Effects of jumping exercise on muscular power in older adults: a meta-analysis

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ABSTRACT

Background: Jump training (JT) can be used to enhance the ability of skeletal muscle to exert maximal force in as short a time as possible. Despite its usefulness as a method of performance enhancement in athletes, only a small number of studies have investigated its effects on muscle power in older adults.

Objectives: The objectives of this meta-analysis were to measure the effect of JT on muscular power in older adults (≥50 years), and to establish appropriate programming guidelines for this population.

Data sources: The data sources utilised were Google Scholar, PubMed, Microsoft Academic.

Study eligibility criteria: Studies were eligible for inclusion if they comprised JT interventions in healthy adults (≥50 years) who were free of any medical condition which could impair movement.

Study appraisal and synthesis methods: The inverse-variance random effects model for meta-analyses was used because it allocates a proportionate weight to trials based on the size of their individual standard errors and facilitates analysis whilst accounting for heterogeneity across studies. Effect sizes, calculated from a measure of muscular power, were represented by the standardised mean difference and presented alongside 95% confidence intervals (CI).

Results: Thirteen training groups across nine studies were included in this meta-analysis. The magnitude of the main effect was ‘moderate’ (0.66, 95% confidence interval: 0.33, 0.98). Effect sizes [ES] were larger in non-obese participants (body mass index [BMI] < vs. ≥30 kg.m-2; 1.03 [95% CI: 0.34, 1.73] vs. 0.53 [95% CI: -0.03, 1.09]). Among the studies included in this review, just one reported an acute injury, which did not result in the participant ceasing their involvement. JT was more effective in programmes with more than one exercise (range: 1-4 exercises; ES =0.74 [95% CI: -0.49, 1.96] vs. 0.53 [95% CI: 0.29, 0.78]), more than two sets per exercise (range: 1-4 sets; ES =0.91 [95% CI: 0.04, 1.77] vs. 0.68 [95% CI: 0.15, 1.21]), more than three jumps per set (range 1-14 jumps; ES = 1.02 [95% CI: 0.16, 1.87] vs. 0.53 [95% CI: -0.03, 1.09]) and more than 25 jumps per session (range 6-200 jumps; ES = 0.88 [95% CI: 0.05, 1.70] vs. 0.49 [95% CI: 0.14, 0.83]).

Conclusions: JT is safe and effective in older adults. Practitioners should construct varied JT programmes that include more than one exercise and comprise more than two sets per exercise, more than three jumps per set and 60 seconds of recovery between sets. An upper limit of three sets per exercise and ten jumps per set is recommended. Up to three training sessions per week can be performed.

Key points:

- Jump training is a safe and effective way of increasing muscular power in older adults.
- Jump training seems to be more effective in non-obese individuals.
- Practitioners should construct varied jump training programmes that include more than one exercise and comprise more than two sets per exercise, more than three jumps per set and 60 seconds of recovery between sets. An upper limit of three sets per exercise and ten jumps per set is recommended. Up to three training sessions per week can be performed.

1. Introduction

The stretch forces that occur during dynamic movement incite eccentric muscle actions with the resultant elastic energy potentiating force production in subsequent concentric actions [1,2]. This mechanism is an important factor in physical performance with rapid movement underpinned by efficient usage of the stretch-shortening cycle (SSC) [3]. The SSC has traditionally been targeted through appropriate training prescription in athletes but less attention has been paid to the utilisation of such techniques in clinical populations, particularly older adults. This is surprising given the importance of rapid muscle actions for carrying out functional everyday tasks, such as rising from a chair and using stairs; indeed, low muscle power has been associated with risk of falling, reduced quality of life and poor functional performance in advanced age [4,5] .

Jump training (JT) can be used to enhance the ability of skeletal muscle to exert maximal force in as short a time as possible [6]. This training method typically includes various unilateral and bilateral jumps, hops and bounds [6,7]. Despite its usefulness as a method of performance enhancement in athletes, only a small number of studies have investigated its effects on muscle power in older adults. It is possible that this is due to a common perception that JT may not be a suitable exercise modality for older individuals [5,8]. This may be due to the relatively low number of studies on JT that have been carried out with existing meta-analyses on power training in older adults relating only to those studies which incorporated high-velocity movements into traditional resistance training protocols [9,10]. However, it has been suggested that the type of studies included in these analyses may not have utilised protocols that were optimal for power development. For example, Newton et al. [11] state that power training with resistive loads (i.e. fast movement with relatively light resistance) may be suboptimal because a substantial portion of the concentric phase of the movement involves a declarative component to achieve zero velocity at the end range. As the primary intention during power training should be to move a load as fast as possible [12], it is rather contradictory that this may not actually occur to its full extent during such training. This could potentially undermine the effectiveness of this type of training. Moreover, the aforementioned phase of concentric deceleration is also characterised by a decrease in the electromyographic activity of agonist muscles [13]; yet, in contrast, this is not an inhibitory factor in JT as there is no deceleration component required during the concentric phase of the jump.

We sought to carry out the first meta-analysis on JT in older adults, relating to its effects on the ability to enhance muscular power. Previous work has focused only on the effects of such impact exercise on bone density [14]. If it could be determined that JT is a safe and beneficial training modality to increase muscular power in older adults, there is great potential for it to be programmed on a more regular basis to underpin good health and quality of life [15,16]. Sarcopenia and dynapenia refer to the age-related loss of skeletal muscle and muscle force capability due to ageing [17]. Associated losses in function can be detrimental to health with increased frailty and decreased mobility resulting in a reduction in the independence of the affected individual [18]. Sarcopenia is particularly damaging to the fast twitch muscle fibres with a resultant impairment of the adaptive response of satellite cells to the effects of damaging exercise [19]. As JT preferentially damages fast twitch fibres to a greater degree than slow twitch oxidative fibres [20], it may be an effective way in which to slow down the loss of function by serving as a highly specific training stimulus. Because many studies have reported a positive relationship between the incidence of falls in older adults and low muscle power [21–23], exposure to this type of exercise could be vital in this population. On that basis we looked to determine the effectiveness of JT in adults of 50 years of age or older. A concurrent objective was to describe statistically-supported parameters for optimal training prescription in this population.

2. Methods

This meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [24].

2.1 Literature search

With no date restrictions, a systematic search of the Google Scholar, PubMed and Microsoft Academic databases was undertaken. Only articles published in the English language were considered. These searches were performed in April, 2018. Using Boolean logic, we used the search term: 'older adults' AND training AND plyometric OR jump. In selecting studies for inclusion, a review of all relevant article titles was conducted before an examination of article abstracts and, then, full published articles. Only peer-reviewed articles were included in the meta-analysis. Following the formal systematic searches, additional hand-searches were conducted.

The search process is outlined in Figure 1 and the search strategy used for the Google Scholar database can be viewed in the Electronic Supplementary Material Appendix.

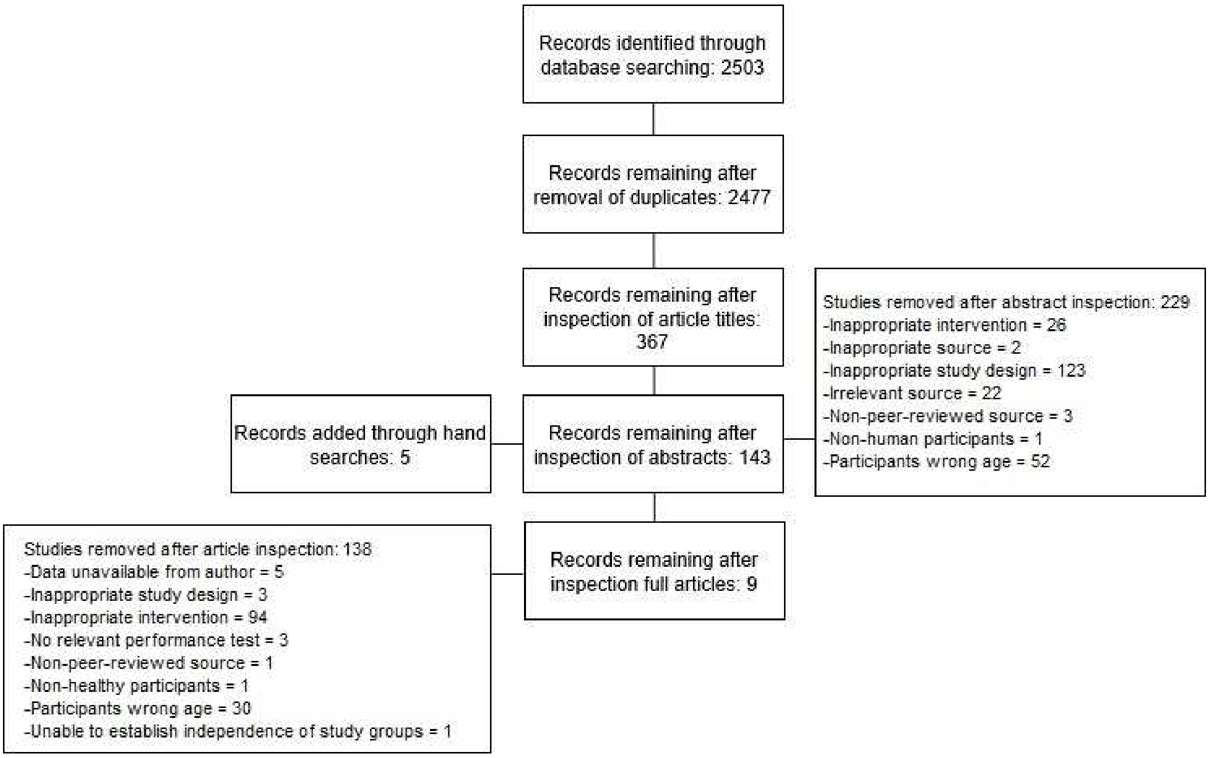


Figure 1 Flow chart for inclusion and exclusion of studies

2.2 Inclusion and exclusion criteria

Data were extracted from gathered articles with a form created in Microsoft Excel.

Where required data were not clearly or completely reported, article authors were contacted for clarification.

2.3 Inclusion and exclusion criteria

To qualify for inclusion in the meta-analysis, studies must have included a JT programme that was prescribed to healthy adults (≥ 50 years of age), who were free of musculoskeletal injuries or any condition which could impair movement. The JT was defined as “lower body unilateral and bilateral bounds, jumps and hops that utilise a pre-stretch or countermovement that incites usage of the stretch-shortening cycle” [6,25]. The age criterion was chosen on the basis that the atrophy of skeletal muscle due to age starts around the age of 50 years [26]. Each study must have included a control group and a measure of muscular power which was selected based on a logically defensible rationale [27], most often some form of countermovement jump (CMJ). The CMJ is an appropriate measure of muscular power because it is performed with a fast transition between the downward and upward stages of the action which requires utilisation of the stretch-shortening cycle [28]. The measure also has very high test-retest reliability [29] and so was chosen on the basis of establishing a degree of consistency between analysed studies. Protocols that were conducted in water were excluded. The characteristics of the study participants are displayed in Table 1.

Table 1 Characteristics of study participants

Study	Age (yrs)	Height (cm)	Body mass (kg)	Body fat (%)	BMI (kg.m-2)	LBM (kg)	Study group	Population	N	Drop outs	Sex	Performance test	Baseline	Follow up
Allison et al. [30]	70.2 (3.8)	176.4 (6.6)	81.6 (8.7)		26.0 (2.0)		Multidirectional hopping	Healthy men	39	0	M	Hop impulse (N/s)	76.0 (3.0)	84.0 (3.0)
	70.1 (4.1)	174.9 (6.7)	82.1 (14.6)		27.0 (4.0)		Control	Healthy men	18		M	Hop impulse (N/s)	79 (4.0)	76.0 (6.0)
Correa et al. [31]	68 (5.0)	158.1 (10.2)		38 (5.3)			Rapid training	Healthy women	14	0	F	Rate of force development in 0.25s (N·s – 1)	1.7 (0.6)	2.4 (0.7)
	67 (5.0)	158.1 (10.2)		38 (5.3)			Control	Healthy women	17		F	Rate of force development in 0.25s (N·s – 1)	1.8 (0.6)	1.8 (0.6)
Fishbeck et al. [32]	55.1 (7)	169.6 (9.6)	84.73 (21.3)				Training	Active adults	14	0	M+F (53%M)	Vertical jump (cm)	28.7 (12.7)	27.5 (13.2)
	61.2 (7.7)	174.1 (7.5)	99.2 (22.3)				Control	Active adults	5		M+F (60%M)	Vertical jump (cm)	25.7 (8.9)	26.9 (10.0)
Miszko et al. [33]	72.3 (6.7)	170.4 (11.3)	79.7 (15.7)	29.0 (7.3)		56.4 (11.8)	Power training	Adults with low functional performance	11	0	M+F (54.5%F)	Wingate peak power (W kg-1)	91.5 (35.6)	91.4 (34.0)
	72.4 (7.2)	169.9 (10.0)	68.22 (13.5)	26.8 (6.2)		49.8 (10.1)	Control	Adults with low functional performance	15		M+F (60% F)	Wingate peak power (W kg-1)	88.0 (32.3)	83.0 (27.1)
Ramirez-Campillo et al. [34]	70 (6.9)	149.0 (4.1)	62.1 (7.8)		28 (4.1)		Resistance training (2 days)	Healthy women	8	0	F	30s sit-to-stand test (repetitions)	15.3 (2.6)	18.7 (2.7)
	71.9 (6.3)	148.0 (6.5)	64.7 (6.5)		29.6 (3.4)		Resistance training (3 days)	Healthy women	8	0	F	30s sit-to-stand test (repetitions)	12.5 (3.5)	15.6 (3.7)
	68.9 (7.5)	148.0 (5.8)	59.6 (7.2)		27.4 (4.0)		Control	Healthy women	8		F	30s sit-to-stand test (repetitions)	12.3 (2.6)	12.1 (2.9)
Ramírez-Campillo et al. [16]	67.5 (5.3)	151.2 (5.6)	71.7 (14.1)		31.4 (5.7)		High supervision	Healthy women	30	0	F	Countermovement jump (cm)	8.5 (2.9)	9.8 (2.7)

	65.7 (3.7)	150.3 (5.3)	69.8 (14.3)		30.9 95.9)		Low supervision	Healthy women	28	0	F	Countermovement jump (cm)	8.9 (3.0)	9.3 (3.5)
	66.7 (4.9)	148.6 (5.0)	65.2 (7.2)		29.5 (3.0)		Control	Healthy women	15		F	Countermovement jump (cm)	8.1 (2.2)	8.2 (2.1)
Ramírez-Campillo et al. [35]	66.3 (3.7)	150.8 (5.4)	72.3 (13.1)		31.7 (5.0)		High-speed	Healthy women	15	0	F	Countermovement jump (cm)	7.8 (2.2)	9.5 (2.0)
	68.7 (6.4)	151.6 (5.9)	71.1 (15.5)		31.0 (6.5)		Low-speed	Healthy women	15	0	F	Countermovement jump (cm)	9.2 (3.4)	10.1 (3.3)
	66.7 (4.9)	148.6 (5.0)	65.2 (7.2)		29.5 (3.0)		Control	Healthy women	15		F	Countermovement jump (cm)	8.1 (2.2)	8.2 (2.1)
Shaw and Snow [36]	64.2 (5.8)	165.0 (7.0)	70.2 (11.3)	33.3 (6.6)		44.2 (5.6)	Exercise	Healthy women	18	4	F	Wingate peak power (W kg lean mass-1)	22.5 (4.7)	25.1 (4.1)
	62.5 (6.6)	163.0 (5.0)	63.7 (7.7)	28.6 (4.5)		43.3 (4.3)	Control	Healthy women	22		F	Wingate peak power (W kg lean mass-1)	23.4 (4.7)	24.2 (4.7)
Uusi-Rasi et al. [37]	53.0 (2.8)	164.1 (5.7)	70.9 (9.4)		26.3 (3.5)		5 mg of alendronate daily + exercise	Postmenopausal women	38	0	F	Countermovement jump (cm)	19.5 (3.2)	21.9 (3.7)
	54.2 (2.4)	164.1 (5.2)	71.7 (10.6)		26.7 (3.6)		5 mg of alendronate daily	Postmenopausal women	38		F	Countermovement jump (cm)	19.5 (3.6)	20.5 (3.8)
	53.3 (2.2)	164.0 (4.6)	73.8 (10.8)		27.4 (4.1)		Placebo + exercise	Postmenopausal women	37	0	F	Countermovement jump (cm)	20.1 (5.0)	22.9 (4.9)
	53.2 (2.1)	162.5 (6.2)	71.4 (10.8)		27.0 (3.7)		Placebo	Postmenopausal women	39		F	Countermovement jump (cm)	20.1 (3.7)	20.8 (3.9)

Values are represented by means ± standard deviations

BMI: body mass index; LBM: lean body mass; M: males only; F: females only; M+F: males and females

Table 1 Characteristics of study participants

2.4 Analysis and interpretation of results

Meta-analytical comparisons were carried out in RevMan version 5.3 [38]. Means and standard deviations for a measure of post-intervention performance were used to calculate an effect size. The inverse-variance random effects model for meta-analyses was used because it allocates a proportionate weight to trials based on the size of their individual standard errors [39] and facilitates analysis whilst accounting for heterogeneity across studies [40]. Effect sizes are represented by the standardised mean difference and are presented alongside 95% confidence intervals (CI). The calculated effect sizes were interpreted using the conventions outlined for standardised mean difference by Hopkins et al [41] (<0.2 = trivial; 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, 2.0-4.0 = very large, >4.0 = extremely large). In cases in which there was more than one intervention group in a given study, the control group was proportionately divided to facilitate comparison across all participants [42].

To gauge the degree of heterogeneity amongst the included studies, the I^2 statistic was referred to. This represents the proportion of effects that are due to heterogeneity as opposed to chance [24]. Low, moderate and high levels of heterogeneity correspond to I^2 values of 25%, 50% and 75% respectively; however, these thresholds are considered tentative [43]. The X^2 (chi square) assesses if any observed differences in results are compatible with chance alone. A low P value, or a large chi-squared statistic relative to its degree of freedom, provides evidence of heterogeneity of intervention effects beyond those attributed to chance [39].

2.5 Assessment of risk of bias

The Physiotherapy Evidence Database (PEDro) scale was used to assess the risk of bias and methodological quality of eligible studies included in the meta-analysis. This scale evaluates internal study validity on a scale from 0 (high risk of bias) to 10 (low risk of bias). A score of ≥6 represents the threshold for studies with low risk of bias [44]. All studies included in this meta-analysis achieved this standard.

2.6 Analysis of moderator variables

To assess the potential effects of moderator variables, subgroup analyses were performed. Using a random effects model, we selected potential moderators likely to influence the effects of training. Participants were divided using a median split for the following variables: age (≥67 yrs), height (>160 cm), body mass (>72 kg), programme duration (>12 weeks), training frequency (≥3 sessions per week), total number of training sessions (>36), mean number of exercises per session (>1), mean number of sets per exercise (>2), mean number of sets per session (>2), mean number of jumps per set (>3), mean number of jumps per session (>25), mean number of jumps per programme (>300). For the calculation of effect sizes based on programming parameters, mean values for variables such as sets and number of jumps were used. Where study authors provided a range for sets or jumps (i.e. 3-5 sets of 8-10 repetitions), a median value (i.e. 4 sets of 9 repetitions) was used in the calculation of subgroup median. Studies which provided a time variable to quantify work sets were excluded. Other subgroups were formed based on body mass index body mass index (BMI; < vs. ≥30 kg.m-2) and sex (female vs. male+female). The final grouping was made on the basis that just one study [30] that examined JT in older males fulfilled our inclusion criteria. Two further studies included both males and females together [32,33].

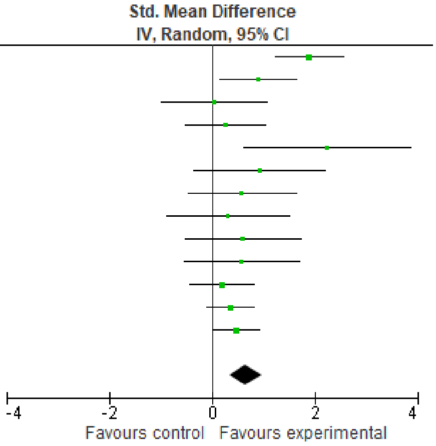
3. Results

3.1 Main effect

Nine studies were included in this meta-analysis and they comprised 13 individual experimental groups. Across all included studies, there was a moderate, significant improvement in power (0.66 [95% CI: 0.33, 0.98], Z = 3.98 [p = 0.0001]). The overall estimate was of small magnitude and showed a significant level of between-study heterogeneity (I^2 = 51% [p = 0.02]). These results are displayed in Figure 2.

	Experimental			Control				Std. Mean Difference
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI
Allison et al. [30]	84	3	39	76	6	18	9.9%	1.89 [1.23, 2.56]
Correa et al. [31]	2.4	0.7	14	1.8	0.6	17	8.9%	0.90 [0.16, 1.65]
Fishbeck et al. [32]	27.5	13.2	14	26.9	10	5	6.3%	0.05 [-0.98, 1.07]
Miszko et al. [33]	91.5	34	11	83	27.1	15	8.6%	0.27 [-0.51, 1.06]
Ramirez-Campillo et al. [34] (RT2)	18.8	2.7	8	12.1	2.9	4	3.2%	2.24 [0.62, 3.86]
Ramirez-Campillo et al. [34] (RT3)	15.6	3.7	8	12.1	2.9	4	4.6%	0.93 [-0.35, 2.21]
Ramírez-Campillo et al. [16] (HSG)	9.8	2.7	30	8.2	2.1	4	6.1%	0.59 [-0.46, 1.64]
Ramírez-Campillo et al. [16] (LSG)	9.3	3.5	28	8.2	2.1	3	5.1%	0.31 [-0.88, 1.51]
Ramírez-Campillo et al. [35] (EG)	9.5	2	15	8.2	2.1	4	5.6%	0.62 [-0.51, 1.74]
Ramírez-Campillo et al. [35] (SG)	10.1	3.3	15	8.2	2.1	4	5.6%	0.58 [-0.54, 1.70]
Shaw and Snow [36]	25.1	4.1	18	24.2	4.7	22	10.4%	0.20 [-0.43, 0.82]
Uusi-Rasi et al. [37] (AL+Ex+)	21.9	3.7	38	20.5	3.8	38	12.8%	0.37 [-0.08, 0.82]
Uusi-Rasi et al. [37] (AL-Ex+)	22.9	4.9	37	20.8	3.9	39	12.8%	0.47 [0.01, 0.93]
Total (95% CI)			**275**			**177**	**100.0%**	**0.66 [0.33, 0.98]**

Heterogeneity: Tau² = 0.16; Chi² = 24.28, df = 12 (P = 0.02); I² = 51%
Test for overall effect: Z = 3.98 (P < 0.0001)



Values shown are effect sizes with 95% confidence intervals

RT2: Resistance training (2 days); RT3: Resistance training (3 days); HSG: High supervision; LSG: Low supervision; EG: High-speed; SG: Low-speed; AL+Ex+: 5 mg of alendronate daily + exercise; Al-Ex+: Placebo + exercise

Figure 2 Forest plot of increases in muscular power in older adults participating in jump training

3.2 Effect of moderator variables

Subgroup analysis suggested variable levels of between-group heterogeneity that were mostly found to be insignificant (p > 0.05). Effect sizes were larger in older, shorter and heavier individuals. Non-obese individuals demonstrated higher effect sizes than those who were obese (1.03 [95% CI: 0.34, 1.73] vs. 0.53 [95% CI: -0.03, 1.09]).

For programming parameters (see Table 2), effect sizes were of a similar magnitude in programmes of more than (0.71 [95% CI: 0.06, 1.36]) and fewer than (0.61 [95% CI: 0.27, 0.95]) 12 weeks and in programmes with three or more (0.63 [95% CI: 0.16, 1.10]) or fewer than 3 sessions per week (0.65 [95% CI: 0.20, 1.10]) (see Table 3).

Table 2 Characteristics of jump training programmes

Study	Study group	Weeks	Training frequency (p/week)	Total sessions	No. of exercises per session	Exercise type	Session duration (mins)	Sets per exercise	Jumps per set	Rest between sets (s)	Jumps per session	Jumps per programme
Allison et al. [30]	Multidirectional hopping	24	7	168	4	Unilateral hops	5	1-2	10	15	50	8400
Correa et al. [31] *	Rapid training	6	2	12	1	Lateral box jump		3-4	15-20s			
Fishbeck et al. [32]	Training	6	3	18	3	Squat jumps, box jumps, jumping jacks, star jumps		1	45s			
Miszko et al. [33] †	Power training	8	3	24	1	jump squats		3	6-8		21	504
Ramírez-Campillo et al. [35]	High-speed	12	3	36	1	Countermovement jumps		2	3	60	6	216
Ramírez-Campillo et al. [35]	Low-speed	12	3	36	1	Countermovement jumps		2	3	60	6	216
Ramirez-Campillo et al. [34]	Resistance training (2 days)	12	2	24	1	Countermovement jumps		3	4	60	12	288
Ramirez-Campillo et al. [34]	Resistance training (3 days)	12	3	36	1	Countermovement jumps		2	4	60	8	288
Ramírez-Campillo et al. [16]	High supervision	12	3	36	1	Countermovement jumps		2	3	60	6	216
Ramírez-Campillo et al. [16]	Low supervision	12	3	36	1	Countermovement jumps		2	3	60	6	216
Shaw and Snow [36]	Exercise	24	3	72	2	Jumps in place, 4-8 in jump landings		1	1-14		1-28	72-2016
Uusi-Rasi et al. [37] ‡ §	Placebo + exercise	26	1.6	41.6	1	Hurdle jumps	20				100-200	6240

Uusi-Rasi et al. [37] ‡ §	5 mg of alendronate daily + exercise	26	1.6	41.6	1	Hurdle jumps	20			100-200	6240

[a]JT comprised 6 weeks of a 12 week intervention

[b] JT comprised 8 weeks of a 16 week intervention

[c] JT comprised 26 weeks of a 52 week intervention

[d] Training adherence reported instead of frequency

Table 2 Characteristics of jump training programmes

For training session parameters, programmes with more than one exercise were more effective than those with one only (0.74 [95% CI: -0.49, 1.96] vs. 0.53 [95% CI: 0.29, 0.78]). Those programmes with more than two sets per exercise were more effective than those with two or fewer sets per exercise (0.91 [95% CI: 0.04, 1.77] vs. 0.68 [95% CI: 0.15, 1.21]). This difference was accentuated when total sets per session were considered (1.23 [95% CI: 0.37, 2.09] vs. 0.38 [95% CI: 0.02, 0.75]). Similarly, sessions with more than three jumps per set demonstrated larger effect sizes than those with three only (1.02 [95% CI: 0.16, 1.87] vs. 0.53 [95% CI: -0.03, 1.09]), which was the only alternative repetition scheme based on mean and median jumps per set. Programmes with more than 25 jumps per session were more effective than those with fewer than 25 jumps (0.88 [95% CI: 0.05, 1.70] vs. 0.49 [95% CI: 0.14, 0.83]). However, programmes with more than 300 jumps in total were similar in effect to those with fewer than 300 (0.63 [95% CI: 0.08, 1.18] vs. 0.75 [95% CI: 0.26, 1.24]). A summary of the effect of moderator variables can be viewed in Table 3.

Among the studies included in this review, just one reported an acute injury [37], which did not result in the participant ceasing their involvement. The only other adverse effects were some minor overuse symptoms which did not preclude any individual from partaking in the training intervention [37].

Table 3 Subgroup analyses

Subgroup	Studies	Participants	Effect estimate [95% CI]
Main effect on muscle power	13	452	0.66 [0.33, 0.98]
Age	13	452	0.66 [0.33, 0.98]
≥67 yrs	7	191	1.01 [0.46, 1.56]
<67 yrs	6	261	0.36 [0.10, 0.62]

Height	13	452	0.66 [0.33, 0.98]
>160 cm	6	294	0.56 [0.06, 1.06]
<160 cm	7	158	0.79 [0.38, 1.20]
Body mass	12	421	0.64 [0.29, 0.99]
>72 kg	5	197	0.69 [0.02, 1.37]
<72 kg	7	224	0.46 [0.15, 0.77]
BMI	9	336	0.82 [0.37, 1.26]
≥30 kg.m-2	4	103	0.53 [-0.03, 1.09]
<30 kg.m-2	5	233	1.03 [0.34, 1.73]
Sex	13	452	0.66 [0.33, 0.98]
Females	10	350	0.51 [0.28, 0.75]
Females and Males	3	102	0.77 [-0.45, 2.00]
Programme duration	13	452	0.66 [0.33, 0.98]
>12 weeks	4	249	0.71 [0.06, 1.36]
<12 weeks	9	203	0.61 [0.27, 0.95]
Frequency	13	452	0.66 [0.33, 0.98]
3 sessions per week	9	257	0.63 [0.16, 1.10]
<3 sessions per week	4	195	0.65 [0.20, 1.10]
Total sessions	13	452	0.66 [0.33, 0.98]
>36	4	249	0.71 [0.06, 1.36]
≤36	9	203	0.61 [0.27, 0.95]
Sets per exercise	11	300	0.74 [0.32, 1.16]
>2	3	69	0.91 [0.04, 1.77]
≤2	8	231	0.68 [0.15, 1.21]
Jumps per set	9	250	0.80 [0.28, 1.31]
>3	5	147	1.02 [0.16, 1.87]
3	4	103	0.53 [-0.03, 1.09]

Jumps per session	11	402	0.68 [0.31, 1.05]
>25	3	209	0.88 [0.05, 1.70]
<25	8	193	0.49 [0.14, 0.83]
Sets per session	11	300	0.74 [0.32, 1.16]
>2 sets	4	126	1.23 [0.37, 2.09]
2 sets	7	174	0.38 [0.02, 0.75]
Jumps per programme	11	402	0.68 [0.31, 1.05]
>300	5	275	0.63 [0.08, 1.18]
<300	6	127	0.75 [0.26, 1.24]
Number of exercises	13	452	0.66 [0.33, 0.98]
>1 exercise	3	116	0.74 [-0.49, 1.96]
1 exercise	10	336	0.53 [0.29, 0.78]

BMI: body mass index

Effect size scale: (<0.2 = trivial; 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, 2.0-4.0 = very large, >4.0 = extremely large

Table 3 Subgroup analyses

4. Discussion

4.1 Main findings

The purpose of this systematic review and meta-analysis was to evaluate the effects of JT on muscle power in adults older than 50 years of age and to establish programming parameters for optimal exercise prescription. We also wanted to assess the safety of this type of exercise in this population in light of previous suggestions that it could be unsuitable [5,8]. Because of the lack of studies examining the effects of JT in older adults, the effects of this type of exercise on increasing muscle power and function, as well as its general safety, are unclear. The main finding of our analysis was that JT is effective in increasing muscle power in older adults with a moderate main effect being found. This complements a previous review which supported the use of high impact exercise for the preservation of bone mass [14]. Other meta-analyses [9,10] have described the benefits of high-velocity resistance training but, as outlined in section 1, this type of exercise may have differing effects on force expression due to the way muscle actions are utilised during lifting movements with external resistive loads.

The preservation of muscle mass in older adults is of great importance. Strength, balance, stamina and quality of life are dependent on skeletal muscle function [45]. Loss of muscle mass beyond a critical threshold can lead to impaired function and physical disability [45]. Resultant falls can cause injuries and even death, whilst the costs of rehabilitation represent a major public health issue [31,46]. As the age-related decline in muscle mass is more obvious in the legs [47], JT may be particularly helpful in that it directly targets these limbs. The importance of JT is further demonstrated by the different adaptations it can achieve in comparison to training with resistive external loads. This was demonstrated in a study by Correa et al. [31] who found that older adults (67 ± 5 years) who participated in 12 weeks of power or rapid strength (jump) training showed an increased rate of force development within the range of 0 to 0.15s. Conversely, a group that engaged in traditional resistance training demonstrated no increase in that variable despite experiencing a 21% increase in maximal knee extensor strength. These results support the principle of training specificity in older adults with an important distinction to be made between training for power and training for strength.

Muscle power declines at a faster rate with aging compared with muscle strength [48]. Also, muscle power, and not strength, reflects more accurately the ability of older adults to perform functional tasks [49]. For example, as muscle power is correlated with an individual's ability to repeatedly rise from a chair [35], the importance of incorporating power-based activities into exercise programmes is emphasised. Furthermore, the relevance of muscle action type must be taken into account when formulating exercise programmes. It has been suggested that training that focuses on eccentric muscle actions, such as those experienced in a jump landing, are an important determinant of balance maintenance and joint stability [50]. Muscles act eccentrically to decelerate a moving limb and to accumulate elastic energy for utilisation in subsequent concentric actions [51]. This makes efficient eccentric muscle activity particularly important for everyday activities that involve deceleration, such as descending stairs [51]. Previous experimental work has shown that JT enhances eccentric lower body force production to a greater extent than traditional resistance training which induces mostly concentric adaptations [52].

4.2 Training parameters

Subgroup analyses revealed some interesting findings. It is notable that effect sizes were almost twice as large in non-obese (<30 BMI kg.m-2) individuals than in obese individuals. This has implications for the effectiveness of JT in older adults. Previous work has revealed that those individuals who jump higher are capable of doing so through the manipulation of concentric force expression or eccentric rate of force development [53]. It is suggested that these factors could change the properties of musculotendinous tissue which, in turn, could increase velocity during jump take off. In this way, the greater jumping ability of a lighter individual, due to lower fat mass, could result in greater drop heights and, as a result, increased effectiveness of JT due to resultant higher impact forces [54]. Because of this, it may be advantageous to combine JT with weight loss techniques in obese individuals. Indeed, this could be essential for heavier individuals because jumping activities could result in joint injuries due to higher impact forces upon landing [55]. However, this does not mean that obese individuals need to completely abstain from JT. Low-impact jumping activities, such as bunny hops and calf pushes can be used whilst double leg jumps and landings can afford greater stability than single leg variations to the trainee [56]. Exercises such as box jumps (i.e. jumps to, not from, a box) can substantially reduce impact forces as the trainee lands on an elevated platform instead of the ground [57]. Coaching techniques such as demonstrating proper joint positioning, encouraging the trainee to use correct landing mechanics, both physically and by listening to the sound of their landing, can be effective ways of teaching force absorption skills [58].

Further to the above, it was found that JT was more effective in older, shorter and heavier individuals. The latter finding directly opposes the result relating to JT being more effective in non-obese individuals but is perhaps an indication that other unaccounted for factors play a role in the magnitude of adaptation. For example, ageing may affect fascicle length and angle due to sarcopenia but this process can be reversed with resistance training which can increase fibre cross-sectional area [59]. Furthermore, there seems to be a relationship between limb dimensions and muscle architecture with taller individuals thought to exhibit longer fascicles and smaller angles of pennation [60]. These factors are likely to influence force producing capabilities and, potentially, the magnitude of adaptation to JT.

The results of our subgroup analyses could form a basis from which practitioners can programme effective and appropriate JT interventions in older adults. We found that programmes of longer duration (>12 weeks; >36 sessions) were only slightly more effective than those of a shorter duration. Despite this finding, we recommend that JT should be a permanent component of a well-rounded exercise programme in the older adult. Transient bouts of JT, though likely to be effective, are unlikely to confer the benefits of a long-term approach to exercise prescription. However, training practitioners must be cognisant of the concept of the optimal dose of JT: we found that three or more sessions per week was equally as effective as fewer than three. In a similar vein, programmes that included fewer than 300 jumps in total were slightly more effective than those with more than 300 jumps whilst programmes with more than 36 sessions were roughly as effective as those with fewer than 36. Together, these findings indicate that higher training loads are not necessarily more beneficial than lower training loads, an important finding considering that for absolute exercise intensity, fatigue is likely to be greater in older adults [61], especially during high-speed muscle actions [62]. This could result in a greater risk of overtraining if workloads are not appropriately balanced with intervention studies supporting the relative effectiveness of lower training loads [63,34]. We recommend that training practitioners should programme JT over the long term, exposing individuals to no more than three sessions per week. However, given the results of subgroup analyses, it seems that overall training volume is a more important factor to consider than training frequency. If JT is delivered in time-restricted blocks over the longer term, it seems prudent to place an upper limit of 300 jumps over the course of the programme given that training volumes which exceeded this amount were marginally less effective. This makes logical sense: responses to training do not continue indefinitely and are restricted by an upper threshold above which functional gains are not possible [64]. With this in mind, it may not be worth exposing an individual to exercise stimuli when there exists an unfavourable risk to reward ratio.

Practitioners must also consider the importance of in-session programming parameters. The most effective JT programmes were those that comprised more than one exercise (range: 1-4), more than two sets per exercise (range: 1-4), and more than three jumps per set (range: 1-14). It was also apparent that more effective programmes comprised more than 25 jumps per session (range: 6-200), which, in practice, could be divided between the aforementioned exercise, set and jump programming schemes. An effective programme could be structured as such: three exercises comprising three sets of 8 jumps per set, using the principles of periodisation [65,66] to add volume and intensity (increasing jump height) as the trainee adapts to the applied stimulus. Practitioners should adopt a conservative approach in determining the optimal volume of jumps per session building up to 25 jumps and adding volume only after the attainment of technical competency with no contraindications. Training recommendations are summarised in Table 4.

Table 4 Recommendations for configuration of jump training

Training variable	Programme duration	Session frequency	Jumps per programme	Jumps per session	Jumps per set	Number of exercises	Sets per exercise	Sets per session	Recovery between sets
Recommendation	12 weeks[a]	Up to 3 per week	300 or fewer	25 or more [b]	3-10[†]	More than 1	2 to 3[†]	2 or more [†]	60 s

[a]After an introductory programme, practitioners should aim for jump training to be continued indefinitely

[b]Increases in jump training volume should be gradual and conservative

Table 4 Recommendations for configuration of jump training

The results of the subgroup analysis in relation to these training variables are logical. Variation of training stimuli can underpin continued adaptation whilst training monotony, more likely to occur in single-exercise programmes, can impede progress [67]. Indeed, we observed that programmes with more than two exercises were most effective, with the most varied programmes being predominantly the longest (>12 weeks). The importance of variation in JT programming is further underlined by the specificity of adaptation to imposed training stimuli as demonstrated by Ramirez-Campillo et al. [68]. A previous study showed that a varied training programme proved to be more effective than an unvaried programme over a 14 week period [69]. This same study showed that multiple sets were more effective than a single set protocol. We encourage exercise professionals to programme between two and four sets per exercise and previous work seems to support this recommendation [70,71]. This is also an important issue for compliance to a training strategy. Monotonous exercise could result in a trainee disengaging from an intervention, either during it or after its conclusion, due to illness, boredom or strain [72]. This could result in detraining [73] whilst compliance issues are further compounded if training is unsupervised [74].

In relation to the amount of jumps per set, 10 seems an adequate number [71,75] given our results though practitioners must recognise the varying intensity of different JT methods. For example, exercises such as depth jumps and tuck jumps may be far less suitable than box jumps and in-place or submaximal jumps for the older adult due to the high forces than must be absorbed during performance [75]. Any individual who is not experienced in undertaking high-intensity plyometric activities should begin training at the lowest level of challenge, progressing only when technical competency is attained and never if pain is present during any movement. Most studies in this review used 60s rest periods between sets meaning it is difficult to expand further on this particular variable.

4.3 Safety

Previous reviews have indicated that power training in older adults resulted in back injuries and the aggravation of pre-existing overuse injuries [5]. Contrary to this finding, out of the 275 individuals involved in the nine studies analysed in the current review, only one acute injury due to training (ankle sprain) was reported. We believe that this goes some way to underlining the safety of this type of exercise relative to what has previously been stated. A recent comprehensive review [71] reinforced this stance with the authors reporting no relationship between participation in JT and injury incidence, even when high-intensity movements such as drop jumps were considered. Similar concerns to the above have previously been expressed as to the safety of resistance training in other populations [76] but it is likely that sufficiently qualified coaches can offset the risks associated with this type of exercise [77]. To complement this approach, any individual who is being exposed to JT for the first time should receive a programme that is appropriate to their movement capabilities and training history. To this end, technical competency should be present before the initiation of any programme and this could be enhanced through a programme of preparatory exercise [78]. Nevertheless, it must be highlighted that the studies in this meta-analysis were carried out in healthy individuals. If an individual has already developed age-related health problems our recommendations may not be suitable.

4.4 Future research

For future research purposes we recommend that researchers carry out specific jump training interventions independent of any other forms of exercise training. Ramirez-Campillo et al. [7] have previously stated the difficulty in distinguishing the effects of multiple concurrent training types on outcome variables in intervention studies. This makes it difficult to determine the true effects of JT in this population with this study design a feature of all but one investigation [30] in the current analysis. Further to this point, just a single JT study [30] in this review was carried out in a male population only. This is surprising given the extensive number of studies that have been carried out in male populations in general [7] and this represents a viable avenue of investigation for researchers in the future. The same study [30] was the only one to examine the effect of unilateral JT and this is a line of inquiry that should be further pursued. As per recommendations for resistance training in other populations [79], researchers should always provide data for males and females separately for any main effects in JT studies in older adults.

4.5 Limitations

There are some limitations to the current study so our results should be interpreted with caution. For subgroup analyses, the dichotomisation of continuous data with median split could result in residual confounding and reduced statistical power [80,81]. Furthermore, the effects of these programming variables were calculated independently, and not interdependently. Univariate analysis must be interpreted with caution because the programming parameters were calculated as single factors, irrespective of between-parameter interactions. The conclusions are, nonetheless, in line with conventional recommendations for the programming of JT [75]. The low number of adverse responses to JT is encouraging but it is possible that in some cases authors did not report this information. We reiterate our stance on the safety of JT exercise in adults older than 50 years but recommend that practitioners take a cautious approach to programming. In addition, the reader must consider the lack of uniformity in how training programmes were prescribed and tested. We observed only moderate heterogeneity between trials but nonetheless encourage practitioners to formulate programmes that are appropriate to the individual(s) with whom they are working.

5. Conclusion

Based on these results we conclude that JT is a safe and effective way to increase muscle power in older adults. However, practitioners must consider some individuallyspecific factors when formulating JT programmes. It seems that JT is far less effective in obese individuals than it is in those of normal bodyweight. This means the effectiveness of JT could be enhanced when combined with other exercise and dietary interventions to control bodyweight and concurrently increase muscular power. This should influence the programming decisions of the practitioner who should use exercises that minimise landing forces and, by extension, the impact exerted on joints utilised during performance. On the whole, it seems that programming parameters relating to training session design are more influential than the duration of the JT intervention. This implies that exercise type, number, volume and intensity should be considered more important than programme duration but we encourage exercise practitioners to maintain an element of JT in a fitness regime at all times. Practitioners should construct varied JT programmes that include more than one exercise and comprise more than two sets per exercise, more than three jumps per set and 60 seconds of recovery between sets. An upper limit of three sets per exercise and ten jumps per set is recommended. When utilising higher volumes and intensities, practitioners should take a gradual approach to exposing trainees to greater training loads. Furthermore, JT does and should, not have to be carried out in isolation as complementary forms of exercise, such as resistance training, are likely to induce an additive response to imposed stimuli.

Compliance with Ethical Standards

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Conflicts of Interest

Jason Moran, Rodrigo Ramirez-Campillo and Urs Granacher declare that they have no conflicts of interest relevant to the content of this review.

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