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RESEARCH

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A meta-analysis of the effects of plyometric training on muscle strength and power in martial arts athletes

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Abstract

Background Plyometric training (PT) was explored as an effective intervention for enhancing muscle strength and power. However, its specific impact on these attributes in martial arts athletes had not been systematically evaluated. Therefore, the objective of this meta-analysis was to provide a quantitative assessment of the impact of PT on muscle strength and power in martial arts athletes. Additionally, it aimed to investigate potential moderators that could influence this relationship.

Methods A systematic literature search was conducted across several databases, including SPORTDiscus, PubMed, CNKI, Scopus, and Web of Science Core Collection. Studies were included if they were controlled trials that examined the effects of PT on measures of muscle strength and/or muscle power in martial arts athletes. Effect sizes (ESs) were calculated using a random-effects model based on weighted and averaged standardized mean differences. Moderator analyses were performed for variables related to age and training. The ROB2 and ROBINS-I tools were used to assess the methodological quality of the included studies. Publication bias was evaluated using funnel plots and the extended Egger's test.

Results The analysis included fifteen studies with a total of 499 participants aged 12 to 24 years. The findings indicated that PT had a small-to-moderate effect on muscle strength (ES = 0.62; 95% CI = 0.38 to 0.87, $p < 0.001$) and power (ES = 0.45; 95% CI = 0.20 to 0.71, $p = 0.001$). Furthermore, neither age nor training parameters significantly moderated the effect of PT on muscle strength and power.

Conclusions The findings of the present study indicated that PT effectively enhanced muscle strength and power in martial arts athletes. However, additional trials are recommended to determine the optimal training doses and further explore the interactions among training variables to improve muscle strength and power in these athletes.

Trial registration https//www.crd.york.ac.uk/prospero/display_record.php? Record ID = 579,901, identifier CRD42024579901.

Keywords Stretch-shortening cycle, Vertical jump, Taekwondo, Karate, Combat sports

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Background

Martial arts refer to athletic activities governed by specific rules, involving striking, kicking, and/or grappling, where participants aim to physically overcome their opponents while avoiding defeat [1]. Athletes in martial arts are typically trained to balance power and muscle recruitment, a concept known as muscular optimization [2]. Muscle strength and power are essential for achieving success in martial arts. For example, in taekwondo, variations in kicking techniques and movement speed play a significant role in performance, emphasizing the need to develop hip and lower-extremity strength to enhance attack power and speed [3]. Research indicates that well-developed muscular strength and power, particularly in the limbs, are crucial for successful karate performance [4, 5]. Furthermore, leg muscle power is a key factor in determining the effectiveness of a sickle kick in Silat athletes [6].

The primary goal of sports performance professionals is to enhance athletic performance, and plyometric training (PT) is one of the most widely used methods to achieve this [7–10]. PT typically includes exercises such as jumping, hopping, and skipping, which promote robust muscle activities through dynamic movements [11]. These exercises utilize the stretch-shortening cycle, involving a rapid muscle stretch followed by an explosive contraction [12]. Physiologically, PT leverages this cycle, where a powerful concentric contraction immediately follows a high-intensity eccentric contraction [13]. This type of training induces various physiological and biomechanical adaptations, including increased motor unit recruitment, a higher rate of force development, enhanced neuromuscular coordination, improved muscle fiber hypertrophy, and greater tendon stiffness [11, 14]. Consequently, numerous studies highlight PT's effectiveness in improving muscle strength and power [15–18].

Researchers have recognized the benefits of PT, leading to the publication of numerous systematic reviews and meta-analyses. These works provide evidence of PT's effectiveness in improving strength and power attributes across various sports disciplines, including soccer [19], handball [20], tennis [21], badminton [22], basketball [23], and volleyball [24]. Despite this extensive research, there is a notable absence of systematic reviews or meta-analyses focusing on the effects of PT on muscle strength and power in martial arts athletes, indicating a gap in the current literature. To address this, a meta-analysis is needed. The primary objective of this meta-analysis is to estimate the effect size (ES) of PT on muscle strength and power in martial arts athletes, while also examining potential moderators, such as age, sex, and key intervention variables (e.g., training duration and frequency).

Table 1 Eligibility criteria according to the PICOS conditions

Category	Inclusion criteria	Exclusion criteria
Population	Healthy male or female martial arts athletes	Participants from other sports
Intervention type	Plyometric training, with a minimum duration of two weeks	Intervention not involving plyometric exercises
Comparator	Active control group	No control or passive control group
Outcome	Included outcome measurements for muscle strength and/or muscle power	The data were not reported in means and standard deviations for the intervention and control groups at pre- and post-test
Study design	Controlled study	Case study, observational study

Methods

This meta-analysis was registered in PROSPERO (CRD42024579901) and conducted following the latest PRISMA guidelines [25].

Search strategy

Five electronic databases (SPORTDiscus, PubMed, CNKI, Scopus, and Web of Science Core Collection) were systematically searched to identify eligible studies from the earliest available records up to August 12, 2024. The search strategy employed Boolean operators "AND" and "OR" with the following terms: ("martial arts" OR "fighting arts" OR "combat sports" OR karate OR "Brazilian jiu-jitsu" OR judo OR "wu shu" OR "kung fu" OR taekwondo OR silat OR "Muay Thai") AND ("plyometric training" OR "ballistic training" OR "jump training" OR "plyometric exercise*" OR "power training" OR "stretch-shortening cycle"). In addition to these formal systematic searches, manual searches were performed using Google Scholar and by reviewing the reference lists of the included studies to identify additional relevant articles. Detailed search strategies for each database are provided in Appendix File 1.

Selection criteria

The present meta-analysis selected studies that adhered to the PICOS framework. This standardized methodology encompasses five key components for systematic review and meta-analysis: population (P), interventions (I), comparators (C), main outcomes (O), and study design (S) [26]. A comprehensive assessment of potentially relevant papers was conducted by two independent evaluators (QY and ND) according to the established inclusion and exclusion criteria (Table 1). This process involved reviewing the titles, abstracts, and full texts of the papers to determine their eligibility for inclusion in the meta-analysis. If the two authors (QY and ND) disagreed on the inclusion or exclusion of an article, a third author (KGS) was consulted to resolve the disagreement.

Data extraction

The data extraction process was carried out by the first reviewer (QY) using a standardized form developed in Microsoft Excel. The second reviewer (ND) then independently verified all the extracted data. In cases where discrepancies arose between the two reviewers, the study information was rechecked to resolve any differences. From each included study, the following information was extracted: (1) general publication details (e.g., author name, year of publication); (2) participant details (e.g., age, sample size, sex); (3) intervention specifics (e.g., duration, frequency); and (4) outcome measures related to muscle power and strength.

Methodological quality

The risk of bias for each selected randomized controlled trial (RCT) was carefully assessed using the revised Cochrane risk of bias tool for randomized trials (RoB-2) [27]. This tool provides a detailed framework for evaluating potential biases in various aspects of trial design and execution. For non-RCTs, the assessment was conducted using the Risk Of Bias In Non-randomized Studies of Interventions (ROBINS-I) tool [28]. ROBINS-I is specifically designed to evaluate the risk of bias in studies that do not employ randomization, 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.

Meta-analyses

The Comprehensive Meta-Analysis (Version 3.0; Biostat, Englewood, NJ, USA) software, renowned for its robust capabilities in conducting meta-analyses, was used to perform all statistical analyses. A meta-analysis was performed when at least three studies were available for a specific outcome measure [24, 29]. Given that most included studies had small sample sizes (fewer than 20 participants), it was necessary to adjust the calculations accordingly [30]. Therefore, Hedges' g ESs were computed using the mean difference from baseline and the standard deviation of these mean differences for both experimental and control groups. To provide a fair comparison between all participants in the different groups, the sample size of the control group was proportionately split in trials with multiple intervention groups [31]. The meta-analysis employed a random effects model for continuous data, utilizing inverse variance and a 95% confidence interval (CI). The calculated ES values were categorized according to the following scale: trivial ($ES < 0.2$), small ($0.2 \leq ES \leq 0.6$), moderate ($0.6 < ES \leq 1.2$), large ($1.2 < ES \leq 2.0$), very large ($2.0 < ES \leq 4.0$), and extremely large ($ES > 4.0$) [32]. To assess variability among the studies, the I^2 statistic was used, which quantifies the proportion of variability due to heterogeneity rather than chance, ranging from 0 to 100%. The thresholds for heterogeneity were defined as low ($I^2 = 25\%$), moderate ($I^2 = 50\%$), and high ($I^2 = 75\%$) [33]. Publication bias was assessed through the examination of funnel plots and the calculation of Egger's test [34]. The trim-and-fill procedure was applied when bias was identified. A significance level of $p < 0.05$ was used to determine statistical significance.

Moderators potentially influencing muscle strength and power in martial arts athletes were predetermined, and participants were categorized into two sub-groups for each parameter. Age was classified into younger (< 18 years old) and older (≥ 18 years old) groups. Training frequency was divided into lower frequency (2 times per week) and higher frequency (3 times per week) groups. Training duration was grouped into shorter duration (< 7 weeks) and longer duration (≥ 7 weeks).

Results

Study selection

As depicted in Fig. 1, the initial search of the database yielded a total of 277 documents. An additional 25 relevant publications were identified through an extensive review of references and supplementary searches via Google Scholar. After removing duplicates, the number of unique records was reduced to 223. The titles and abstracts of these papers were carefully screened, narrowing down the selection to 71 papers for full-text review. Following an in-depth evaluation of these full texts, 56 documents were deemed unsuitable and excluded. Ultimately, 15 trials met all the predefined criteria and were selected in the meta-analysis, ensuring a rigorous and thorough selection process.

Methodological quality

The RoB-2 assessments were applied to ten RCTs [35–44], while the ROBINS-I tool was used for five non-RCTs [45–49]. Of these studies, 13 had a moderate overall risk of bias or raised some concerns, one had a high risk of bias, and one had a low risk of bias, as depicted in Fig. 2. Figure 2a shows the RoB-2 assessment results, with none of the RCTs reporting their method of randomization sequence generation. One RCT was at high risk of bias due to selective outcome reporting. Figure 2b presents the ROBINS-I assessment findings, highlighting that three non-RCTs had a moderate risk of bias due to confounding factors and concerns over selective outcome reporting.

Study characteristics

Table 2 provides an overview of the key participant and intervention characteristics. The details of the plyometric exercises in each study are provided in Appendix File 2. The studies included a total of 499 martial arts athletes,

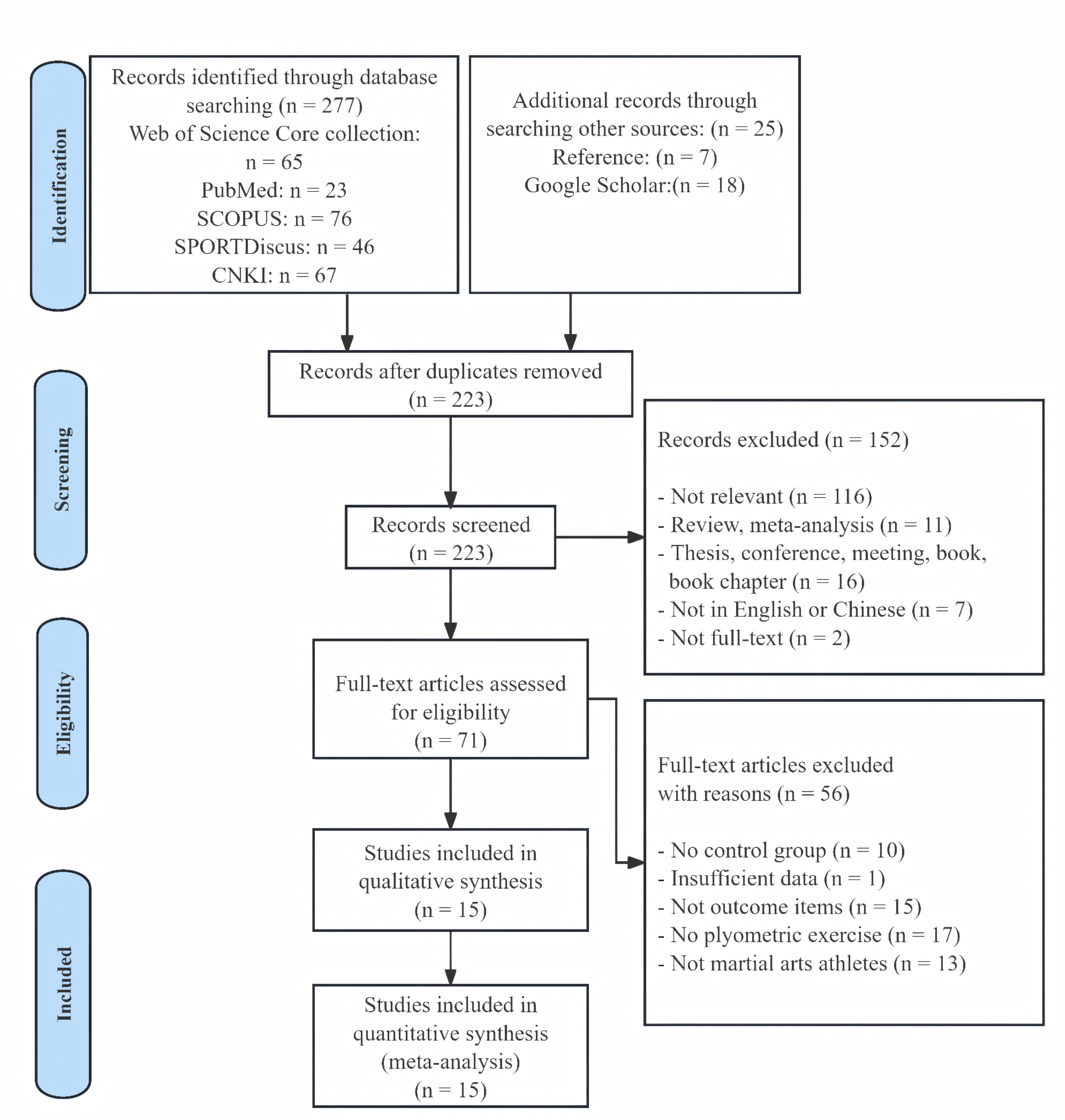

Fig. 1 PRISMA flow diagram

aged between 12 and 24 years. Eleven studies assessed only males [35–38, 40, 42, 43, 45, 47–49], one assessed only females [41], and two studies included both sexes [44, 46], while one study did not report gender [39]. Five studies focused on taekwondo athletes [35, 39, 41, 44], five on karate athletes [38, 45–48], two on judo athletes [37, 42], two on boxers [36, 43], and one on Silat athletes [40]. The duration of PT interventions ranged from 4 to 12 weeks: six trials implemented 8-week programs [38, 42, 43, 47–49], six conducted 6-week programs [35, 39, 40, 44–46], one used a 12-week program [36], one utilized a 10-week program [37], and one employed a 4-week program [41]. Participants trained three times per week in nine studies [35, 37, 39, 42–44, 47–49], twice per week in four studies [36, 40, 41, 46], and either once or four times per week in the remaining studies [38, 45]. Session durations varied between 20 and 120 min across nine studies [35–37, 40, 42–44], while seven studies

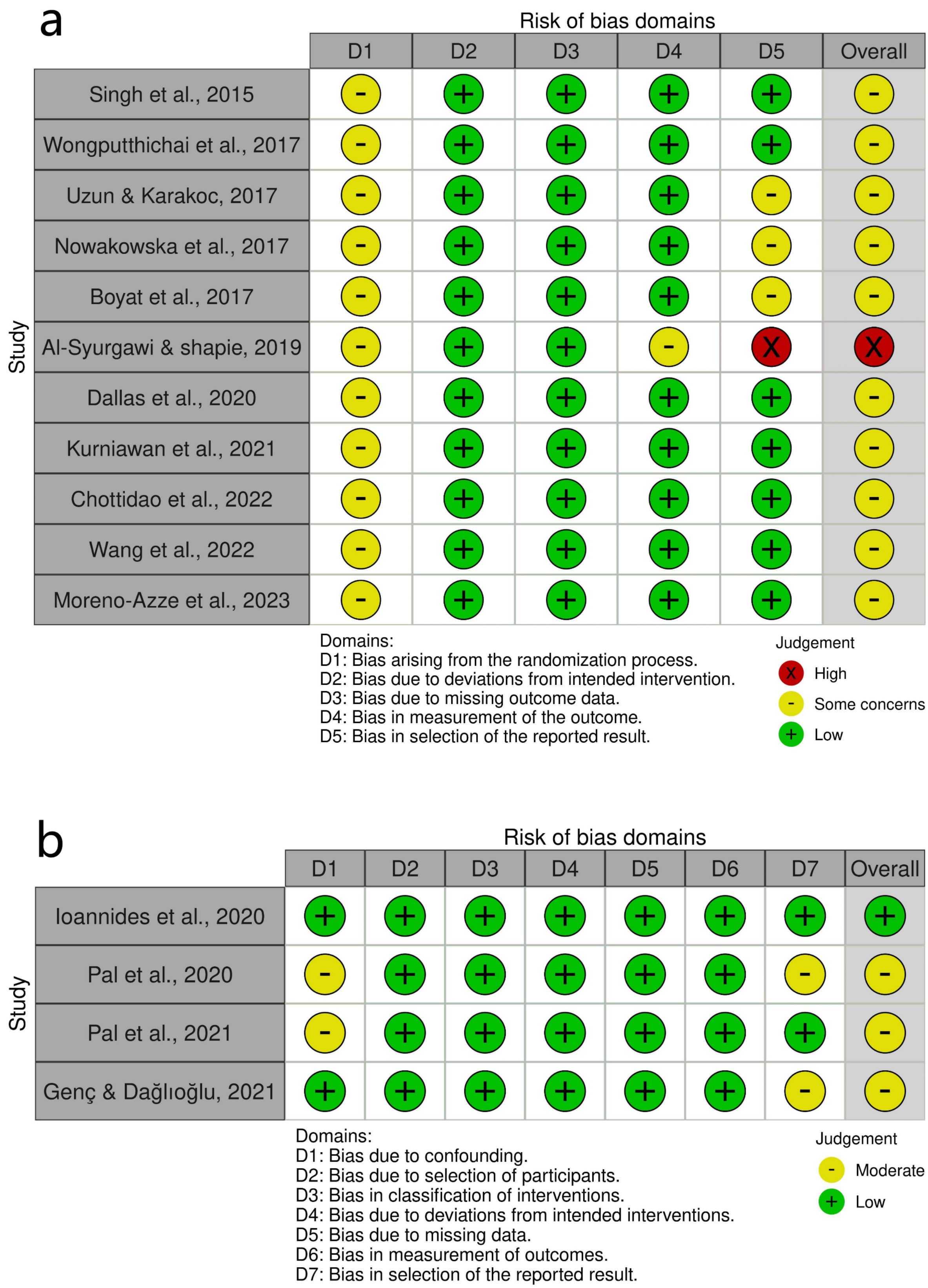

Fig. 2 **a**: RoB-2, **b**: ROBINS-I. Created using Robvis tool

Table 2 Characteristics of included studies

Study	Participants				Training program							Outcome
	n	Age (yrs)	Sex	Athletes	Content	Weeks	Freq	Time	Sets x reps	RBS (s)	Int	
Singh et al., 2015 [35]	30	22.0 ± 1.6	M	Taekwondo	EG: plyometric training CG: regular Taekwondo training	6	3	120	2–5 × 6–15	120-180	Low to medium	Power (VJ)
Wongputthichai et al., 2017 [36]	33	EG: 21.24 ± 1.15 CG: 21.50 ± 1.10	M	Thai boxing	EG: plyometric training CG: normal Thai boxing training	12	2	30	3 × 8–10	NR	85–100% HRmax	Strength (knee extension)
Uzun & Karakoc, 2017 [37]	30	EG: 21.40 ± 1,99 CG: 21.53 ± 1,80	M	Judo	EG: plyometric training CG: regular judo training	10	3	20	NR	NR	NR	Strength (leg strength
Nowakowska et al., 2017 [38]	19	17.2 ± 0.92 16.44 ± 1.33	M	Karate	EG: plyometric training CG: traditional karate training	8	4	60–90	NR	NR	NR	Power (lower extremity peak power)
Boyat et al., 2017 [39]	20	18–21	NR	Taekwondo	EG: plyometric training CG: regular Taekwondo training	6	3	NR	3 × 10–15	60	NR	Power (VJ)
Syurgawi & shapie, 2019 [40]	34	14 ± 3.22	M	Silat	EG: plyometric training CG: conventional silat training	6	2	60	NR	NR	low to high	Strength (1RM squat test)
Dallas et al., 2020 [41]	25	EG: 13.91 ± 3.02 CG: 12.80 ± 2.89	F	Taekwondo	EG: plyometric training CG: regular PE lessons	4	2	NR	2–4 × 4–10	90	NR	Strength (RSI)
Kurniawan et al., 2021 [42]	36	21.8 ± 1.78	M	Judo	EG1: plyometric training with active recovery EG2: plyometric training with passive recovery CG: judo training	8	3	90	NR	NR	NR	Power (force plate test) Strength (hand grip)
Chottidao et al., 2022 [43]	24	EG: 15.5 ± 1.6 CG: 15.6 ± 1.6	M	Boxing	EG: plyometric training CG: normal boxing training	8	3	30	2–4 × 4–10	NR	NR	Power (jump power) Strength (peak rate of force development)
Wang et al., 2022 [44]	36	EG1: 17.1 ± 0.7 EG2: 17.1 ± 0.7 CG: 17.8 ± 0.7	24 M/12F	Taekwondo	EG: plyometric training CG: normal Taekwondo training	6	3	120	6–8 × 12	120	NR	Power (CMJ)
Moreno-Azze et al., 2023 [45]	20	19 ± 4 years	M	Karate	EG: plyometric training CG: regular karate training	6	1	NR	2–4 × 4–8	NR	NR	Power (CMJ)
Ioannides et al., 2020 [46]	12	EG: 17.6 ± 1.5 CG: 17.0 ± 0.9	10 M/2F	Karate	EG: plyometric training CG: kumite training	6	2	NR	4 × 4–8	60	NR	Power (CMJ), strength (Leg extension isometric force)
Pal et al., 2020 [47]	80	21.00 ± 1.77	M	Karate	EG: plyometric training CG: conventional karate training	8	3	NR	6–15 × 2–5	NR	NR	Power (Sargent Test)
Pal et al., 2021 [48]	80	18–24	M	Karate	EG: plyometric training CG: regular karate training	8	3	NR	6–15 × 2–5	NR	NR	Strength (trunk extensor test)
Genç & Dağlıoğlu, 2021 [49]	20	EG: 20.10 ± 1.66 CG: 20.40 ± 1.71	M	Taekwondo	EG: plyometric Training CG: taekwondo training	8	3	NR	3–4 × 10	90	Moderate to high	Power (VJ), strength (hand grip)

EG, experimental group; CG, control group; M, male; F, female; yrs, years; NR, not reported; PE, physical education; HRmax, heart rate max; CMJ, countermovement jump; VJ, vertical jump; reps, repetitions; Freq, frequency; Min, minutes; Int, intensity; RSI, reactive strength index; RBS, rest between sets did not specify the duration [39, 41, 45–49]. Additionally, most studies included 2 to 8 sets per exercise, with 2 to 15 repetitions per set, and rest periods of 60–180 s between sets. Only four studies reported training intensity [35, 36, 40, 49], using various indices such as heart rate and exercise intensity levels.

Meta-analyses results

Effects of PT on muscle strength

Pooled data from ten studies ($n = 331$) demonstrated that PT significantly increased muscle strength compared to the control group (ES = 1.16, large, 95% CI = 0.29–2.03, $p < 0.001$). Of note, the heterogeneity was high ($I^2 = 91.92\%$). After removing one outlier [47], the ES was adjusted to 0.62 (moderate, 95% CI = 0.38–0.87, $p < 0.001$, Fig. 3), and the heterogeneity decreased to 0%.

In younger athletes (< 18 years), pooled data from four studies showed significant increases in muscle strength with PT compared to the control group (ES = 0.63, 95% CI = 0.21–1.06, $p = 0.003$). Similarly, in older athletes (≥ 18 years), pooled data from five studies also indicated significant improvements in muscle strength with PT (ES = 0.61, 95% CI = 0.27–0.91, $p < 0.001$). The effectiveness between the younger and older subgroups did not demonstrate a statistically significant difference ($p = 0.942$).

For the shorter duration studies (< 7 weeks), pooled data from five studies showed that the PT group experienced significantly greater increases in muscle strength compared to the control group (ES = 0.59, 95% CI = 0.26–0.93; $I^2 = 38.01\%$, $p = 0.001$). Significant increases in muscle strength were also observed in the longer duration studies (≥ 7 weeks), with pooled data from four studies showing improvements in the PT group (ES = 0.66, 95% CI = 0.23–0.88; $I^2 = 0\%$, $p = 0.003$). However, no statistically significant differences were observed between the subgroups ($p = 0.801$).

Regarding PT frequency, significant increases in muscle strength were found with a training frequency of twice per week (ES = 0.91; 95% CI = 0.52–1.31, $p < 0.001$; $I^2 = 21.26\%$, four studies). A frequency of three times per week resulted in increases in muscle strength (ES = 0.43; 95% CI = 0.11–0.75, $p = 0.008$; $I^2 = 0\%$, five studies). However, no statistically significant differences were observed between these subgroups ($p = 0.064$).

Effects of PT on muscle power

Pooled data from nine studies ($n = 314$) indicated that PT significantly increased muscle power compared to the control group (ES = 0.70, moderate, 95% CI = 0.05–1.35, $p = 0.035$). Of note, the heterogeneity was high ($I^2 = 85.95\%$). After removing one outlier [47], the ES was adjusted to 0.45 (small, 95% CI = 0.20–0.71, $p = 0.001$, Fig. 4), and the heterogeneity decreased to 0%.

For the younger athletes (< 18 years), pooled data from four studies showed significant increases in muscle power with PT compared to the control group (ES = 0.63, 95% CI = 0.21–1.06, $p = 0.003$). Similarly, significant increases were observed in pooled data from five studies involving older athletes (≥ 18 years) (ES = 0.61, 95% CI = 0.27–0.91, $p < 0.001$). However, no statistically significant differences were found between the subgroups ($p = 0.942$).

For studies with a shorter duration (< 7 weeks), pooled data from five studies indicated no significant differences in muscle power between the PT group and the control group (ES = 0.31, 95% CI = -0.07–0.69; $I^2 = 0\%$, $p = 0.107$). In contrast, significant increases in muscle power were found in pooled data from five studies with

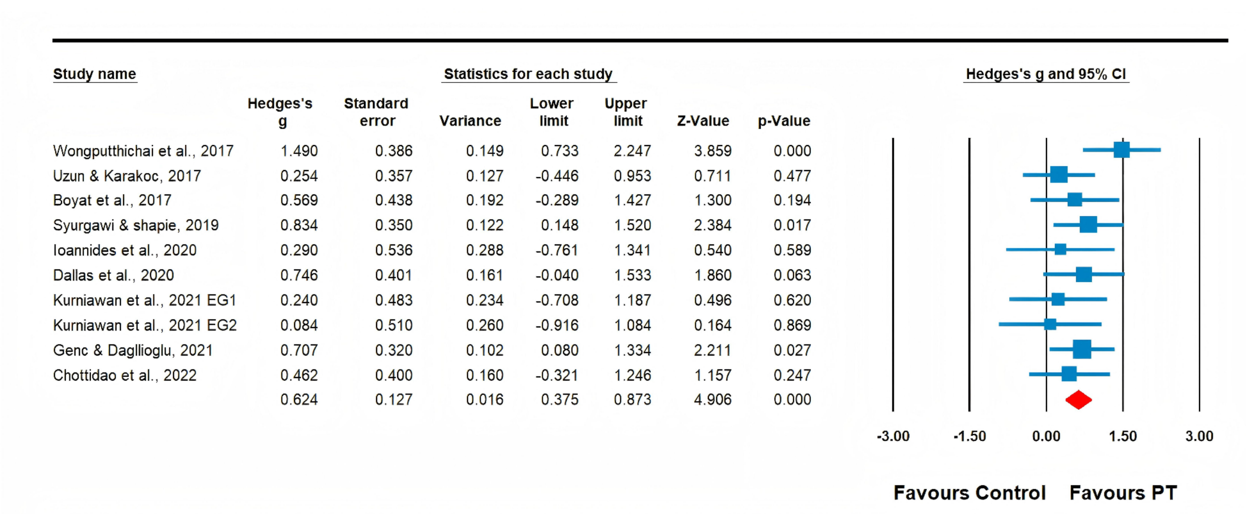

Fig. 3 Forest plot for the overall effect of plyometric training (PT) on muscle strength

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
		Statistics for each study					
Singh et al., 2015	0.529	0.362	0.131	-0.181	1.238	1.461	0.144
Nowakowska et al., 2017	0.176	0.440	0.193	-0.686	1.038	0.400	0.689
Boyat et al., 2017	0.520	0.436	0.190	-0.335	1.375	1.193	0.233
Ioannides et al., 2020	0.160	0.534	0.285	-0.886	1.207	0.301	0.764
Kurniawan et al., 2021EG1	0.517	0.490	0.240	-0.443	1.477	1.055	0.291
Kurniawan et al., 2021EG2	0.363	0.514	0.264	-0.644	1.370	0.706	0.480
Genc & Daglioglu, 2021	0.993	0.329	0.108	0.347	1.638	3.015	0.003
Chottidao et al., 2022	0.684	0.406	0.165	-0.113	1.480	1.683	0.092
Wang et al., 2022 EG1	0.015	0.476	0.227	-0.918	0.948	0.032	0.975
Wang et al., 2022 EG2	0.246	0.478	0.228	-0.691	1.183	0.515	0.606
Moreno-Azze et al., 2023	0.088	0.429	0.184	-0.752	0.927	0.204	0.838
	0.452	0.130	0.017	0.197	0.707	3.474	0.001

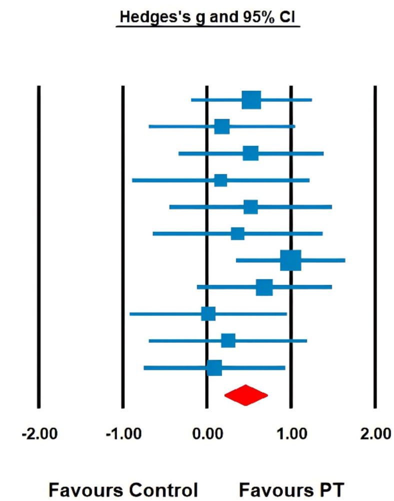

Fig. 4 Forest plot for the overall effect of plyometric training (PT) on muscle power

a longer duration (≥7 weeks) (ES = 0.57, 95% CI = 0.23–0.92, p = 0.001; I^2 = 0%). Nevertheless, no statistically significant differences were observed between these subgroups (p = 0.312).

Publication bias

Publication bias was evaluated through the use of funnel plots, which visually assess the symmetry of study data, and Egger's test, a statistical method that quantitatively detects any asymmetry in the funnel plots. For muscle strength, visual analysis of the funnel plot did not indicate significant asymmetry (Fig. 5a), and the results of Egger's test (p = 0.215) suggested no significant publication bias. However, evidence of publication bias was found for muscle power. Both the inspection of the funnel plot (Fig. 5b) and Egger's test (p = 0.010) indicated significant publication bias. Following the application of the trim-and-fill method to account for the five missing studies, the ES was adjusted upward from 0.45 to 0.65 (95% CI = 0.44 to 0.87).

Discussion

The available literature lacks studies assessing the effects of implementing plyometrics in martial arts athletes. Our meta-analysis reveals that PT results in small-to-moderate improvements in muscle strength and power, with no significant moderating effects from participants' age or training variables (i.e., duration and frequency). These findings support previous research and provide new insights into the benefits of PT for martial arts athletes. This evidence-based information is valuable for practitioners in designing effective training programs.

Muscle strength is crucial for martial arts performance, particularly in grappling actions and developing high-velocity movements [50]. The analysis indicated a moderate increase (ES = 0.62) in muscle strength following PT. The strength assessments included various tests, such as the one-repetition maximum squat test, knee extension, handgrip strength, reactive strength index, and peak rate of force test. De Villarreal et al. [16] conducted a meta-analysis focusing on PT's effects on muscle strength, reporting substantial gains. This meta-analysis aligns with previous findings, confirming PT's effectiveness in enhancing muscle strength across various populations. For example, Váczi et al. [51] found that PT significantly boosts muscle strength, helping soccer players maintain performance during extended high-intensity competitions. Moreover, a recent systematic review by Deng et al. [52] demonstrated PT's positive impact on muscle strength in untrained individuals. Ramírez-Campillo et al. [53] observed significant increases in muscle strength in middle- and long-distance runners after six weeks of PT. Furthermore, Deng et al. [53] confirmed that PT substantially enhances both upper and lower body muscle strength among athletes. However, Uzun and Karakoc [37] observed no significant changes in handgrip or leg strength following a 10-week PT program in young taekwondo athletes. Similarly, Sadeghi et al. [54] reported that a six-week PT regimen did not enhance seated medicine ball throw performance in athletes. The lack of improvement in these studies may be attributed to the training program's duration being insufficient to elicit measurable adaptations, or to the selection of exercises that did not effectively target the desired outcomes [55].

In this study, we performed a subgroup analysis to investigate how age, training duration, and training frequency influenced the effectiveness of PT. The

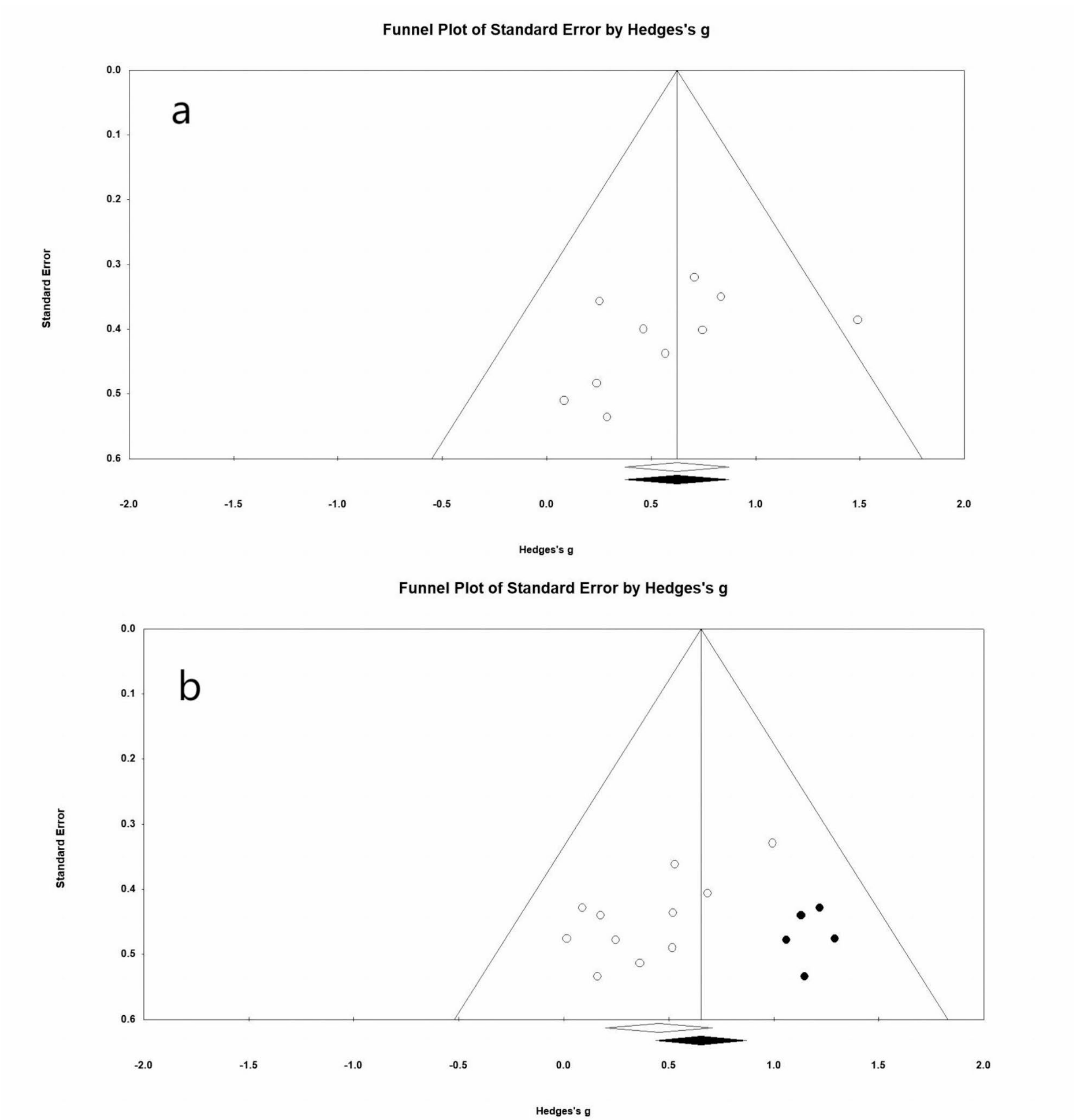

Fig. 5 Funnel plot analysis; (**a**) muscle strength; (**b**) muscle power. White circles: observed studies; blue circles: studies imputed by the trim and fill procedure; white diamond: pooled mean effect size of observed studies only; blue diamond: pooled mean effect size of both observed and imputed studies

comparison between different age groups (youth vs. adults) showed no significant differences in outcomes. Similarly, muscle strength gains did not vary significantly between training durations of ≤7 weeks and >7 weeks, or between 2 and 3 sessions per week. These results align with previous research, which has consistently demonstrated that PT improves muscle strength across athletes of all ages, regardless of variations in PT parameters [22, 24, 29, 56]. Some researchers suggest that maintaining a relatively low volume of PT can still significantly enhance athletes' physical fitness while allowing more time to focus on other critical areas of their training regimen [24].

Several mechanisms have been identified regarding the role of PT in enhancing muscle strength in martial arts athletes. The strength gains resulting from PT can be attributed to adaptations in motor learning, improved coordination, and increased motor unit recruitment

[11]. Additionally, these improvements may stem from changes in the mechanical properties of the muscle-tendon complex, where increased stiffness allows for greater storage and reuse of elastic energy [57]. PT also enhances muscle explosiveness and reactivity by utilizing the rapid stretch-shortening cycle, in which muscles quickly stretch and then immediately contract, leading to greater force output [12]. Furthermore, PT can improve the neural recruitment of muscle fibers, increasing the activation rate of fast-twitch fibers, which is crucial for generating explosive strength [11].

A prior review emphasized the critical role of muscle strength in both general and sport-specific skills, as well as their underlying force characteristics [58]. As previously noted, muscle strength significantly influences key force-time characteristics essential for athletic performance. Enhanced force-time characteristics are theorized to improve the execution of sport-specific skills [59]. For example, a critical review reported a positive association between muscular strength and golf performance metrics [60]. Similarly, Miyaguchi and Demura [61] found a correlation between upper-body strength and bat swing speed ($r = 0.59$) among high school baseball players. Moreover, strength levels have proven effective in differentiating athletes across competition levels in various sports, including rugby league [62], wrestling [63], and volleyball [64]. A recent meta-analysis further demonstrated superior strength performance in elite Brazilian jiu-jitsu athletes compared to non-elite athletes [65]. Serafini et al. [66] suggested that while top-performing athletes excel across multiple fitness and skill domains, lower-ranking athletes should prioritize developing strength and power after achieving sufficient sport-specific skill proficiency.

Notably, resistance training is widely regarded as an effective method for enhancing muscle strength in athletes [67–69]. Several studies have compared the effects of resistance training and PT, with equal time and effort, reporting comparable improvements in muscle strength between the two approaches [55, 70]. However, Zghal et al. [71] found that combining resistance training and PT produced greater muscle strength gains than PT alone in pubertal soccer players. This highlights an intriguing area for future research, particularly in exploring how the integration of these training modalities could optimize strength development in martial arts athletes. Overall, current evidence indicates that implementing a PT program significantly enhances muscle strength in martial arts athletes.

Muscle power is essential for martial arts athletes as it significantly influences their performance and effectiveness in executing techniques [72]. The results of the present study showed a small and significant increase in muscle power (ES = 0.45) following the PT program. Power assessments included a range of tests, such as the countermovement jump, vertical jump, force plate analysis, and the Sargent test. These findings align with earlier meta-analyses conducted on athletes across various sports [23, 29, 73]. The vertical jump is commonly used to measure lower limb power or explosive leg strength [74, 75]. In martial arts, superior leg power is critical for executing a range of kicks (e.g., jump kicks, standing kicks, and airborne kicks) [76], as the majority of competition scores are determined by the quality of kicking techniques [77, 78]. In other sports, a significant correlation ($r = 0.557$) was observed between muscle power and dribbling skills in futsal players. Similarly, Arboix-Alió et al. [79] reported strong positive correlations between upper limb power and shooting velocity in dynamic slap shots ($r = 0.86$) and static slap shots ($r = 0.62$) in hockey players.

PT is a high-intensity interval training method that involves rapid explosive movements, causing muscles to quickly transition from the eccentric to the concentric phase [80]. The stretch-shortening cycle shortens the amortization phase, enabling the generation of greater force than typically produced [12]. This process allows for better utilization of the stored elastic energy and stretch reflex response in muscles, enabling them to perform more work during the concentric phase and, consequently, increasing force output [11]. Additionally, PT has a significant impact on the nervous system. Studies have shown that PT enhances neuromuscular coordination, improving athletic performance [81–83]. Through repeated high-intensity practice, this training method promotes adaptation and coordination between the nervous and muscular systems, ultimately leading to a significant increase in power output [84].

Some researchers suggest that the effects of PT may vary based on subject characteristics such as gender and age [83, 85]. However, no significant differences were observed in the impact of PT on muscle power when comparing younger and older athletes, different training durations (≤ 7 weeks vs. > 7 weeks), or training frequencies (2 vs. 3 sessions per week). Similarly, Skurvydas and Brazaitis [86] found no sex-related differences in muscle power and muscle thickness after eight weeks of PT. Additionally, previous PT meta-analyses have also reported no significant subgroup differences in training parameters (i.e., duration and frequency) and muscle power gains [23, 24, 29]. In addition, research indicates that higher-level athletes demonstrate superior strength and power output compared to their lower-level counterparts [62, 87]. For example, elite martial arts athletes outperform sub-elite athletes with faster, more powerful kicks, higher angular and linear velocities, and shorter kick execution times [88]. A recent meta-analysis also found that elite Brazilian jiu-jitsu athletes exhibited greater power performance compared to their non-elite counterparts [65]. Similarly, previous findings highlighted enhanced physical fitness attributes (e.g., muscle power) and superior stroke execution in elite versus sub-elite tennis players [89].

Muscle power plays a crucial role in athletic performance, prompting researchers to explore various training methods, such as weightlifting and resistance training. Two meta-analyses [90, 91] compared the effects of different training methods (i.e., weightlifting, resistance training, and PT) on countermovement jump performance. These studies found that weightlifting was more effective than resistance training in enhancing countermovement jump performance, while PT and weightlifting produced similar improvements. Some researchers have recommended integrating weightlifting, plyometrics, and traditional resistance training into a periodized training plan [92]. Overall, the current evidence indicates that PT programs are effective in improving muscle power in martial arts athletes.

Limitation

The primary limitation of this research is the small number of studies included in the meta-analysis, which limits the robustness of the evidence and the strength of the recommendations derived from the analyzed studies. Additionally, several moderator analyses (e.g., sex, training intensity) could not be conducted due to the insufficient number of relevant studies (fewer than three) for each moderator. Many studies failed to provide comprehensive descriptions of the training programs, often omitting key details; for instance, 12 studies did not specify the intensity of PT. Furthermore, there was inconsistency in how intensity was reported, with some studies using maximum heart rate while others referred to exercise intensity levels. The small sample sizes (6–20 participants per group) in these studies also limited the statistical power and generalizability of the results. Another significant limitation is the short duration of the intervention studies (4–12 weeks), which may not fully capture the long-term effects and adaptations resulting from PT.

Practical applications

The findings of this meta-analysis have significant implications for practitioners and coaches. Firstly, it is recommended that PT be incorporated into the training programs for martial arts athletes to enhance muscle strength and power. While the moderator analyses did not yield precise recommendations for each training parameter, the meta-analysis provides preliminary evidence-based guidelines: a training duration of four to twelve weeks, a frequency of one to four sessions weekly, a volume of two to eight sets per exercise, and two to fifteen repetitions per set. Secondly, there is a strong need for rigorously designed trials to explore the effects of PT in various martial arts disciplines, such as Brazilian Jiu-Jitsu and Kung Fu, to confirm and strengthen the findings of this analysis. Future research could explore other potential influencing factors, such as gender, initial fitness levels, or specific martial arts disciplines, to gain a more comprehensive understanding of the applicability and effects of PT. Additionally, investigating the long-term effects and potential cumulative benefits of different PT intensities and volumes would be beneficial. Thirdly, PT is a cost-effective training strategy that often requires little to no equipment, as it typically involves exercises utilizing the athlete's own body weight for resistance [93]. For practitioners, understanding the benefits and mechanisms of PT can lead to more informed decisions in training program design. Emphasizing proper technique and gradual progression can maximize the effectiveness of PT while minimizing injury risks. The flexibility of PT also allows it to be incorporated into various phases of an athlete's training cycle, from off-season conditioning to pre-competition preparation. Finally, the findings underscore the importance of continued education and professional development among coaches and trainers. Staying updated with the latest research and advancements in PT can enable practitioners to implement evidence-based practices that enhance athlete performance.

Conclusions

This meta-analysis demonstrates that PT effectively increases muscle strength and power in martial arts athletes, including those practicing taekwondo, judo, boxing, karate, and silat. Further research is needed to determine the optimal doses and explore the interactions among training variables to further enhance muscle strength and power in martial arts athletes.

Abbreviations

PT	Plyometric training
RCT	Randomized controlled trial
ROB	Risk of bias
ROBINS-I	Risk of bias in non-randomized studies of interventions
CI	Confidence interval
ES	Effect size

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

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Author contributions

All authors played a role in the conception and design of the study. Q.Y. and N.D. were responsible for data synthesis and analysis, with N.D. and K.G.S. verifying the study exclusion and data extraction. Q.Y. wrote the first draft of the manuscript, and all authors reviewed and contributed to both the drafts and the final version of the manuscript.

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Declarations

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