and without elastic band tension on upper-body strength and muscular endurance: A randomized parallel trial. *J Strength Perform* 1(1), 2022. doi:10.21428/6404b16e.0b7e2b05.
71. Sousa H, Abade E, Maia F, Costa JA, Marcelino R. Acute and chronic effects of elastic band resistance training on athletes’ physical performance: A systematic review. *Sport Sci Health* 21: 69–82, 2025.
72. Sterne JAC, Savović J, Page MJ, et al. RoB 2: A revised tool for assessing risk of bias in randomised trials. *BMJ* 366: 14898, 2019.
73. Swinton PA, Schoenfeld BJ, Murphy A. Dose–response modelling of resistance exercise across outcome domains in strength and conditioning: A meta-analysis. *Sports Med* 54: 1579–1594, 2024.
74. Swinton PA, Stewart AD, Keogh JW, Agouris I, Lloyd R. Kinematic and kinetic analysis of maximal velocity deadlifts performed with and without the inclusion of chain resistance. *J Strength Cond Res* 25: 3163–3174, 2011.
75. Thompson SG, Higgins JPT. How should meta-regression analyses be undertaken and interpreted? *Stat Med* 21: 1559–1573, 2002.
76. van den Tillaar R, Saeterbakken AH, Andersen V. The acute effects of attaching chains to the barbell on kinematics and muscle activation in bench press in resistance-trained men. *J Funct Morphol Kinesiol* 7: 39, 2022.
77. Vojinovic A, Janicijevic D, Petrovic MR, et al. Free weight training vs. elastic band training: What is a more effective strategy for increasing maximal velocity ability during handball throws? *Kinesiology* 55: 21–29, 2023.
78. Wallace BJ, Winchester JB, McGuigan MR. Effects of elastic bands on force and power characteristics during the back squat exercise. *J Strength Cond Res* 20: 268–272, 2006.
79. Xu K, Blazeovich AJ, Boullosa D, et al. Optimizing post-activation performance enhancement in athletic tasks: A systematic review with meta-analysis for prescription variables and research methods. *Sports Med* 55: 977–1008, 2025.