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Body composition adaptations to lower-body plyometric training: a systematic review and meta-analysis

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ABSTRACT: The aim of this meta-analysis was to explore the effects of plyometric jump training (PJT) on body composition parameters among males. Relevant articles were searched in the electronic databases PubMed, MEDLINE, WOS, and SCOPUS, using the key words "ballistic", "complex", "explosive", "force-velocity", "plyometric", "stretch-shortening cycle", "jump", "training", and "body composition". We included randomized controlled trials (RCTs) that investigating the effects of PJT in healthy male's body composition (e.g., muscle mass; body fat), irrespective of age. From database searching 21 RCTs were included (separate experimental groups = 28; pooled number of participants = 594). Compared to control, PJT produced significant increases in total leg muscle volume (small ES = 0.55, $p = 0.009$), thigh muscle volume (small ES = 0.38, $p = 0.043$), thigh girth (large ES = 1.78, $p = 0.011$), calf girth (large ES = 1.89, $p = 0.022$), and muscle pennation angle (small ES = 0.53, $p = 0.040$). However, we did not find significant difference between PJT and control for muscle cross-sectional area, body fat, and skinfold thickness. Heterogeneity remained low-to-moderate for most analyses, and using the Egger's test publication bias was not found in any of the analyses ($p = 0.300$–0.900). No injuries were reported among the included studies. PJT seems to be an effective and safe mode of exercise for increasing leg muscle volume, thigh muscle volume, thigh and calf girth, and muscle pennation angle. Therefore, PJT may be effective to improve muscle size and architecture, with potential implications in several clinical and sport-related contexts.

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INTRODUCTION

From an anatomical perspective, body composition is divided into the following sections: adipose tissue, skeletal muscle, bone, and organs. As such, body composition is considered as one of the main health-related components of physical fitness [1]. For example, poor body composition (i.e., low amounts of muscle mass and high amounts of adipose tissue) is associated with major chronic conditions, such as type 2 diabetes, cardiovascular diseases, cancers, and mortality [2]. From an athletic perspective, body composition in general, and lean body mass in particular is associated with performance in several exercise tests [3]. Besides adipose tissue and lean body mass, bone mass is another important aspect of body composition as the loss of bone mass and micro-architectural deterioration in bone tissue may lead to bone fragility and increased fracture risk (i.e., osteoporosis) [4, 5].

Several preventive and treatment strategies for 'healthy' body composition are available, one of such being physical exercise [6–8]. World-leading organizations for physical activity promote aerobic exercise for fat loss and resistance training for increases in bone and lean body mass [9]. One mode of exercise that has received less attention in this context is plyometric jump training (PJT). Generally, PJT programs are associated with jump drills that are conducted using the stretch-shortening cycle (SSC) [10, 11], classified as fast SSC (i.e., short ground contact time; < 250 ms; usually involving the stretch reflex) or slow SSC (i.e., long ground contact time;

> 250 ms) exercises [12–14]. During PJT exercises the SSC includes a rapid eccentric action immediately followed by a rapid concentric contraction of the same muscles, allowing efficient use of accumulated elastic energy and facilitating greater mechanical work in subsequent actions [10, 11]. Lower-body PJT involves the utilization of different types of jumping movements as depth jumps, hops, bounding, or skipping [12, 13, 15].

In a 2010 comprehensive review, Markovic and Mikulic [16] established that PJT has a positive effect on bone mass, particularly among pre-pubertal and early pubertal children, young women, and premenopausal women. Subsequently, these results were also confirmed in two meta-analyses [17, 18]. Even though previous studies explored the effects of PJT on other components of body composition, such as lean body mass and adipose tissue, the results between studies remain equivocal [19–22]. The contrasting evidence may be in part due to the generally low sample sizes of primary studies. A recent scoping review of 242 studies established that studies exploring the effects of PJT are generally limited by the small sample size, as they usually include less than sixteen participants per study [15]; this problem of underpowered studies may be resolved by conducting a meta-analysis [23–25]. Specifically, by pooling the results of several primary studies, we may be able to increase the total statistical power allowing us to draw a stronger conclusion of the effectiveness of PJT on reducing fat mass and increasing lean body mass [23–25].

In recent years, the number of scientific publications on PJT has experienced a dramatic increase [26]. Given the increased scientific awareness of PJT relevance, and the lack of systematic reviews and meta-analyses with a focus on human body composition adaptations (other than bone mass), the aim of this review with meta-analysis was to assess the effects of PJT in males body composition (e.g., muscle mass; body fat). Due to potential differences according to sex in body composition changes due to training [27], it would be relevant to conduct separate analyses according to participant's sex. However, in a piloting over the PJT literature, we noted only four randomized-controlled PJT studies in female participants that analysed body composition-related outcomes. Among these, less than three studies provided data for the same outcome, precluding a robust meta-analysis. Therefore, only studies conducted in males were selected.

MATERIALS AND METHODS

A systematic review and meta-analysis was conducted in accordance to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [28].

Search strategy

For this review, we search through PubMed, MEDLINE, Web of Science, and SCOPUS electronic databases from the inception of indexing until November, 2020. Keywords were collected through experts' opinion, literature review, and controlled vocabulary (e.g., Medical Subject Headings: MeSH). In PubMed/MEDLINE database, the following search syntax was used: (((((((((("randomized controlled trial"[Publication Type]) OR "controlled clinical trial"[Publication Type]) OR "randomised"[Title/Abstract]) OR "trial"[Title]) OR "clinical trials as topic"[MeSH Major Topic]) OR "men"[Title/Abstract]) OR "male"[Title/Abstract]) AND "training"[Title/Abstract]) OR "plyometric"[Title/Abstract])) AND "body composition"[MeSH Terms]. Studies were excluded based on title, abstract, or full-text. Following the main systematic searches, additional hand-searches were conducted. Grey literature sources in the form of conference proceedings were also considered only if the full-text was available. Secondary searches were performed by reviewing the reference lists of the included studies and previous reviews and meta-analysis to detect additional studies potentially eligible for inclusion [15, 29–32]. Two authors conducted the process independently; discrepancies between the two reviewers were resolved through discussion and consensus with a third author.

Eligibility Criteria

The *a priori* inclusion criteria for this review were as follows: (i) population: cohorts of healthy male participants, with no restriction for age; (ii) intervention: a PJT programme, involving (but not limited to) the following lower-body drills: unilateral or bilateral bounds, jumps, hops, squat jumps, repeated jumps actions; (iii) comparator: a control group of male participants; (iv) outcome: a pre-to-post intervention assessment of some body composition parameters (e.g., muscle mass; body fat). Laboratory body composition measurement techniques (e.g., DEXA) and field-based techniques (e.g., skinfolds) were considered as appropriate, as long as the validity and reliability of the techniques were reported; (v): study design: randomised-controlled studies (RCTs). Trials that included PJT combined with another intervention (co-intervention) were included when an active control group was included, as long as the PJT intervention was not simply an added load and comprised ≥ 50% of the intervention.

Exclusion criteria

Articles were excluded if they were cross-sectional (transversal), a review, or a training-related study not focused on the effect of PJT exercises. Also excluded were retrospective studies, prospective studies, studies in which the use of jump exercises was not clearly described, studies for which only the abstract was available, case reports, studies with ambiguous study protocols, non-human investigations, special communications, repeated references, letters to the editor, invited commentaries, errata, overtraining studies, and detraining studies. If the studies included a detraining component, we only considered the data obtained during the training period (i.e., results obtained prior to the detraining period). Finally, non-English studies were not explored, as a previous scoping review [15] in the field of PJT observed that 99.6% of published studies are in English, and the remaining studies may not be feasibly translated.

Data extraction

Data were extracted from the included studies independently by two authors, using a form created in Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). Extracted data included the following information: the first author's name, year of publication, country of the first author institution, PJT treatment description, description of the control comparison, type of randomization, number of participants per group. We also extracted data regarding the participants' sex, age (years), body mass (kg), height (m), previous experience with PJT. If applicable, the type and level (e.g., professional, amateur) of sport practice were also extracted. Regarding PJT characteristics, extracted data also included the frequency of training (days/week), duration (weeks), intensity level (e.g., maximal) and marker of intensity (e.g., jumping height), jump box height (cm), number of total jumps completed during the intervention, types of jump drills performed, combination (if applicable) of PJT with another form of training type, rest time between sets (s), rest time between repetitions (s), rest time between sessions (hours), type of jumping surface (e.g., grass), type of progressive PJT overload (e.g., volume-based; technique-based), training period of the year (e.g., in-season), replace (if applicable) portion of the regular training with PJT, tapering strategy (if applicable). A complete description of these PJT characteristics has been previously published [15].

Risk of bias of individual studies

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). As in similar previous PJT meta-analysis [33], the quality assessment was interpreted using the following 10-point scale: ≤ 3 points was considered poor quality, 4–5 points as moderate quality, and 6–10 points as high quality. Two independent reviewers performed this process; disagreements in the rating of the studies between the reviewers were resolved through discussion and consensus with a third author. Agreement between reviewers was assessed using a Kappa correlation for risk of bias. The agreement rate between reviewers was k = 0.81.

Statistical analyses

For analysis and interpretation of results, meta-analyses were conducted if at least three studies provided effect sizes for the same parameter [29, 34, 35]. Means and standard deviations for a measure of post-intervention body composition were converted to a standardised mean difference (ES). 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 [36] and facilitates analysis while accounting for heterogeneity across studies [37]. In this sense, the likelihood approach with random effects was used to better account for the inaccuracy in the estimate of between-study variance [38]. The ES are represented by the standardised mean difference and are presented alongside 95% confidence intervals (CIs). The calculated ES were interpreted using the conventions outlined for standardised mean difference: < 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 [39]. In some studies in which there was more than one intervention group, the control group was proportionately divided to facilitate comparison across all participants [40]. All analyses were carried out using the Comprehensive Meta-Analysis program (version 2; Biostat, Englewood, NJ, USA).

Heterogeneity

To gauge the degree of heterogeneity amongst the included studies, the percentage of total variation across the studies due to heterogeneity (Cochran's *Q*-statistic) [41] was used to calculate the I^2 statistic. This represents the proportion of effects that are due to heterogeneity as opposed to chance [28]. Low, moderate and high levels of heterogeneity correspond to I^2 values of < 25%, 25–75%, and > 75%, respectively [41, 42]. The Chi square test assesses if any observed differences in results are compatible with chance alone. A low *p* value, or a large Chi square statistic relative to its degree of freedom, provides evidence of heterogeneity of intervention effects beyond those attributed to chance [36].

Publication bias

Risk of bias across studies was assessed using the extended Egger's test [43]. Sensitivity analyses were conducted to assess the robustness of the summary estimates in order to determine whether a particular study accounted for the heterogeneity. Thus, in order to examine the effects of each result from each study on the overall findings, results were analysed with each study deleted from the model once. It is acknowledge that other factors, such as differences in trial quality or true study heterogeneity, could produce asymmetry.

Subgroup analyses

To assess the potential effects of moderator variables selected according to the median split technique, additional subgroup analyses were performed according to programme duration (≤ 10 vs. > 10 weeks), training frequency (< 3 vs. ≥ 3 sessions per week), and the total number of training sessions (≥ 30 vs. < 30 sessions). These variables were chosen based on the accepted influence of such factors on adaptations to exercise [44], as previously demonstrated in meta-analyses related to PJT [45, 46]. Participants were divided using a median split [32, 45, 46]. Meta-analyses stratification by each of these factors was performed, with a *p* value of < 0.050 considered as the threshold for statistical significance.

Meta-regression

A multivariate random-effects meta-regression was conducted to verify if any of the training variables (frequency, duration, and total number of sessions) predicted the effects of PJT on body composition variables. Computation of meta-regression was performed with at least 10 studies per covariate [24].

RESULTS

Study selection

The Figure 1 provides a graphical schematization of the study selection process. Through database searching, 8,730 records were initially identified, and 31 were considered for qualitative synthesis. However, from the 31 studies only one study provided data on percentage of muscle fiber types [47], five studies did not provide clear data for post-intervention outcomes [48–52], three studies provided repeated results (i.e., results already published elsewhere) [53–55], and one study mixed jumps with resistance training and/or sprints [56]. Therefore, 21 RCTs [20–22, 57–74] were included in the meta-analysis.

The included studies provided mean and standard deviation post-intervention data for at least one main outcome. The included studies comprised 28 individual experimental groups and 594 participants (251 in the control groups).

Study characteristics

The characteristics of the participants from the included studies are displayed in Table 1, while the programming parameters of the PJT interventions from the included studies are indicated in Table 2.

Risk of bias within studies

The median for total points attained in the PEDro scale was 6 among the included studies. From these, 5 RCTs achieved a quality assessment of 4–5 points (i.e., moderate quality), while the other 16 studies achieved a quality assessment of 6–8 points and were therefore classified as being of high-quality (Table 3).

Muscle mass

From the included studies, five [21, 22, 60, 70, 72] provided data for whole body muscle mass (i.e., fat-free mass, lean mass, muscle mass), involving eight experimental groups. From the five studies, three included DXA measurements [22, 70, 72]. The relative weight of each study in the analysis varied between 8.6% and 15.7%. Of note, in the sensitivity analysis, the results remained consistent across all deletions, except for the study from Daehlin et al. [22]. When removed, there was a near-significant favouring of PJT for increase in muscle mass (small ES = 0.28 [95%CI = -0.01 to 0.57], $p = 0.053$) (supplementary Figure 1, A). A moderate heterogeneity ($I^2 = 43.4\%$) was observed, and publication bias was not found using the Egger's test ($p = 0.400$).

Total leg muscle volume

From the included studies, five provided data for total leg muscle volume [21, 58, 59, 64, 68], involving five experimental groups. The relative weight of each study in the analysis varied between 18.7% and 21.5%, demonstrating an equilibrated weight distribution. In the sensitivity analysis, the results remained consistent across all deletions, except for the study from Chelly et al. [64]. When removed, there was favouring of PJT for increase in total leg muscle volume (small ES = 0.55 [95%CI = 0.14 to 0.96], $p = 0.009$) (supplementary Figure 1, B). A moderate heterogeneity ($I^2 = 50.5\%$)

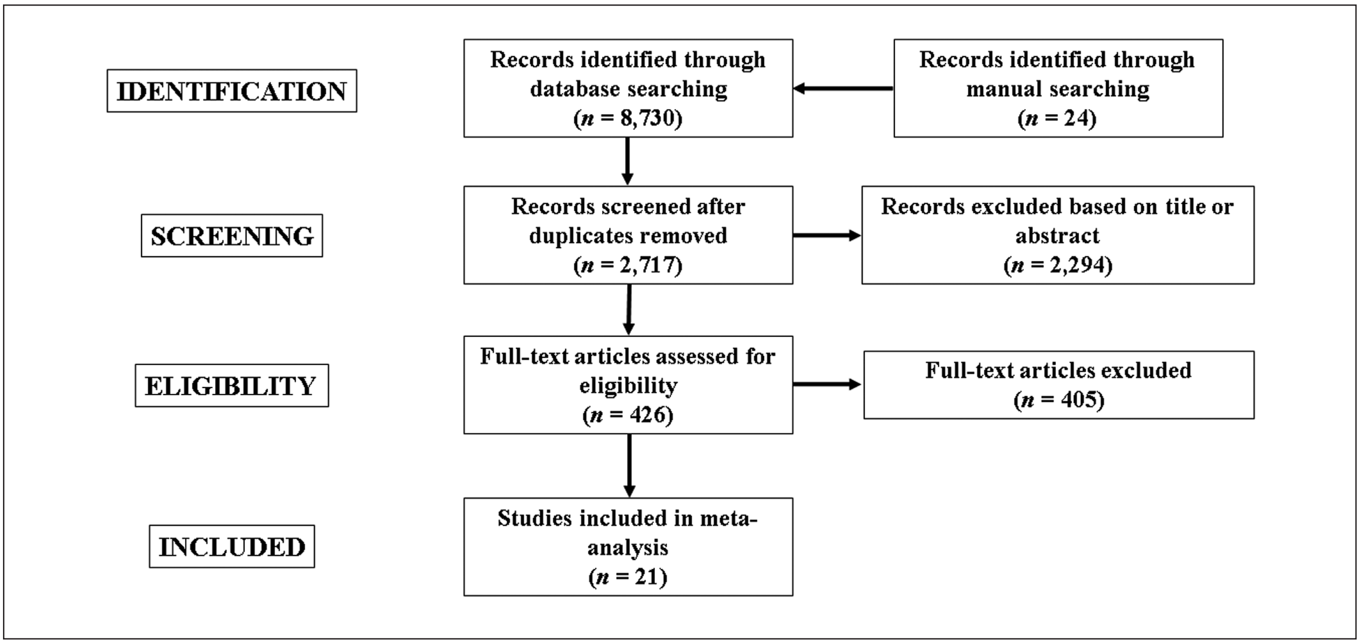

FIG. 1. PRISMA flow diagram.

TABLE 1. Characteristics of included study participants.

	Age (years)	Body mass (kg)	Height (m)	SPT	Sport	Fitness level	TP
Chelly et al. 2015	11.7	43.0	1.58	No	Runners (100-m to 3-km)	Moderate	IS
Chaouachi et al. 2014	11.0	40.1	1.5	No	Wrestling and judo	Normal	NA
Chelly et al. 2014	17.1	80.1	1.81	No	Handball	Moderate - high	IS
Pienaar and Coetzee 2013	18.9	90.0	1.83	NR	Rugby	Moderate - high	PS
Michailidis et al. 2013	10.7	42.5	1.47	No	Soccer	Moderate	IS
Sedano et al. 2011	18.4	70.7	1.74	Yes	Soccer	Moderate-high	IS
Fouré et al. 2011	18.8	68.4	1.77	NR	NR	High	NR
Chelly et al. 2010	19.1	70.3	1.76	NR	Soccer	Moderate - high	IS
Berryman et al. 2010	29.0	74.6	1.78	No	Endurance runners	Moderate - high	NR
Diallo et al. 2001	12.3	41.2	1.53	NR	Soccer	Moderate	NR
Egan-Shuttler et al. 2017	16.0	71.4	1.79	No	Rowers	Moderate	IS
Dæhlin et al. 2017	17.2	84.8	1.82	NR	Ice-hockey	Moderate - high	NR
Gomez-Molina et al. 2018	20.4	75.0	1.77	No	Mix (handball; tennis; judo)	NR	NR
Hammami et al. 2019	15.7	58.9	1.75	NR	Soccer	Moderate	IS
Fathi et al. 2019	14.6	67.9	1.78	No	Volleyball	Moderate-high	IS
Vlachopoulos et al. 2018 (swimmers)	14.5	57.2	1.70	NR	Swimmers	Normal - high	NR
Vlachopoulos et al. 2018 (footballers)	13.8	49.3	1.61	*	Footballers		
Vlachopoulos et al. 2018 (cyclists)	14.1	57.7	1.68		Cyclists		
Cormie et al. 2010 C (stronger)	23.4	79.1	1.79	NR	NR	Moderate-high	NR
Cormie et al. 2010 C (weaker)						Normal	
Cimenli et al. 2016 (wood)	18–24	73.7	1.84	NR	Volleyball	Moderate – high	PS
Cimenli et al. 2016 (synthetic)		83.1	1.85				
Coratella et al. 2018 (unloaded)	18–25	73.0	1.78	NR	Soccer	Moderate	OS
Coratella et al. 2018 (loaded)							
Hortobagyi et al. 1990 (vertical)	13.4	48.9	1.59	Yes	None	Normal	NA
Hortobagyi et al. 1990 (horizontal)		53.1	1.66				
Hortobagyi et al. 1991 (bounding)	16	61.2	1.75	No	None	Normal	NA
Hortobagyi et al. 1991 (technical)		65.9	1.76				

Note: abbreviations descriptions ordered alphabetically. IS: in-season; NA: non-applicable; NR: non-reported; PJT: plyometric jump training; SPT: indicates if the participants had previous systematic experience with PJT; OS: off-season; PS: pre-season; TP: training period. *: blank blocks: as more than on experimental group participated in some interventions, blank-block information denote that the corresponding group share the same information as the previous depicted group.

was observed, and publication bias was not found using the Egger's test ($p = 0.900$).

Thigh muscle volume

From the included studies, five provided data for thigh muscle volume [58, 59, 64, 68, 69], involving five experimental groups. The relative weight of each study in the analysis varied between 15.8% and 21.6%. In the sensitivity analysis, the results remained consistent across all deletions, except for the study from Chelly et al. [64]. When removed, there was favouring of PJT for increase in thigh muscle volume (small ES = 0.38 [95%CI = 0.01 to 0.75], $p = 0.043$) (supplementary Figure 1, C). A low heterogeneity ($I^2 = 0\%$) was observed, and publication bias was not found using the Egger's test ($p = 0.800$).

Thigh girth

From the included studies, 4 [60, 66, 73, 74] provided data for thigh girth, involving 6 experimental groups. The relative weight of each study in the analysis varied between 14.9% and 18.0%. In the sensitivity analysis, the results remained consistent across all deletions, except for the study from Hortobagyi et al. [74]. When removed, there was favouring of PJT for increase in thigh girth (large ES = 1.78 [95%CI = 0.41 to 3.12], $p = 0.011$) (supplementary Figure 1, D). A high heterogeneity ($I^2 = 92.3\%$) was observed, and publication bias was not found using the Egger's test ($p = 0.800$).

Calf girth

From the included studies, 4 [60, 66, 73, 74] provided data for calf girth, involving 6 experimental groups. The relative weight of each

TABLE 2. Characteristics of PJT programs.

Study	PJT	Freq	Duration (weeks)	Intensity	BH (cm)	NTJ	Tply	RBS (s)	RBR (s)	RBTS (hours)	Surf	PO	Repl	Taper
Chelly et al. 2015	WD	3	10	Max	30–40	1,800	Mix	NR	5	48	NR	I, V, T	No	No
Chaouachi et al. 2014	WD	2	12	Max	NR	1,080	Mix	180	NR	72	NR	V	Yes	Yes
Chelly et al. 2010	WD	2	8	Max	40	860	Mix	NR	5	48	NR	V, I, T	Yes	No
Pienaar and Coetzee 2013	ID	3	4	NR	NR	740	Mix	30	NR	NR	NR	No	No	No
Michailidis et al. 2013	ID	2	12	Max	10–20–30	> 1,560	Mix	90–180	NR	72	Grass	I, V	Yes	No
Sedano et al. 2011	WD	3	10	Max	NA	2,880	Mix	50–300	~1	48–72	Hard synthetic floor	V	Yes	No
Foure et al. 2011	ID	2–3	14	NR	35–50–65	~6,800	Mix	NR	NR	NR	NR	V, T, I	NR	NR
Chelly et al. 2014	WD	2	8	Max	40	860	Mix	NR	5	≥ 48	Grass	V, I, T	No	No
Berryman et al. 2010	WD	1	7–8	Max	20–40–60	240	Drop jump	180	NR	168	NR	V	No	Yes
Diallo et al. 2001	ID	3	10	NR	30–40	7,500	Mix	NR	NR	NR	NR	V, I	NR	No
Egan-Shuttler 2017	ID	3	4	NR	NR	1,705	Mix	NR	NR	48–72	NR	V	Yes	No
Dæhlin et al. 2017	WD	2–3	8	Max	NA	819	Mix	NR	NR	24 to > 48	NR	V	Yes	No
Gomez-Molina et al. 2018	WD	2	8	Max	NR	2,080	Mix	45–90	NR	NR	NR	V, T	No	No
Hammami M et al. 2019	WD	2	8	Max	50–70	722	Mix	NR	5	48–120	Tartan track	T, I, V	Yes	No
Fathi et al. 2019	ID	2	16	Max	30–40	1,184	Mix	90	NR	≥ 48	NR	V, T, I	NR	No
Vlachopoulos et al. 2018	ID	3–4	36	NR	NA	8,880	Mix (repeated jumps)	21,600	NA	NR	Hard surface	V, I	NR	Yes
Cormie et al. 2010 C	WD	3	10	Max	NA	1,090	Loaded jump squat	180	NR	≥ 24	NR	I	Yes	No
Cimenli et al. 2016	ID	3	8	NR	30–70	3,000	Mix	120	NR	48–72	Wood	T, V	NR	No
*											Synthetic			
Coratella et al. 2018	WD	2	8	Max	NA	800	Squat jumps	180	NR	≥ 48	NR	No	NR	No
						656	Loaded squat jumps					V, I		
Hortobagyi et al. 1990	WD	2	10	Max	NR	2,600	Mix (vertical)	NR	NR	NR	Wooden parquet	V	Yes	No
				Max			Mix (horizontal)				Gym mat			
Hortobagyi et al. 1991	ID	3	10	Max	NA	2,280	Mix (horizontal)	NR	NR	NR	Mixed surfaces	V, T	Yes	Yes
				NR		820	Mix (running long jumps)							

Note: abbreviations descriptions ordered alphabetically. BH: box height (for those drills that required the use of a box or hurdle, not necessarily applied to drop jumps); Freq: PJT frequency (sessions per week); ID: insufficiently described, when the PJT treatment description omitted the reporting of any of the following: duration, frequency, intensity, type of exercises, sets, repetitions; Max: maximal, involving either maximal effort to achieve maximal height, distance, RSI, velocity (time contact or fast stretch-shortening cycle), or another marker of intensity; Mix: mixed PJT involved a combination of 2 or more of the following jumping drills: vertical, horizontal, bilateral, unilateral, repeated, non-repeated, lateral, cyclic, sport-specific, slow stretch-shortening cycle, fast stretch-shortening cycle; NA: non-applicable; NR: non-clearly reported; NTJ: number of total jumps (usually counted as jumps per each leg); PJT: plyometric jump training; PO: progressive overload, in the form of either volume (i.e., V), intensity (i.e., I), type of drill (i.e., T), or a combination of these; RBR: rest time between repetitions (only when the PJT programme incorporated non-repeated jumps); RBS: rest time between sets; RBTS: rest between training sessions; Repl: Replace, denoting if the athletes replace some common drills from their regular training with PJT drills. If not, the PJT load was added to their regular training load; RSI: reactive strength index; Surf: type of surface used during the intervention; Tply: type of PJT drills used; WD: well described, when treatment description allowed for adequate study PJT replication, including the reporting of duration, frequency, intensity, type of exercises, sets, and repetitions. *: Blank blocks: as more than on experimental group participated in some interventions, blank-block information denote that the corresponding group share the same information as the previous depicted group.

TABLE 3. Physiotherapy Evidence Database (PEDro) scale ratings.

	PEDro scale item N° 1*	PEDro scale item N° 2	PEDro scale item N° 3	PEDro scale item N° 4	PEDro scale item N° 5	PEDro scale item N° 6	PEDro scale item N° 7	PEDro scale item N° 8	PEDro scale item N° 9	PEDro scale item N° 10	PEDro scale item N° 11	Total
Berryman et al. 2010	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7
Chaouachi et al. 2014	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Chelly et al. 2015	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Chelly et al. 2014	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Chelly et al. 2010	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Cimenli et al. 2016	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Coratella et al. 2018	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	8
Cormie et al. 2010 C	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Dæhlin et al. 2017	Yes	Yes	No	No	No	No	No	Yes	No	Yes	Yes	4
Diallo et al. 2001	Yes	Yes	No	Yes	No	No	No	Yes	Yes	No	Yes	5
Egan-Shuttler et al. 2017	Yes	Yes	No	Yes	No	No	No	Yes	No	Yes	Yes	5
Fathi et al. 2019	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	7
Fouré et al. 2011	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Gomez-Molina et al. 2018	Yes	Yes	No	Yes	No	No	No	Yes	No	Yes	Yes	5
Hammami et al. 2019	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Hortobagyi et al. 1991	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Hortobagyi et al. 1990	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Michailidis et al. 2013	Yes	Yes	No	Yes	No	No	No	No	No	Yes	Yes	4
Pienaar and Coetzee 2013	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Sedano et al. 2011	Yes	Yes	No	Yes	No	No	No	Yes	Yes	Yes	Yes	6
Vlachopoulos et al. 2018	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	7

**: a detailed explanation for each PEDro scale item can be accessed at* https://www.pedro.org.au/english/downloads/pedro-scale

study in the analysis varied between 14.4% and 18.4%. In the sensitivity analysis, the results remained consistent across all deletions, except for the study from Hortobagyi et al. [74]. When removed, there was favouring of PJT for increase in calf girth (large ES = 1.89 [95%CI = 0.28 to 3.51], $p = 0.022$) (supplementary Figure 1, E). A high heterogeneity ($I^2 = 88.7\%$) was observed, and publication bias was not found using the Egger's test ($p = 0.500$).

Muscle pennation angle

From the included studies, three [20, 63, 72] provided data for muscle pennation angle, involving five experimental groups. In one of the studies [63] analyses were conducted in three different muscle groups. Therefore, the final analysis comprised seven data sets. However, in the aforementioned study [63] we calculated the ES and variance for each muscle group and then the average was used for the analysis. The studies analysed knee extensor (i.e., vastus lateralis) [20, 72] and plantar-flexors muscles [63]. The relative weight of each study in the analysis varied between 13.3% and 25.8%. In the sensitivity analysis, the results remained consistent across all deletions, except for the study of Foure et al. [63]. When removed, there was favouring of PJT for increase in muscle pennation angle (small ES = 0.53 [95%CI = 0.03 to 1.03], $p = 0.041$) (supplementary Figure 1, F). A low heterogeneity ($I^2 = 14.7\%$) was observed, and publication bias was not found using the Egger's test ($p = 0.800$).

Muscle cross-sectional area

From the included studies, four provided data for muscle cross-sectional area, including the thigh [58, 64, 68] and the triceps surae muscles [63]. We did not find a significant difference between control and PJT in muscle cross-sectional area (trivial ES = -0.05 [95%CI = -0.46 to 0.35], $p = 0.796$) (supplementary Figure 1, G). The relative weight of each study in the analysis varied between 20.2% and 28.4%. In the sensitivity analysis, the results remained consistent across all deletions. A low heterogeneity ($I^2 = 0\%$) was observed, and publication bias was not found using the Egger's test ($p = 0.300$).

Body fat

From the included studies, ten [20–22, 57, 60–62, 69–71] provided data for whole body fat (i.e., percentage; mass), including measures through DXA [20, 22, 70], for a total of 14 experimental groups. We did not find a significant difference between PJT and control for reduction in body fat (trivial ES = -0.11 [95%CI = -0.35

to 0.13], $p = 0.368$) (supplementary Figure 1, H). The relative weight of each study in the analysis varied between 3.4% and 11.5%. In the sensitivity analysis, the results remained consistent across all deletions. A low heterogeneity ($I^2 = 19.9\%$) was observed, and publication bias was not found using the Egger's test ($p = 0.600$).

Skinfold thickness

From the included studies, four [21, 60, 65, 67] provided data for skinfold thickness (i.e., 4 to 8 summed skinfolds). We did not find a significant difference between PJT and control for change in skinfold thickness (trivial ES = -0.012 [95%CI = -0.74 to 0.71], $p = 0.975$) (supplementary Figure 1, I). The relative weight of each study in the analysis varied between 21.2% and 29.2%. In the sensitivity analysis, the results remained consistent across all deletions. A moderate heterogeneity ($I^2 = 65.1\%$) was observed, and publication bias was not found using the Egger's test ($p = 0.600$).

Leg lean mass, muscle fascicle length and muscle thickness

From the included studies, two [20, 22] provided data for quadriceps lean mass (determined through DXA scans), involving three experimental groups. In addition, from the included studies, two [63, 72] provided data for muscle fascicle length, involving three experimental groups, that analysed knee extensor (i.e., vastus lateralis) [72] and plantar-flexors muscles [63]. Moreover, two studies [20, 72] provided data for muscle thickness (determined through ultrasound, for the vastus lateralis muscle), involving four experimental groups. Due to the reduced number of studies for all these three measures, a meta-analysis was not possible.

Additional analysis

The limited number of studies providing data for most outcomes precluded analyses regarding the potential role of the moderator variables. However, an adequate number of studies were available for body fat. Interventions with a duration of ≤ 10 weeks and those with > 10 weeks produced similar non-significant reductions in body fat (trivial ES = -0.17 to -0.07), with no significant subgroup differences ($p = 0.700$). Similarly, interventions with a frequency of < 3 sessions per week and those with ≥ 3 produced similar non-significant effects (trivial ES = -0.18 to 0.004), with no significant subgroup differences ($p = 0.462$). The analyses regarding the total number of training sessions revealed that interventions with ≥ 30 PJT sessions produced a greater reduction of body fat compared to interventions with < 30 sessions (small ES = -0.32 vs. 0.14, respectively; $p = 0.068$).

Results of meta-regression

Computation of meta-regression was performed with at least 10 studies per covariate. Therefore, only body fat was considered for meta-regression analyses, and included three training variables (frequency, duration, and total number of sessions). None of the training variables predicted the effects of PJT on body fat changes (coefficient = -1.63 to 4.98; 95% CI = -4.03 to 12.44; Z value = -1.34 to 1.31; $p = 0.180$ to 0.200; $R^2 = 0$).

Adverse effects

Among the included studies, one [70] reported soreness in the lower leg muscle groups (13% of participants), pain in the knees mainly during the last stage of the intervention (8% of participants), and fatigue (13% of participants), however, no intervention-related injuries were reported. The rest of the studies did not report soreness, pain, fatigue, injury, damage or adverse effects related to the PJT intervention.

DISCUSSION

The aim of this meta-analysis was to assess the effects of PJT in males' body composition. From 8,321 records initially identified, 21 studies were included in the meta-analysis, comprising 28 individual experimental groups, and 594 participants. The analyses revealed a significant effect of PJT on increased muscle mass, total leg muscle volume, thigh muscle volume, thigh girth, calf girth, and muscle pennation angle. Among the included studies, only one reported low-mild adverse effects (e.g., soreness, fatigue), however, no intervention-related injuries were observed.

The significant effects of PJT on muscle mass (small ES = 0.28, $p = 0.053$), total leg muscle volume (small ES = 0.55, $p = 0.009$), thigh muscle volume (small ES = 0.38, $p = 0.043$), thigh girth (large ES = 1.77, $p = 0.011$), calf girth (large ES = 1.89, $p = 0.022$) and muscle pennation angle (small ES = 0.53, $p = 0.041$) offer novel and meaningful findings. The observed improvements in muscle-related measures in the present study resembled those achieved by traditional methods of resistance training [75]. Resistance training has a specialized method of conditioning that involved a variety of training modalities, including PJT, designed to enhance muscular fitness, athletic performance [76, 77], health [31], and body composition [78–80]. Of note, PJT involved different types of jumps, some capable of inducing important eccentric muscle force [18, 81]. Eccentric muscle tension seemed an important factor for muscle fiber hypertrophy [78, 82, 83]. In this sense, the positive effects of PJT on muscle-related mass, volume and girth might be mediated through increased muscle tension, particularly during the eccentric portion of the jumps [84]. Of note, compared to thigh muscles, calf muscles have proved resilient to hypertrophy after traditional resistance training methods [85]. The fact that in the current meta-analysis both the thigh (small-large ES = 0.38–1.78) and the calf (large ES = 1.89) muscles improved after PJT may be related to the important eccentric stimulus induced by PJT. However, in addition to these changes, improvements in the muscle pennation angle were also noticed in the current meta-analysis. Across the studies that analysed muscle pennation angle, both knee extensor (i.e., vastus lateralis) and plantar-flexors muscles were analysed. However, only when the study of Fouré et al. [63] was removed from the analysis, thus allowing an analysis of the PJT effects only on the vastus lateralis muscle, a significant increase in muscle pennation angle was observed (small ES = 0.53). In a previous review, it was already suggested that adaptations to PJT might vary between different types of muscles, where the muscle-tendon complex of gastrocnemii (bi-articular muscle) and soleus (mono-articular muscle) may have a different response to PJT [16]. However, an alternative explanation might be that the PJT programs used jumps with a greater impact on the knee extensors muscles (e.g., CMJ) than on the ankle muscles (e.g., repeated jumps with brief ground contact times) [20, 63, 72]. Moreover, the initial fitness level of the participants differed between the studies that analysed muscle pennation angle [20, 63, 72]. In this sense, the selection of specific types of jumps and the initial physical fitness of the participants might be considered as important factors for PJT prescription. In fact, more studies should be conducted to analyze which type of exercises should be included based on fitness levels, experience and main goal of intervention. Overall, the results from the current meta-analysis supported PJT as a potential alternative seeking improvements in muscle size and architecture, with potential implications in several clinical and sport-related contexts.

Alterations in body composition, such as overweight and obesity (i.e., abnormal or excessive fat accumulation) might impair health [86]. In addition, in sport-related contexts, an excessive amount of fat would impair performance, acting as added non-functional weight, thus reducing relative anaerobic and aerobic power, major determinants for propelling the body in short-term (e.g., high-jump) and long-term (e.g., 5 km run) sport events. Across the included studies in the current meta-analysis, there was a trivial, non-significant change in body fat (trivial ES = -0.11; p = 0.368). This finding was in agreement with a trivial, non-significant change (trivial ES = -0.01; p = 0.975) in skinfold thickness. In addition, when the effect of PJT interventions on body fat was meta-analysed according to the moderator variables total duration (i.e., ≤ 10 weeks compared to > 10 weeks) and training frequency (i.e., < 3 sessions per week compared to ≥ 3), no significant subgroup differences were noted (trivial ES = -0.18 to 0.004; p = 0.462–700). Further, results of the multivariate random-effect meta-regression revealed that none of the training variables (training; duration; frequency; total sessions) predicted the effects of PJT on body fat. Therefore, it seemed that PJT had no effect on fat-related measures. Moreover, although not considered a priori, an analysis of the moderator role of the initial physical fitness level of the participants revealed that interventions in those with an initial normal-moderate physical fitness produced a similar reduction in body fat compared to participants with greater initial physical fitness level (trivial ES = -0.11 and -0.11, respectively; p = 0.987).

However, the analyses regarding total number of training sessions (i.e., PJT duration multiplied by training frequency) revealed that ≥ 30 PJT sessions induced a larger near-significant (p = 0.068) reduction of body fat compared with < 30 PJT sessions (ES = -0.32 vs 0.14, respectively). In this line, after 36 PJT sessions, a study [19] found that PJT, when added to high-intensity interval training (HIIT) in overweight-obese females, aside from inducing a reduction in body fat from 41.7 to 38.8%, also improved some metabolic (e.g., plasma glucose) and physical fitness (e.g., squat jump) measures, when compared to HIIT alone. Of note, in the aforementioned study [19], the participants completed a high-volume (i.e., 8,640 seconds) of repeated (continuous) jumps. This type of PJT approach was relatively different to those PJT approaches commonly used in an attempt to improve short-term maximal-intensity explosive performance (i.e., vertical jump; sprint). In this sense, traditional PJT sessions, usually involved a single jump effort, followed by an inter-repetition rest, and then repeating this sequence, thus involving a low-frequency of jumps [15]. A recent cross-sectional study revealed that a high jumping frequency involved an important cardioventilatory stimulation (e.g., ≥ 90% of VO2max) [87]. Moreover, PJT may also have a role on cardiovascular and metabolic responses [88–91]. As most PJT studies published so far have involved a total of ~14 training sessions and drills involving jump efforts with a low frequency [15], the potential effect of some forms of PJT on fat-related measures may have been masked. Pending confirmatory research, PJT interventions including drills with high jumping frequency (i.e., one jump every 0.6 s) [87], short inter-set resting intervals (e.g., 15–30 s), and a high number of training session (e.g., ≥ 30) might favourable affect body composition in relation to fat-measures.

Although with several strengths (e.g., novelty; large database search; large number of descriptive study characteristics), the current meta-analysis is not without potential limitations. Among these, the limited number of studies precluded a robust analysis of moderator variables, aside from total training duration, training frequency and total number of training sessions. Similarly, although some studies reported outcomes relevant for the current meta-analysis (i.e., leg lean mass, muscle fascicle length and muscle thickness), the limited number of studies providing such data precluded their inclusion in the analyses. Finally, although heterogeneity remained low-moderate for most studies, and publication bias was not found using the Egger's test (p = 0.300-0.900), a high heterogeneity was observed for thigh girth and calf girth analysis.

From a practical perspective, compared to other methods of resistance training (e.g., machine or free-weight resistance training), PJT sessions usually require reduced physical space, time and equipment to be completed, which make it especially well-suited to be implemented in several settings. Current findings could be useful for practitioners seeking meaningful improvements in measures at the muscle-level, related to both sport performance and health. Such improvements may be of relevance for athletes, but also for patients under dynapenia and sarcopenia-related treatments. Moreover, although PJT demonstrated no effects on fat-related outcomes, future studies may look over the potential effects of non-conventional PJT methods (e.g., rope jumping) on measures related to body composition, especially after interventions with ≥ 30 sessions. In addition, the physiological mechanisms underlying body composition improvements after PJT need to be substantiated by future research. Finally, the lack of adverse responses to PJT is encouraging, but it is possible that in some cases authors did not report this information, therefore, practitioners should take a cautious approach to programming.

CONCLUSIONS

The meta-analysis revealed a significant effect of PJT on increased muscle mass, total leg muscle volume, thigh muscle volume, thigh girth, calf girth, and muscle pennation angle without adverse effects and intervention-related injuries. Therefore, PJT seemed effective (and safe) to induce plastic effects on several measures at the muscle-level. However, its effects on fat-related outcomes were not substantiated.improvements after PJT need to be substantiated by future research. Finally, the lack of adverse responses to PJT is encouraging, but it is possible that in some cases authors did not report this information, therefore, practitioners should take a cautious approach to programming.

Conflict of interest declaration

The authors declare that they have no conflict of interest relevant to the content of this review.

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SUPPLEMENTARY FIGURES

Effect of plyometric jump training on body composition.

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Coratella et al. 2018 (unloaded)	0.000	0.433	0.188	-0.849	0.849	0.000	1.000
Coratella et al. 2018 (loaded)	0.045	0.433	0.188	-0.804	0.894	0.105	0.917
Diallo et al. 2001	0.826	0.466	0.217	-0.087	1.739	1.773	0.076
Pienaar and Coetzee 2013	0.594	0.347	0.120	-0.086	1.273	1.712	0.087
Vlachopoulos et al. 2018 (swimmers)	-0.091	0.329	0.108	-0.736	0.554	-0.277	0.782
Vlachopoulos et al. 2018 (footballers)	0.133	0.366	0.134	-0.583	0.850	0.365	0.715
Vlachopoulos et al. 2018 (cyclists)	0.657	0.404	0.163	-0.134	1.448	1.627	0.104
	0.284	0.147	0.022	-0.004	0.571	1.933	0.053

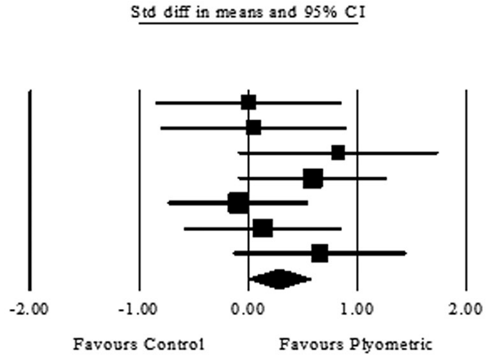

FIG. 1A. Effect of plyometric jump training on muscle mass.

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Chelly et al. 2015	0.481	0.391	0.153	-0.285	1.246	1.230	0.219
Chelly et al. 2014	0.973	0.441	0.195	0.108	1.838	2.204	0.028
Diallo et al. 2001	0.345	0.451	0.203	-0.538	1.228	0.765	0.444
Hammami et al. 2019	0.429	0.398	0.158	-0.351	1.208	1.077	0.281
	0.547	0.209	0.044	0.138	0.957	2.620	0.009

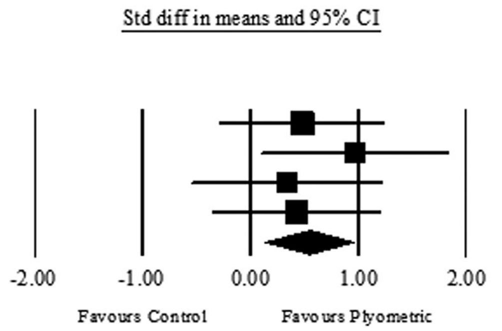

FIG. 1B. Effect of plyometric jump training on total leg muscle volume.

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Chelly et al. 2015	0.330	0.388	0.150	-0.430	1.090	0.851	0.395
Chelly et al. 2014	0.667	0.429	0.184	-0.174	1.507	1.555	0.120
Fathi et al. 2019	0.575	0.323	0.104	-0.058	1.207	1.782	0.075
Hammami et al. 2019	-0.100	0.394	0.155	-0.872	0.671	-0.255	0.799
	0.380	0.188	0.036	0.010	0.749	2.015	0.044

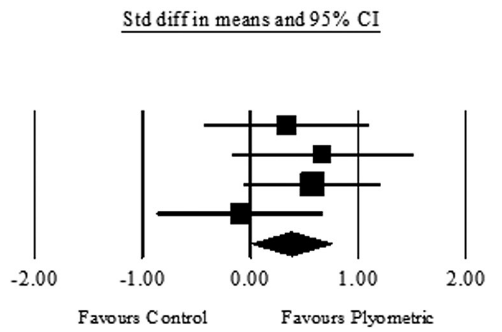

FIG. 1C. Effect of plyometric jump training on thigh muscle volume.

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Egan-Shuttler et al. 2017	1.227	0.545	0.297	0.159	2.295	2.252	0.024
Hortobagyi et al. 1990 (vertical)	2.227	0.625	0.391	1.002	3.452	3.563	0.000
Hortobagyi et al. 1990 (horizontal)	3.763	0.788	0.621	2.219	5.307	4.776	0.000
Pienaar and Coetzee 2013	0.341	0.342	0.117	-0.329	1.010	0.997	0.319
	1.775	0.699	0.489	0.405	3.145	2.539	0.011

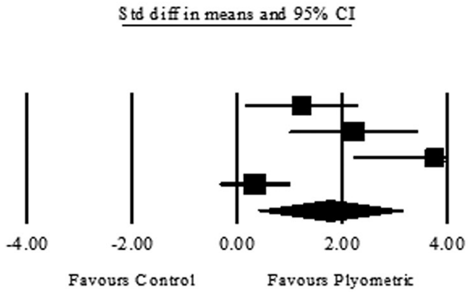

FIG. 1D. Effect of plyometric jump training on thigh girth.

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Egan-Shuttler et al. 2017	0.315	0.503	0.253	-0.671	1.301	0.627	0.531
Hortobagyi et al. 1990 (vertical)	2.568	0.657	0.432	1.280	3.855	3.909	0.000
Hortobagyi et al. 1990 (horizontal)	4.811	0.919	0.845	3.009	6.613	5.233	0.000
Pienaar and Coetzee 2013	0.538	0.345	0.119	-0.139	1.215	1.558	0.119
	1.893	0.826	0.682	0.275	3.511	2.293	0.022

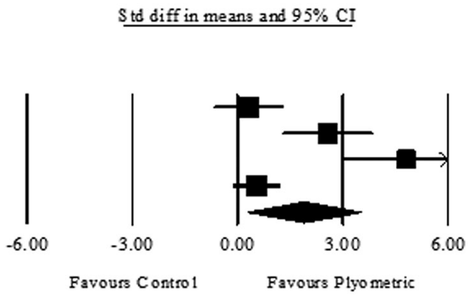

FIG. 1E. Effect of plyometric jump training on calf girth.

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Coratella et al. 2018 (unloaded)	0.963	0.455	0.207	0.071	1.854	2.117	0.034
Coratella et al. 2018 (loaded)	0.510	0.439	0.193	-0.351	1.370	1.160	0.246
Cormie et al. 2010 C (stronger)	0.138	0.613	0.376	-1.063	1.340	0.225	0.822
Cormie et al. 2010 C (weaker)	0.148	0.613	0.376	-1.054	1.350	0.241	0.809
	0.525	0.255	0.065	0.025	1.026	2.057	0.040

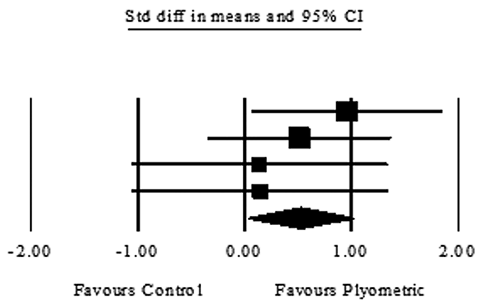

FIG. 1F. Effect of plyometric jump training on muscle pennation angle.

Studyname	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Chelly et al. 2015	0.387	0.389	0.151	-0.375	1.149	0.997	0.319
Chelly et al. 2010	-0.553	0.425	0.181	-1.387	0.280	-1.301	0.193
Fouré et al. 2011	-0.215	0.461	0.212	-1.118	0.688	-0.467	0.641
Hammami M et al. 2019	0.040	0.393	0.155	-0.731	0.811	0.102	0.919
	-0.054	0.207	0.043	-0.459	0.352	-0.259	0.796

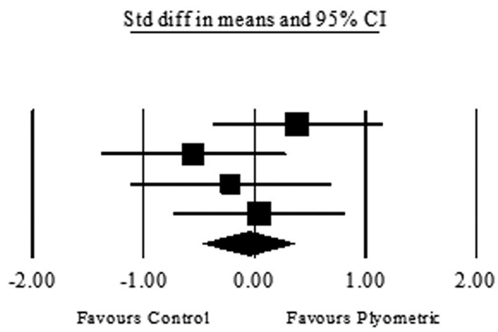

FIG. 1G. Effect of plyometric jump training on muscle cross-sectional area.

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Chaouachi et al. 2014	-0.074	0.369	0.136	-0.797	0.648	-0.202	0.840
Cimenli et al. 2016 (wood)	0.000	0.500	0.250	-0.980	0.980	0.000	1.000
Cimenli et al. 2016 (synthetic)	0.151	0.501	0.251	-0.830	1.133	0.302	0.762
Cormie et al. 2010 C (stronger)	-0.585	0.624	0.389	-1.807	0.638	-0.937	0.349
Cormie et al. 2010 C (weaker)	0.819	0.635	0.403	-0.425	2.064	1.291	0.197
Dæhlin et al. 2017	0.148	0.505	0.255	-0.841	1.137	0.293	0.770
Diallo et al. 2001	-1.257	0.489	0.240	-2.216	-0.298	-2.569	0.010
Fathi et al. 2019	-0.215	0.317	0.101	-0.837	0.406	-0.679	0.497
Michailidis et al. 2013	0.200	0.300	0.090	-0.387	0.787	0.667	0.505
Pienaar and Coetzee 2013	0.302	0.341	0.116	-0.367	0.971	0.884	0.377
Sedano et al. 2011	-0.883	0.447	0.200	-1.759	-0.008	-1.978	0.048
Vlachopoulos et al. 2018 (swimmers)	-0.059	0.329	0.108	-0.704	0.585	-0.181	0.857
Vlachopoulos et al. 2018 (footballers)	-0.507	0.371	0.138	-1.234	0.221	-1.365	0.172
Vlachopoulos et al. 2018 (cyclists)	0.203	0.394	0.156	-0.570	0.976	0.514	0.607
	-0.110	0.122	0.015	-0.350	0.130	-0.900	0.368

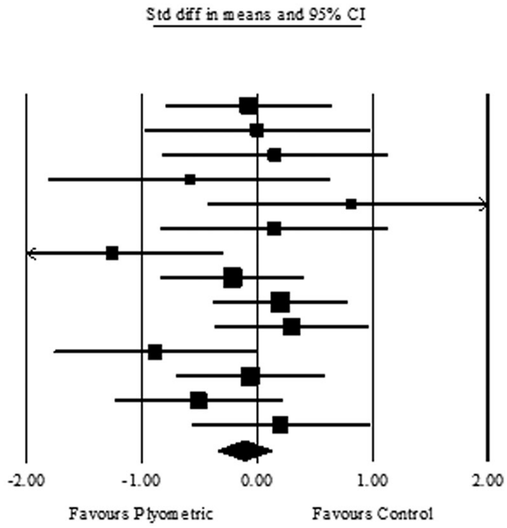

FIG. 1H. Effect of plyometric jump training on body fat.

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Berryman et al. 2010	0.354	0.543	0.295	-0.710	1.418	0.652	0.514
Diallo et al. 2001	-1.231	0.488	0.238	-2.187	-0.275	-2.525	0.012
Gomez-Molina et al. 2018	0.442	0.408	0.166	-0.357	1.241	1.084	0.278
Pienaar and Coetzee 2013	0.281	0.341	0.116	-0.387	0.949	0.824	0.410
	-0.012	0.370	0.137	-0.736	0.713	-0.032	0.975

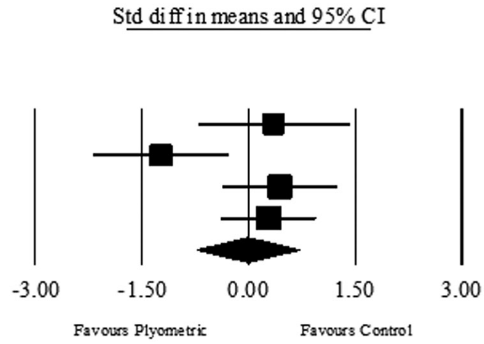

FIG. 1I. Effect of plyometric jump training on skinfold thickness.