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Effects of jump training on physical fitness and athletic performance in endurance runners: A meta-analysis

Jump training in endurance runners

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ABSTRACT
This systematic review and meta-analysis aimed to assess the effects of jump training (JT) on measures of physical fitness and athletic performances in endurance runners. Controlled studies which involved healthy endurance runners, of any age and sex, were considered. A random-effects model was used to calculate effect sizes (ES; Hedge's *g*). Means and standard deviations of outcomes were converted to ES with alongside 95% confidence intervals (95%CI). Twenty-one moderate-to-high quality studies were included in the meta-analysis, and these included 511 participants. The main analyses revealed a significant moderate improvement in time-trial performance (i.e. distances between 2.0 and 5.0 km; ES = 0.88), without enhancements in maximal oxygen consumption (VO_2max), velocity at VO_2max, velocity at submaximal lactate levels, heart rate at submaximal velocities, stride rate at submaximal velocities, stiffness, total body mass or maximal strength performance. However, significant small-to-moderate improvements were noted for jump performance, rate of force development, sprint performance, reactive strength, and running economy (ES = 0.36–0.73; $p < 0.001$ to 0.031; I^2 = 0.0% to 49.3%). JT is effective in improving physical fitness and athletic performance in endurance runners. Improvements in time-trial performance after JT may be mediated through improvements in force generating capabilities and running economy.

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KEYWORDS
Resistance training; high-intensity interval training; plyometric exercise; running; sports

1. Introduction

High performance in endurance running, or in athletic terms, the ability to run over middle and long distances (from 800 m to marathon), in the fastest possible time (Coyle, 1995), depends on several underpinning factors. These include high maximal oxygen consumption (VO_2max), lactate threshold critical power (Poole et al., 2016) and running economy (Coyle, 1995; Margaria et al., 1963). Maintaining submaximal velocity in distance running events, however, may also require optimal neuromuscular qualities related to voluntary and reflex neural activation, muscle force, and elasticity, running mechanics, and anaerobic capacity (Da Rosa et al., 2019; K. Hakkinen, 1994; Noakes, 1988; Sinnett et al., 2001). Indeed, some studies have shown that anaerobic characteristics can differentiate between runners of differing ability according to their running performance (Bulbulian et al., 1986; Houmard et al., 1991). It has been also reported that, when resistance training is applied concurrently with endurance training, simultaneous improvements in strength and endurance performance are possible in endurance runners (Blagrove et al., 2018; Denadai et al., 2017; Taipale et al., 2013). Amongst resistance training methods, high velocity-resistance training may preferentially lead to adaptations such as an increased rate of activation of motor units (Hakkinen, 1994; Hakkinen et al., 1985) without exerting any negative effects on metabolic adaptations (Baar, 2006; Dudley & Djamil, 1985; Hickson, 1980; Hunter et al., 1987), thus enhancing overall performance of the runner.

High velocity-resistance training may involve jump training exercises (Markovic & Mikulic, 2010) which are commonly used to increase physical fitness and athletic performance through utilisation of the stretch-shortening cycle (SSC) (Read & Cisar, 2001). Accordingly, jump training (JT), which is characterised by the incorporation of both slow (i.e. ground contact times >250 ms) and fast (i.e. ground contact times <250 ms) SSC drills (Bobbert, 1990; Komi, 2003; Ramirez-Campillo, Moran, et al., 2020), is a highly effective neuromuscular stimulus which offers practical advantages in terms of time, equipment and the small amount of physical space required in which to perform it (Field, 1991).

Despite its proven advantages, some inconclusive evidence still exists for the combined effect of JT and endurance training regimens on adaptive changes in aerobic capacity, endurance

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performance, and strength performance. For instance, a previous study on ultra-endurance athletes demonstrated no significant improvement in jumping power (Giovanelli et al., 2017). Similarly, recreationally endurance runners showed no improvement in jump performance, rate of force development or running velocity at VO_2max (Taipale et al., 2010). Conversely, significant improvements in jumping, sprinting and time-trial performance have also been reported (Andrade et al., 2018; García-Pinillos et al., 2020a; Ramirez-Campillo et al., 2014) with such contrasting findings possibly related to factors such as loading characteristics of JT interventions (e.g., duration, intensity, frequency) and participants' characteristics (e.g., initial fitness level, previous strength training experience) (Ramirez-Campillo, Alvarez, Garcia-Hermoso, et al., 2018; Ramirez-Campillo, Moran, et al., 2020). One additional limitation in studies exploring the effects of JT interventions is their overall small sample size. A low number (i.e., <10) of participants in experimental groups is very common among JT interventions carried out in endurance runners (Millet et al., 2002; Paavolainen et al., 1999; Saunders et al., 2006; Spurrs et al., 2003), and in the JT literature in general (Ramirez-Campillo, Alvarez, Garcia-Hermoso, et al., 2018; Ramirez-Campillo, Moran, et al., 2020). Because of this, even if significant effects are observed in small samples, it may not be possible to verify the replicability of a result due to considerable overestimation of the population effect size, and the expected low precision in the population estimate (Abt et al., 2020).

This problem of underpowered studies may be partially addressed by the conducting of a systematic review with meta-analysis (SRMA), with the benefits of such an approach recently exemplified by several authors using the method to evaluate the effects of JT on many different components of exercise performance (Asadi et al., 2016; J. J. Moran et al., 2017; De Villarreal et al., 2009). The results of these meta-analyses suggest that JT is effective in improving distinct power-expression abilities in young and adult athletes from different sport disciplines. However, none of these SRMAs have included studies on endurance runners. In a preliminary review without meta-analysis, JT was deemed effective in enhancing running economy (Barnes & Kilding, 2015). Similarly, in two other systematic reviews (Beattie et al., 2014; Yamamoto et al., 2008), it was shown that JT had a positive effect on endurance running performance. However, despite these encouraging results, neither of these reviews included a meta-analysis making it difficult to determine the true effect of JT on endurance-related parameters (Murad et al., 2016). Further to this, although recent SRMAs have maintained a focus on endurance runners, a clearer analysis of the potential effects of JT has not been possible as different strength training methods (e.g., heavy resistance training; endurance resistance training) were merged in the analyses (Trowell et al., 2020), thus confounding results. Two more SRMAs (Balsalobre-Fernández et al., 2016; Denadai et al., 2017) assessed running economy only, with other important factors for endurance performance such as neuromuscular and anaerobic characteristics omitted (Bulbulian et al., 1986; Hakkinen, 1994; Houmard et al., 1991; Noakes, 1988; Sinnett et al., 2001). Of note, among all of the aforementioned SRMAs (Balsalobre-Fernández et al., 2016; Denadai et al., 2017; Trowell et al., 2020), time-trial performances has not previously been assessed meaning the effect of JT on endurance-based athletic performance remains unknown. Considering the current state of the literature, this SRMA explored the effects of JT on several facets of physical fitness and athletic performance in endurance runners.

2. Methods

This SRMA was conducted following the guidelines of the Cochrane Collaboration (Green & Higgins, 2005). Findings were reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statements (Liberati et al., 2009).

2.1. Eligibility criteria

The *a priori* inclusion criteria for this SRMA were as follows: i) randomized-controlled trials that incorporated a JT programme of at least two weeks duration, consisting of lower body unilateral or bilateral bounding, jumping or hopping exercises using the stretch–shortening cycle (Chu & Myer, 2013; Moran et al., 2018; Ramirez-Campillo, Alvarez, Garcia-Hermoso, et al., 2018), ii) cohorts of healthy endurance runners of any age, sex, or performance level, iii) a measure of athletic performance (i.e., time trial; velocity at lactate threshold; sprinting speed; jumping power) and/or physiological-related outcomes associated to athletic performance (i.e. VO_2max; heart rate at submaximal velocities) must have been provided (Moran et al., 2018; Turner & Bernard, 2006). Trials that included JT combined with another intervention (co-intervention) were included when an active control group was also included to differentiate the potential responses between groups. Only peer-reviewed articles were included in this SRMA. Articles were excluded if they were cross-sectional studies, a review of literature, studies that applied training methods other than JT (e.g., explosive isometric muscle actions), 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-bout effect interventions, letters to the editor, invited commentaries, errata, overtraining studies, and detraining studies. In the case of detraining studies, if there was a training period prior to a detraining period, the study was considered for inclusion. Considering the potential difficulties in translating articles written in different languages, and the fact that 99.6% of the JT literature is published in English (Ramirez-Campillo, Alvarez, Garcia-Hermoso, et al., 2018), only original articles written in English were considered.

2.2. Search strategy

The PubMed, Web of Science, and SCOPUS electronic databases were searched from inception until 24 July 2019. Keywords were collected through experts' opinion, a systematic literature review, and MeSH terms. Boolean search syntax using the operators "AND", "OR" was applied. The words "ballistic", "complex", "explosive", "force-velocity", "plyometric", "stretch-shortening cycle", "jump", "training", "endurance", "runners", and "athletes" were subsequently used. An example of a PubMed search is: ("randomized controlled trial" [Publication Type]) OR "controlled clinical trial" [Publication Type]) OR "randomized"[Title/Abstract]) OR "trial" [Title]) OR "clinical trials as topic" [MeSH Major Topic]) AND "endurance runners"[Title/Abstract]) AND "training" [Title/Abstract]) OR "plyometric" [Title/Abstract]. After an initial search, accounts were created in the respective databases. Through these accounts, the lead investigator received automatically generated emails for updates regarding the search terms used. These updates were received on a daily basis (if available), and studies were eligible for inclusion until the initiation of manuscript preparation on 8 April 2020.

2.3. Study selection and data collection process

After identification of relevant articles from databases searches, a review of all titles was conducted before an examination of abstracts and full-text articles. The full-text articles excluded, along with the reasons for their exclusion, were recorded. Data extraction was performed by two reviewers (RRC and YN) using a custom-made Excel® spreadsheet (Microsoft Corporation, Redmond, WA, USA). In the case of disagreement regarding data extraction and study eligibility, DA was consulted for clarifications.

2.4. Data items

Several measures of athletic performance were selected after discussions among the co-authors, including, but not limited to: time to complete different running distances, velocity at lactate threshold, sprinting speed and jumping power measures. Extracted data also included the following information: participants' age (years), body mass (kg), height (m), fitness level and previous experience with JT. With regard to JT characteristics, extracted data also included the frequency of training (days/week), duration of training (weeks) and number of total jumps completed during the intervention. A complete description of the aforementioned JT characteristics have been previously published (Ramirez-Campillo, Alvarez, Garcia-Hermoso, et al., 2018; Ramirez-Campillo, Moran, et al., 2020).

2.5. Study quality

The Physiotherapy Evidence Database (PEDro) scale was used to assess the methodological quality of the included studies. This scale evaluates internal study validity on a scale from 0 (high risk of bias) to 10 (low risk of bias). If trials had already been assessed and listed on the PEDro database (or similar sources), these scores were adopted. However, methodological quality was not an inclusion criterion (Higgins & Altman, 2008). Two of the authors (RRC and DA) independently scored the articles. Any discrepancies in ratings between the two authors were resolved through discussion with a third author (YN). Aiming to control the risk of bias between authors, the Kappa correlation test was used to analyse the agreement level for the included studies. A high agreement level of k = 0.88 was obtained.

2.6. Summary measures

Although a minimum of two studies can form a meta-analytical comparison (Valentine et al., 2010), considering the particularities of the study field (e.g. the low sample sizes) (Pigott, 2012) of sport science and the JT literature (Abt et al., 2020; Lohse et al., 2020; Millet et al., 2002; Paavolainen et al., 1999; Ramirez-Campillo, Alvarez, Garcia-Hermoso, et al., 2018; Ramirez-Campillo, Moran, et al., 2020; Saunders et al., 2006; Spurrs et al., 2003), we conducted meta-analyses only when three or more studies provided data for the aforementioned physical fitness outcomes (Garcia-Hermoso et al., 2019; Moran et al., 2018; Skrede et al., 2019). Means and standard deviations (SD) for a measure of pre-post-intervention performance were used to calculate effect sizes (ES; Edge's *g*). The data were standardised using the post-intervention data for a relevant measure of performance. When data values from a study were not available (omitted or in graphical form), that study's corresponding author was contacted to retrieve the relevant information. When no response was obtained (one attempt was made), a validated (r = 0.99, p < 0.001) (Drevon et al., 2016) software (WebPlotDigitizer; https://apps.automeris.io/wpd/) was used to obtain mean and standard deviation values from graphical representations of the relevant data.

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 (Deeks et al., 2008), and facilitates analysis while accounting for heterogeneity across studies (Kontopantelis et al., 2013). In this way, the likelihood approach with random effects was used to better account for the inaccuracy in the estimate of between-study variance (Hardy & Thompson, 1996). The ESs were presented alongside 95% confidence intervals (95%CIs). The calculated ESs were interpreted using the conventions outlined for standardised mean differences: <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 (Hopkins et al., 2009). In some studies in which there was more than one intervention group, the control group was proportionately divided to facilitate comparison across all participants (Higgins et al., 2008). All analyses were carried out using the Comprehensive Meta-Analysis program (version 2; Biostat, Englewood, NJ, USA).

2.7. Synthesis of results

To identify the degree of heterogeneity across the included studies, Cochran's *Q* (Higgins et al., 2003) was used to calculate the I^2 statistic. This represents the proportion of effects that are due to heterogeneity as opposed to chance (Liberati et al., 2009). Low, moderate and high levels of heterogeneity correspond to I^2 values of <25%, 25–75%, and >75%, respectively (Higgins & Thompson, 2002; Higgins et al., 2003). However, these thresholds are considered arbitrary (Higgins et al., 2003). 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 (Deeks et al., 2008). Risk of bias across studies was assessed using the extended Egger's test (Egger et al., 1997). In case of bias, the trim and fill method was applied (Duval & Tweedie, 2000).

3. Results

3.1. Study selection

A total of 6,920 search records were initially identified. After excluding the duplicates and studies based on title, abstract, or full-text, a final pool of 21 studies were included in the meta-analysis. Figure 1 is a diagram of the study selection process. The included studies involved 23 individual experimental groups with 267 participants with 244 participants allocated to the 23 control groups. The characteristics of the participants from the studies are displayed in Table 1, while the programming parameters of the JT interventions are presented in Table 2. The outcomes for both the control and JT groups are presented in Table 3.

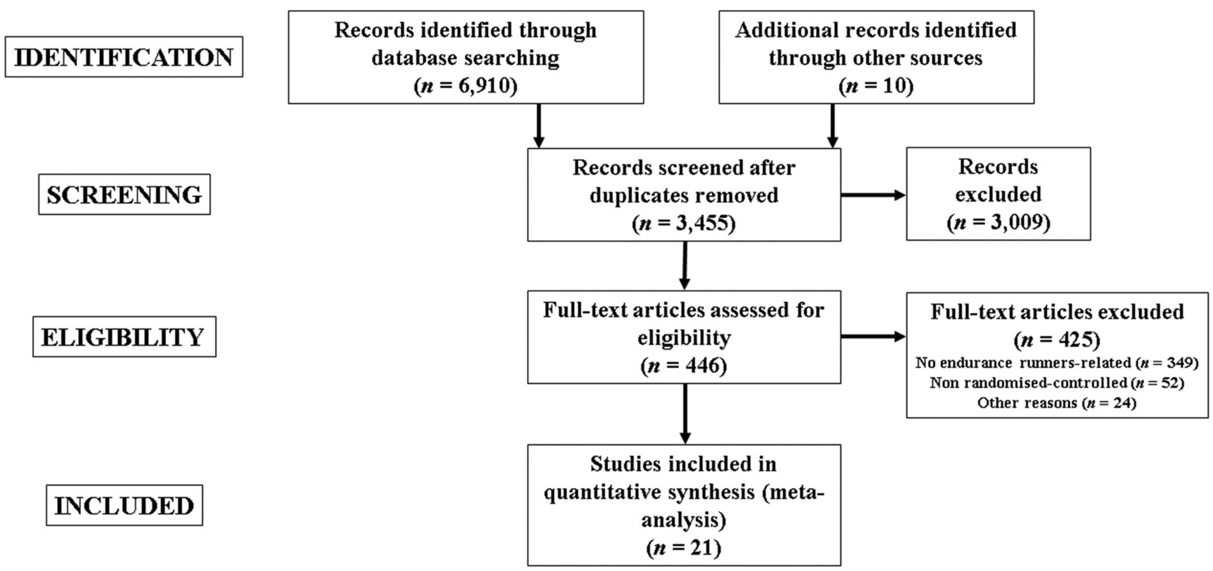

Figure 1. PRISMA flow diagram.

Table 1. Participant's general characteristics.

	Gender	Age (y)*	BM (kg)	Height (m)*	SPT	SpoP	FL	TP	RRT
Ache-Dias et al., 2016	Mix	24.3	63.1	1.6	No	RDR	Normal	NA	No
Andrade et al., 2018	Mix	21.3	62.2	1.63	No	RDR	Normal	NA	No
Barnes et al., 2013	M	20.7	68.7	NR	No	DR (cross-country)	MH	IS	No
	F	20.5	53.4						
Berryman et al. 2010	M	29.0	74.6	1.78	No	DR (5-km to marathon)	MH	NR	No
Blagrove et al., 2018	Mix	16.5	57.8	1.70	No	DR (800-m to 10-km)	NM	OS	No
Bonacci et al. 2011	Mix	21.6	65.3	1.76	No	DR (triathletes)	MH	NR	No
Chelly et al., 2015	M	11.7	43.0	1.58	No	Runners (up to 3-km)	MH	IS	No
García-Pinillos et al., 2020a	Mix	27.2	66.0	1.72	No	RDR	NM	NA	Yes
Giovanelli et al., 2017	M	36.3	71.9	1.76	No	DR (ultra-endurance)	MH	NR	No
Gomez-Molina et al., 2018	M	20.4	75.0	1.77	No	Novice runners	NR	NR	No
Hamilton et al. 2006	M	28.0	72.0	1.78	NR	DR (road and cross-country)	MH	IS	Yes
Li et al. 2019b	M	22.2	63.1	1.78	NR	DR (NR)	High	NR	Yes
Lundstrom et al. 2017	M	20.8	79.8	NR	No	DR (recreational marathoners)	NM	IS	Yes
	F		65.9						
Paavolainen et al., 1999	M	23	71.9	1.79	Yes	DR (cross-country orienteers)	High	OS	Yes
Pellegrino et al. 2016	Mix	32.5	68.2	1.72	No	RDR	Normal	NA	No
Ramirez-Campillo et al., 2014	Mix	22.1	60.0	NR	No	DR (1,500-m to marathon)	High	IS	No
Saunders et al., 2006	M	23.4	67.6	NR	No	DR (middle-long distance)	High	NR	No
Sedano et al., 2013	M	24.1	68.5	1.81	No	DR (3-km to 5-km)	High	PS	Yes
Spurrs et al., 2003	M	25.0	72.4	1.78	No	DR (NR)	NM	NR	No
Taipale et al., 2010	M	36.4	78.4	1.81	Yes	RDR	NM	NA	Yes
Turner et al. 2003	Mix	31.0	65.4	1.70	No	RDR	Normal	NR	No

*: mean for the group. **BM**: body mass (mean for the group). **DR**: distance runners (included cross-country, triathletes). **F**: female. **FL**: Fitness level: **high**, for professional/elite athletes with regular enrolment in national and/or international competitions, highly trained participants with >10 training hours per week or >6 training sessions per week and a regularly scheduled official competition; **moderate**, for non-elite/professional athletes, with a regular attendance in regional and/or national competitions, between 5 and 9.9 training hours per week or 3–5 training sessions per week and a regularly scheduled official competition; **normal**, for recreational athletes with <5 training hours per week with sporadic competitions' participation, and for physically active participants and school-age youths regularly involved in physical education classes. Of note, the jump-training load was not considered as part of the regular training load of participants; hence, it was not considered to classify participants' FL. **IS**: in-season. **M**: male. **MH**: moderate-high. **NA**: not-applicable. **NM**: normal-moderate. **NR**: not clearly reported. **OS**: off-season. **PS**: pre-season. **RDR**: recreationally distance runners. **RRT**: replaced part of the regular distance running training with plyometric jump training. **SpoP**: sport practiced. The specialities of endurance runners are indicated in parenthesis. **SPT**: indicates if the participants had previous systematic experience with plyometric jump training. **TP**: training period.

Table 2. Characteristics of jump training programmes.

	JT	Freq	Weeks	Intensity	BH (cm)	NTJ	Tply	Comb	RBSE	RBR	RBTS	Surf	PO	Taper
Ache-Dias et al., 2016	WD	2	4	Max	NA	1,200 s	CMJ	No	300	NA	≥48	NR	V	Yes
Andrade et al., 2018	WD	3	4	Max	30–50	720	DJ	No	120	15	≥48	Mix	No	No
Barnes et al., 2013	ID	1–2	7–10	NR	NA	>1,396	Mix	RT	NR	NR	NR	NR	V	Yes
Berryman et al. 2010	WD	1	7–8	Max	20–60	240	DJ	No	180	NR	168	NR	V	Yes
Blagrove et al., 2018	ID	2	10	NR	NR	868 + 540 m	Mix	RT	90	NR	48–96	NR	T + V	No
Bonacci et al. 2011	ID	2–3	8	NR	NA	1,221 + 1,650 m	Mix	RT	NR	NR	NR	Mix	T + V	No
Chelly et al., 2015	WD	3	10	Max	30–40	1,800	Mix	No	NR	5	≥48	NR	I + V + T	No
García-Pinillos et al., 2020a	WD	3–4	10	Max	NA	80 min (rope-jump)	Mix	No	20–30	NA	24–48	Mix	V	No
Giovanelli et al., 2017	ID	3	8–12	NR	NA	NR	Mix	RT	0–30	NR	≥48	Mix	NR	NR
Gomez-Molina et al., 2018	WD	2	8	Max	NR	2,080	Mix	No	45–90	NR	NR	NR	V + T	No
Hamilton et al. 2006	ID	1–3	5–7	Max	40	600	Step-up jump	HIT	120	NR	≥48	NR	No	No
Li et al. 2019b	ID	3	8	NR	40–60	1,296	Mix	No	240–480	NR	48–72	NR	No	No
Lundstrom et al. 2017	WD	1	12	Max	NR	1,075	Mix	Sprints	≥60	NR	168	NR	V + T	Yes
Paavolainen et al., 1999	ID	NR	9	NR	NR	NR	Mix	RT + sprints	NR	NR	NR	NR	NR	NR
Pellegrino et al. 2016	WD	2–3	6	Max	NR	NR	Mix	No	NR	NR	NR	NR	I + V + T	No
Ramirez-Campillo et al., 2014	WD	2	6	Max	20–60	720	DJ	No	120	15	≥48	Wood	No	No
Saunders et al., 2006	WD	2–3	9	Max	NR	852 + 2,700 m	Mix	RT	NR	NR	NR	Mix	T + V	No
Sedano et al., 2013	ID	2	12	NR	NA	2,880	Mix	RT	25–300	NR	≥48	Synthetic	NR	No
Spurrs et al., 2003	ID	2–3	6	Max	NR	2,064	Mix	No	NR	NR	NR	NR	V + T	No
Taipale et al., 2010	WD	1–2	8	Max	NA	>320 + >320 s	Mix	RT	120–180	NR	≥48	NR	I	No
Turner et al. 2003	ID	3	6–7	Max	NA	1,287	Mix	No	NR	NR	NR	Mix	V	No

BH: box height (for those drills that required the use of a box or hurdle, not necessarily applied to drop jumps). **CMJ**: countermovement jump. **Comb**: combined JT with another type of resistance training (although JT represented ≥50% of total drills). **DJ**: drop jumps. **Freq**: JT frequency (sessions per week). **HIT**: high-intensity interval training. **HK**: high-knee running drill with ankle weights. **ID**: insufficiently described, when the JT treatment description omitted the reporting of any of the following: duration, frequency, intensity, type of exercises, sets, repetitions. **JT**: jump training. **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 JT involved a combination of two or more surfaces, or two or more of the following jumping drills: vertical (**V**), horizontal, bilateral, unilateral (**U**), repeated, non-repeated, lateral, cyclic, sport-specific, slow stretch-shortening cycle, fast stretch-shortening cycle. **NA**: not applicable. **NR**: not clearly reported. **NTJ**: number of total jumps (usually counted as jumps per each leg). **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 between repetitions (s). **RBSE**: rest between sets and/or exercises (s). **RBTS**: rest between training sessions (hours). **RT**: resistance training. **Surf**: surface type. **Taper**: applied a reduction in the training load (usually as reduced volume) at the end of the training program. **Tply**: type of JT drills used. **WD**: well described, when treatment description allowed for adequate study JT replication, including the reporting of duration, frequency, intensity, type of exercises, sets, and repetitions.

3.2. Methodological quality

The median PEDro score of the included studies was six. This score indicates an acceptable methodological quality (i.e., low risk of bias) of the included studies. Eight studies were classified as being of "moderate" quality, while 13 studies were considered as being of "high" methodological quality (Table 4).

3.3. Meta-analysis results

Ten studies provided data for time-trial performances. These involved eleven experimental and eleven active control groups (pooled n = 285) respectively. Seven studies comprised 2.0–3.2 km time-trial running distances, while three studies comprised a running distance of 5 km. There was a significant moderate effect of JT on time-trial performance (ES = 0.88; 95% CI = 0.22 to 1.54; p = 0.009; I^2 = 83.9%; Egger's test p = 0.045; Figure 2). After the trim and fill method was applied, the adjusted values remained equal as the observed values. The relative weight of each study in the analysis ranged from 6.7% to 11.1%.

Fifteen studies provided data for VO_2max (i.e. VO_2max [13 studies] and VO_2peak [2 studies]), involving 17 experimental and 17 active control groups (pooled n = 304). There was a non-significant effect of JT on VO_2max (ES = −0.05; 95% CI = −0.28 to 0.19; p = 0.700; I^2 = 12.1%; Egger's test p = 0.855; Figure 3). The relative weight of each study in the analysis ranged from 3.2% to 7.8%.

Nine studies provided data for vVO_2max, involving 10 experimental and 10 active control groups (pooled n = 183). There was a non-significant effect of JT on vVO_2max (ES = 0.19; 95% CI = −0.09 to 0.47; p = 0.186; I^2 = 0.0%; Egger's test p = 0.379; Figure 4). The relative weight of each study in the analysis ranged from 6.6% to 13.5%.

Eight studies provided data for velocity at submaximal lactate levels, involving eight experimental and eight active control groups (pooled n = 155). There was a non-significant effect of JT on velocity at submaximal lactate levels performance (ES = 0.26; 95% CI = −0.09 to 0.62; p = 0.150; I^2 = 24.6%; Egger's test p = 0.448; Figure 5). The relative weight of each study in the analysis ranged from 10.4% to 15.2%.

Four studies provided data for heart rate at submaximal velocities, involving four experimental and four active control groups (pooled n = 72). There was a non-significant effect of JT on heart rate at submaximal velocities performance (ES = 0.15; 95% CI = −0.30 to 0.59; p = 0.515; I^2 = 0.0%; Egger's test p = 0.227; Figure 6). The relative weight of each study in the analysis ranged from 21.4% to 27.3%.

Three studies provided data for stride rate at submaximal velocities (i.e. 14 km.h), involving three experimental and three active control groups (pooled n = 65). There was a non-

Table 3. Study groups and their physical fitness.

		Jump training, before[a]			Control, before			Jump training, after			Control, after		
Author (year)	Test	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n
Ache-Dias et al. (2016)	CMJ (cm)	37.74	5.24	9	40.02	6.52	9	39.52	5.06	9	39.37	6.65	9
	VO2peak (l.min)	3.17	0.72	9	3.23	0.73	9	3.46	0.7	9	3.25	0.72	9
	Speed at OBLA (km.h)	10.11	1.64	9	11.39	1.8	9	11.09	1.82	9	11.46	1.77	9
	vVO2peak (km.h)	13.68	1.4	9	14	1.33	9	14.06	1.57	9	14	1.26	9
	HR at 9 km.h (beats.min)	159	20	9	149	5	9	156	17	9	145	17	9
	Isometric knee extension (N.m)	210.45	47.26	9	213.43	60.35	9	218.35	51.13	9	207.75	51.89	9
	RTD knee extensors (N.m.s)	618	250	9	615	317	9	801	312	9	634	249	9
Andrade et al. (2018)	2-km TT sea level (min)	11.3	0.5	11	9.02	0.64	12	8.75	0.4	11	9.01	0.63	12
	VO2max (ml.kg.min)	44.7	3.4	11	44.7	3.4	12	48.6	2.8	11	48.6	2.8	12
Barnes et al., 2013 (males)	VO2max (ml.kg.min)	63.8	4.6	10	63.7	4.7	10	63.9	4.6	10	64.5	4.7	10
	vVO2max (km.h)	17.5	0.8	10	17.5	1.1	10	17.6	0.8	10	17.8	1.1	10
	Stiffness 5-RJ (kN.m)	9.6	2	10	9.3	2	10	9.3	2	10	10.7	2	10
	1RM leg press (kg)	68.7	13.6	10	70.7	13.3	10	85.4	13.6	10	92.7	13.3	10
	5-RJ (s)	0.12	0.02	10	0.12	0.02	10	0.132	0.02	10	0.118	0.02	10
Barnes et al., 2013 (females)	VO2max (ml.kg.min)	51.3	2.8	10	52.3	3.3	10	53.7	2.8	10	54.1	3.3	10
	vVO2max (km.h)	15.3	0.9	10	15.2	0.9	10	15.7	0.9	10	15.4	0.9	10
	Stiffness 5-RJ (kN.m)	13.6	1.5	10	13.5	1.5	10	14.2	1.5	10	15.1	1.5	10
	1RM leg press (kg)	41.2	8	10	35.9	2.3	10	53.4	8	10	51.9	2.3	10
	5-RJ (s)	0.09	0.01	10	0.1	0.02	10	0.094	0.01	10	0.09	0.02	10
Berryman et al, (2010)	3-km TT (s)	748	81	11	711	107	5	712	76	11	690	109	5
	VO2peak (ml.kg.min)	57,5	6.5	11	55.7	8.2	5	57.3	5.5	11	55.3	8.9	5
	vVO2max (km.h)	16.6	1.3	11	17.3	2	5	17.3	1.3	11	17.5	2.4	5
	CMJ (cm)	33.3	4	11	34.2	3.6	5	35.3	3.6	11	35.2	4.2	5
Blagrove et al. (2018)	VO2max (mL.kg$^{0.67}$.min)	229.2	41.3	9	241.2	24.2	9	227.5	36.2	9	242	21.5	9
	vVO2max (km.h)	16.8	2.4	9	17.8	0.8	9	17.3	2.6	9	17.8	1.7	9
	Speed at 4 mmol.L (km.h)	14.9	2.4	9	15.8	1	9	15.4	2.5	9	16.4	1.4	9
	Isometric back squat (N.kg$^{0.61}$)	159.3	28	9	159.4	25.7	9	183.9	26.5	9	161.5	37.1	9
	SJ (m)	0.26	0.03	9	0.26	0.05	9	0.27	0.04	9	0.27	0.05	9
	20-m sprint (s)	2.79	0.22	9	2.64	0.24	9	2.69	0.19	9	2.62	0.23	9
Chelly et al. (2015)	CMJ (m)	0.23	0.03	14	0.21	0.03	13	0.25	0.03	14	0.22	0.03	13
	Velocity at 35–40 m sprint (m.s)	5.3	0.7	14	5	0.5	13	5.5	0.7	14	5.1	0.5	13
	DJ 30-cm (m)	0.22	0.03	14	0.25	0.02	13	0.2	0.02	14	0.2	0.02	13
Garcia-Pinillos et al. (2020a)	3-km TT (s)	774.6	79.5	51	762.1	87.5	45	751.7	65.8	51	750.8	83.6	45
	Arch stiffness (BM/arch height index units)	925.5	388.7	51	947.7	418.8	45	997.95	373.17	51	949.01	427.3	45
	CMJ (cm)	28.95	5.79	51	29.46	7.15	45	31.59	6.01	51	29.3	7.07	45
	DJ 30-cm (ms.ms)	1.92	0.45	51	1.91	0.41	45	2.17	0.42	51	1.92	0.41	45
Giovanelli et al. (2017)	SR at 14 km.h (strides.s)	2.92	0.16	13	2.9	0.14	12	2.98	0.18	13	2.91	0.12	12
	Leg stiffness at 14 km.h (kn.m)	27.37	4	13	27.26	3.47	12	27.2	2.53	13	26.93	3.75	12
	SJ (W)	3257	632	13	2961	422	12	3423	632	13	2973	422	12
Gomez-Molina et al. (2018)	vVO2max (km.h)	17.5	1.3	14	17.5	1.7	11	18.2	1.4	14	17.9	1.8	11
	Speed at RCT (km.h)	13.9	1.2	14	13.7	1.6	11	14.5	1.3	14	14.2	1.6	11
	SR at 14 km.h (Hz)	2.91	0.12	14	2.95	0.12	11	2.86	0.13	14	2.97	0.2	11
	10-RJ (kN.m)	34.7	7.1	14	32.6	5.1	11	34.5	4.3	14	30.4	4	11
	CMJ (m)	0.37	0.03	14	0.36	0.05	11	0.38	0.05	14	0.37	0.04	11
	10-s RJ (m)	0.25	0.03	14	0.28	0.06	11	0.26	0.04	14	0.27	0.04	11
Hamilton et al. (2006)	vVO2max (km.h)	20.5	1.3	10	20.4	1	10	21.1	1.3	10	20.6	1	10
	Speed at lactate threshold (km.h)	14.7	2	10	15.5	1.3	10	15.3	2.1	10	15.6	1.3	10
	Speed at fixed HR (km.h)	14.2	0.8	10	14.3	0.9	10	14.4	0.8	10	14.2	0.9	10
Li et al. (2019b)	5-km TT (s)	953.7	12.3	10	954.1	6.75	9	926.9	9.92	10	947.33	10.03	9
	VO2max (ml.kg.min)	65.65	5.06	10	66.14	5.25	9	64.47	4.31	10	67.79	3.03	9
	Lactate at 16 km.h (mmol.L)	2.56	0.48	10	2.76	0.59	9	1.45	0.45	10	2.41	0.51	9
	HR at 16 km.h (beats.min)	164.81	8.31	10	169.59	14.78	9	160.74	7.51	10	169.93	16.33	9
	1RM back squat (kg)	60.25	8.03	10	63.33	9.35	9	70.5	11.17	10	64.44	8.82	9
	CMJ (cm)	31.06	3.41	10	33.46	4.27	9	34.51	3.85	10	34.26	4.22	9
	50-m sprint (s)	6.25	0.19	10	5.94	0.21	9	6.11	0.24	10	5.92	0.3	9
	DJ 40-cm (cm.s)	59.05	11.63	10	62.11	12.04	9	70.8	15.69	10	62.91	12.07	9
Lundstrom et al. (2017) (male)	2-mile TT (min)	12.5	2.2	4	12.8	0.9	6	12.2	2.5	4	12.1	0.8	6
	VO2max (ml.kg.min)	55.2	13	4	59.1	6.4	6	65.4	4.7	4	62.2	5.6	6
	CMJA (cm)	0.645	0.076	4	0.719	0.147	6	0.617	0.099	4	0.663	0.086	6
	200-m sprint (s)	31.64	4.52	4	29.94	1.27	6	29.2	4.81	4	29.88	1.71	6
Lundstrom et al. 2017 (Female)	2-mile TT (min)	16	1.3	7	15.5	2	5	15.1	1.4	7	14.7	1.5	5
	VO2max (ml.kg.min)	47.7	4.3	7	47.1	4.7	5	53.5	6.6	7	51.5	4.9	5
	CMJA (cm)	0.437	0.074	7	0.409	0.038	5	0.439	0.064	7	0.424	0.058	5
	200-m sprint (s)	39.31	5.45	7	39.42	2.92	5	37.75	5.19	7	38.47	2.41	5
Paavolainen et al. (1999)	5-km TT (min)	18.4	0.3	10	17.9	0.4	8	17.7	0.2	10	18.1	0.2	8
	VO2max (ml.kg.min)	63.7	2.7	10	65.1	4.1	8	62.9	3.2	10	68.3	3.4	8
	VO2 demand at vVO2max (ml.kg.min)	67.7	2.8	10	68.3	3.1	8	70.2	2.5	10	69.2	3.1	8
	Lactate threshold (ml.kg.min)	47.3	3.3	10	48.9	4.5	8	48.1	3.5	10	49.3	2.8	8
	Isometric leg extension (N)	4049	891	10	3899	635	8	4385	1132	10	3396	648	8
	5BJ (m)	12.47	0.9	10	13.17	0.46	8	13.04	0.83	10	12.95	0.5	8
	20-m sprint (m.s)	7.96	0.57	10	8.28	0.35	8	8.23	0.54	10	8.08	0.31	8

(*Continued*)

Table 3. (Continued).

		Jump training, before[α]			Control, before			Jump training, after			Control, after		
Author (year)	Test	Mean	SD	n	Mean	SD	n	Mean	SD	n	Mean	SD	n
Pellegrino et al. (2016)	3-km TT (s)	780.9	29.9	11	830.4	35.6	11	760.8	29.1	11	817.2	39.8	11
	VO2max (ml.kg.min)	48	1.8	11	47.7	2.3	11	50.5	2.1	11	49.2	2.1	11
	Speed at OBLA (m.s)	3.83	0.14	11	3.48	0.12	11	3.88	0.14	11	3.5	0.14	11
	CMJA (cm)	44.7	4.1	11	48.8	4.2	11	44.4	4	11	45.5	4.6	11
Ramirez-Campillo et al. (2014)	2.4-km TT (min)	7.6	0.7	17	8	0.9	15	7.3	0.8	17	7.9	0.9	15
	CMJA (cm)	36.1	5.6	17	34.1	7.1	15	39.3	7	17	36.3	8.1	15
	20-m sprint (s)	3.92	0.3	17	3.97	0.2	15	3.83	0.3	17	3.94	0.4	15
	DJ 40-cm (cm.ms)	0.156	0.041	17	0.166	0.047	15	0.182	0.05	17	0.156	0.046	15
Saunders et al. (2006)	VO2max (ml.kg.min)	67.7	6.2	7	70.4	6.2	8	68.2	7.5	7	72.5	5	8
	Lactate at 18 km.h (mmol.L)	5.8	2.8	7	5.6	4.7	8	5.9	3.9	7	4.1	2.3	8
	HR at 18 km.h (beats.min)	178	11	7	171	11	8	177	10	7	169	11	8
	SR at 14 km.h (strides.min)	84.3	2	7	86.5	4.7	8	84.4	1.4	7	86.4	4.7	8
	RFD jump (N.s)	21,857	4903	7	21,543	4539	8	25,254	5145	7	21,887	4767	8
	5-RJ (cm)	41.2	9.8	7	42.3	6.5	8	44.6	5.8	7	40.1	3.1	8
Sedano et al. (2013)	VO2max (ml.kg.min)	68.83	1.94	6	68.8	1.83	6	69.48	1.85	6	69.11	1.86	6
	vVO2max (km.h)	20.91	0.9	6	21.95	1.21	6	21.87	0.81	6	22.04	1.08	6
	1RM back squat (kg)	202.51	16.35	6	206.6	17.66	6	219.24	14.5	6	210.83	14.48	6
	CMJ (cm)	0.3	0.03	6	0.32	0.02	6	0.33	003	6	0.32	0.03	6
	25-s RJ (m)	0.26	0.02	6	0.26	0.02	6	0.27	0.02	6	0.26	0.02	6
Spurrs et al. (2003)	3-km TT (min)	10.28	1.26	8	9.36	0.57	9	10.12	1.15	8	9.31	0.52	9
	VO2max (ml.kg.min)	57.6	7.7	8	57.8	5.4	9	59.5	8.1	8	61.5	5.9	9
	Stiffness at 75% IMF (N.m)	39.72	10.86	8	39.44	6.386	9	44.058	8.044	8	42.415	5.275	9
	Isometric seated heel rise (N)	1.157	215	8	1.196	212	9	1.314	166	8	1.169	208	9
	CMJ (m)	0.38	0.06	8	0.33	0.04	9	0.43	0.08	8	0.32	0.06	9
	RFD ankle extensors (N.s)	2859	1245	8	3380	1062	9	3289	1684	8	2753	1000	9
Taipale et al. (2010)	VO2max (ml.kg.min)	50.5	2	10	47.1	2.8	7	51.5	1.5	10	50	2.6	7
	vVO2max (km.h)	15.2	0.4	10	14.4	0.4	7	15.6	0.3	10	15	0.4	7
	1RM leg press (kg)	174	8	10	177	11	7	181	8	10	180	10	7
	CMJ (cm)	29.5	0.7	10	25.1	2.2	7	30.2	0.9	10	26.1	1.9	7
Turner et al (2003)	VO2max (ml.kg.min)	50.4	9	11	54	7.2	10	50.4	8	11	54.2	6.4	10
	CMJ (cm)	36	7	11	42	9	10	38	7	11	42	10	10

[α]: before and after values denotes the mean ± standard deviation for each group before and after the intervention, respectively. Note: abbreviations descriptions ordered alphabetically. **1RM**: one repetition maximum. **5-BJ**: five repeated horizontal (bound) jumps. **5-RJ and 10-RJ**: five and ten repeated-reactive vertical jumps. **BM**: body mass. **CMJ**: countermovement jump. **CMJA**: countermovement jump Abalakov. **DJ**: drop jump. **HR**: heart rate. **IMF**: isometric maximal force. **KE**: knee extensors. **MVC**: maximal voluntary contraction. **OBLA**: onset of blood lactate accumulation. **RCT**: respiratory compensation threshold. **RJ**: repeated-reactive vertical jumps. **RFD**: rate of force development. **RTD**: rate of torque development. **SJ**: squat jump. **SR**: stride rate. **TT**: time trial. **VO2peak and VO2max**: peak and maximal volume of oxygen consumption. **vVO2peak and vVO2max**: velocity at peak and maximal volume of oxygen consumption, respectively.

significant effect of JT on stride rate performance (ES = 0.17; 95% CI = −0.31 to 0.64; p = 0.489; I^2 = 0.0%; Egger's test p = 0.826; Figure 7). The relative weight of each study in the analysis ranged from 24.3% to 38.5%.

Five studies provided data for stiffness (i.e. lower limb behavioural active stiffness), involving six experimental and six active control groups (pooled n = 202). There was a non-significant effect of JT on stiffness performance (ES = −0.03; 95% CI = −0.39 to 0.34; p = 0.883; I^2 = 34.2%; Egger's test p = 0.344; Figure 8). The relative weight of each study in the analysis ranged from 12.2% to 31.2%.

Twelve studies provided data for total body mass changes, involving 13 experimental and 13 active control groups (pooled n = 234). There was a non-significant effect of JT on body mass (ES = 0.04; 95% CI = −0.21 to 0.29; p = 0.741; I^2 = 0.0%; Egger's test p = 0.378; Figure 9). The relative weight of each study in the analysis ranged from 3.9% to 13.3%.

Eight studies provided data for maximal strength, involving measures of isometric maximal strength (four studies; leg extension; knee extension; back squat; seated heel rise) and maximal dynamic strength (four studies; 1RM leg press; 1RM back squat; 1RM leg press). The eight studies involved nine experimental and nine active control groups (pooled n = 158). There was a non-significant effect of JT on strength performance (ES = 0.29; 95% CI = −0.07 to 0.65; p = 0.114; I^2 = 28.4%; Egger's test p = 0.122; Figure 10). The relative weight of each study in the analysis ranged from 8.5% to 12.4%.

Sixteen studies provided data for jump performances, involving 17 experimental and 17 active control groups (pooled n = 405). There was a significant small effect of JT on jump performance (ES = 0.36; 95% CI = 0.17 to 0.55; p < 0.001; I^2 = 0.0%; Egger's test p = 0.810; Figure 11). The relative weight of each study in the analysis ranged from 2.8% to 22.6%.

Three studies provided data for RFD, involving three experimental and three active control groups (pooled n = 50). There was a significant moderate effect of JT on RFD (ES = 0.62; 95% CI = 0.08 to 1.16; p = 0.024; I^2 = 0.0%; Egger's test p = 0.884; Figure 12). The relative weight of each study in the analysis ranged from 30.6% to 36.2%.

Six studies provided data for sprint performance, involving distances from 20-m to 50-m (five studies) and 200-m (one study). The six studies involved seven experimental and seven active control groups (pooled n = 136). There was a significant small effect of JT on sprint performance (ES = 0.38; 95% CI = 0.03 to 0.72; p = 0.031; I^2 = 0.0%; Egger's test p = 0.210; Figure 13). The relative weight of each study in the analysis ranged from 6.9% to 24.2%.

Table 4. Physiotherapy Evidence Database (PEDro) scale ratings.

	N° 1*	N° 2	N° 3	N° 4	N° 5	N° 6	N° 7	N° 8	N° 9	N° 10	N° 11	Total (from a possible maximal of 10)
Ache-Dias et al., 2016	1	1	0	1	0	0	0	1	1	0	1	5
Andrade et al., 2018	1	1	0	1	0	0	0	0	1	1	1	5
Barnes et al., 2013	1	1	0	0	0	0	0	1	0	1	1	4
Berryman et al. 2010	1	1	0	1	0	0	0	0	1	1	1	5
Blagrove et al., 2018	1	1	0	1	0	0	0	0	1	1	1	5
Bonacci et al. 2011	1	1	0	1	0	0	0	0	1	1	1	5
Chelly et al., 2015	1	1	0	1	0	0	0	1	1	1	1	6
García-Pinillos et al., 2020a	1	1	0	1	0	0	0	1	1	1	1	6
Giovanelli et al., 2017	1	1	1	1	0	0	0	1	1	1	1	7
Gomez-Molina et al. 2018	1	1	0	1	0	0	0	1	1	1	1	6
Hamilton et al. 2006	1	1	0	1	0	0	0	1	1	1	1	6
Li et al. 2019b	1	1	0	1	0	0	0	1	1	1	1	6
Lundstrom et al. 2017	1	1	1	1	0	0	0	1	1	1	0	6
Paavolainen et al., 1999	1	1	0	1	0	0	0	0	1	1	0	4
Pellegrino et al. 2016	1	1	0	1	0	0	0	1	1	1	1	6
Ramirez-Campillo et al., 2014	1	1	1	1	0	0	0	1	1	1	1	7
Saunders et al., 2006	1	1	0	1	0	0	0	1	1	1	1	6
Sedano et al., 2013	1	1	0	1	0	0	0	1	1	1	1	6
Spurrs et al., 2003	1	1	0	1	0	0	0	1	1	1	1	6
Taipale et al., 2010	1	1	0	0	0	0	0	0	1	1	1	4
Turner et al. 2003	1	1	0	1	0	0	0	1	1	1	1	6

*: A detailed explanation for each PEDro scale item can be accessed at https://www.pedro.org.au/english/downloads/pedro-scale (access for this review: 9 June 2020)

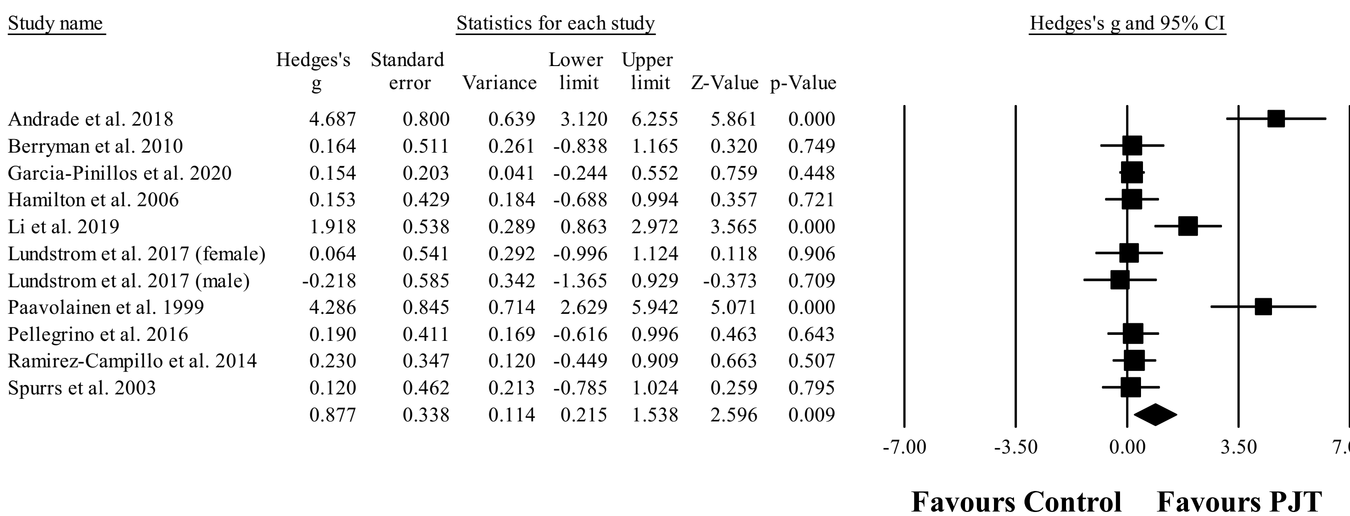

Figure 2. Forest plot of changes in time-trial performance in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Eight studies provided data for reactive strength performances, involving nine experimental and nine active control groups (pooled n = 265). There was a significant moderate effect of JT on reactive strength performances (ES = 0.73; 95% CI = 0.48 to 0.97; $p < 0.001$; $I^2 = 0.0\%$; Egger's test $p = 0.255$; Figure 14). The relative weight of each study in the analysis ranged from 5.3% to 36.0%.

Nine studies provided data for running economy performance, involving 10 experimental and 10 active control groups (pooled n = 169). There was a significant moderate effect of JT on running economy performance (ES = 0.55; 95% CI = 0.12 to 0.98; $p = 0.012$; $I^2 = 49.3\%$; Egger's test $p = 0.546$; Figure 15). The relative weight of each study in the analysis ranged from 8.3% to 12.4%.

4. DISCUSSION

This SRMA explored the effects of JT on endurance runners' physical fitness and athletic performances. The JT interventions enhanced performance in several parameters such as time-trial, sprinting and jumping performances, as well-reactive strength, RFD, and running economy. However, no significant changes were observed for VO_2max, velocity at VO_2max, velocity at submaximal lactate levels, heart rate at submaximal velocities,

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
	Statistics for each study						
Ache-Dias et al. 2016	0.362	0.453	0.205	-0.526	1.250	0.799	0.424
Andrade et al. 2018	0.000	0.394	0.155	-0.773	0.773	0.000	1.000
Barnes et al. 2013 (males)	-0.144	0.429	0.184	-0.985	0.697	-0.336	0.737
Barnes et al. 2013 (females)	0.188	0.429	0.184	-0.654	1.029	0.437	0.662
Berryman et al. 2010	0.028	0.510	0.260	-0.971	1.028	0.056	0.956
Blagrove et al. 2018	-0.080	0.449	0.202	-0.960	0.800	-0.178	0.859
Gomez-Molina. 2018	0.266	0.391	0.153	-0.501	1.033	0.680	0.497
Li et al. 2019	-0.719	0.454	0.206	-1.609	0.172	-1.582	0.114
Lundstrom et al. 2017 (males)	1.214	0.643	0.414	-0.046	2.475	1.888	0.059
Lundstrom et al. 2017 (females)	0.216	0.542	0.294	-0.847	1.279	0.399	0.690
Paavolainen et al. 1999	-1.158	0.491	0.241	-2.121	-0.195	-2.358	0.018
Pellegrino et al. 2016	0.458	0.416	0.173	-0.357	1.273	1.101	0.271
Saunders et al. 2006	-0.240	0.489	0.239	-1.198	0.719	-0.490	0.624
Sedano et al. 2013	0.169	0.534	0.285	-0.878	1.216	0.317	0.751
Spurrs et al. 2003	-0.244	0.463	0.214	-1.151	0.664	-0.526	0.599
Taipale et al. 2010	-0.896	0.492	0.242	-1.861	0.069	-1.819	0.069
Turner et al. 2003	0.026	0.419	0.176	-0.796	0.849	0.063	0.950
	-0.046	0.119	0.014	-0.280	0.188	-0.385	0.700

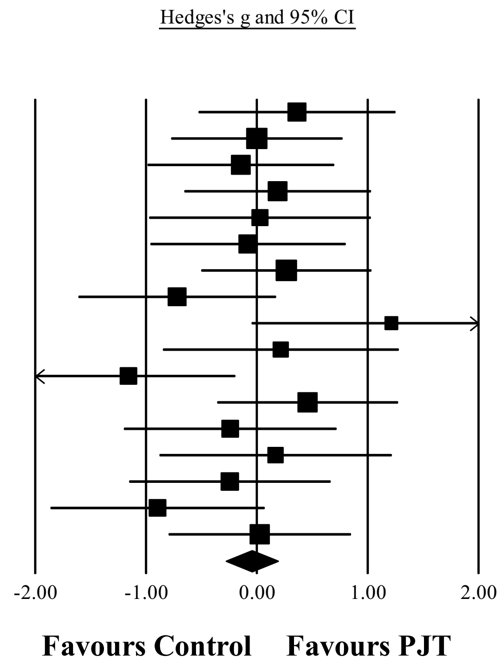

Figure 3. Forest plot of changes in maximum oxygen consumption in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
	Statistics for each study						
Ache-Dias et al	0.254	0.451	0.203	-0.630	1.138	0.564	0.573
Barnes et al. (female)	0.212	0.440	0.194	-0.651	1.075	0.482	0.630
Barnes et al. (male)	-0.199	0.429	0.184	-1.041	0.643	-0.464	0.643
Berryman et al.	0.280	0.512	0.262	-0.724	1.284	0.546	0.585
Blagrove et al.	0.217	0.450	0.203	-0.666	1.100	0.481	0.630
Gomez-Molina et al.	0.183	0.390	0.152	-0.582	0.948	0.468	0.640
Hamilton et al.	0.330	0.431	0.186	-0.515	1.176	0.766	0.444
Paavolainen et al	0.548	0.461	0.212	-0.355	1.452	1.190	0.234
Sedano et al.	0.841	0.560	0.314	-0.256	1.939	1.502	0.133
Taipale et al.	-0.553	0.477	0.228	-1.488	0.383	-1.158	0.247
	0.190	0.144	0.021	-0.091	0.472	1.324	0.186

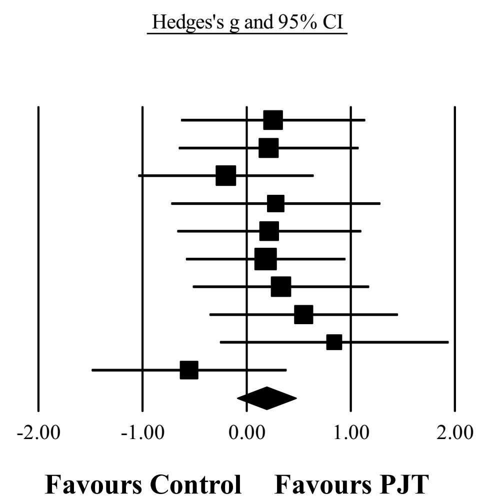

Figure 4. Forest plot of changes in velocity at maximum oxygen consumption in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
	Statistics for each study						
Ache-Dias et al	0.483	0.456	0.208	-0.411	1.377	1.058	0.290
Blagrove et al.	0.047	0.449	0.202	-0.833	0.927	0.105	0.917
Gomez-Molina et al.	0.067	0.390	0.152	-0.697	0.831	0.173	0.863
Hamilton et al.	0.284	0.431	0.185	-0.560	1.128	0.659	0.510
Li et al.	1.515	0.503	0.253	0.529	2.501	3.012	0.003
Paavolainen et al	0.119	0.452	0.204	-0.768	1.005	0.262	0.793
Pellegrino et al.	0.206	0.411	0.169	-0.600	1.012	0.501	0.616
Saunders et al.	-0.479	0.495	0.245	-1.449	0.491	-0.969	0.333
	0.261	0.181	0.033	-0.094	0.616	1.439	0.150

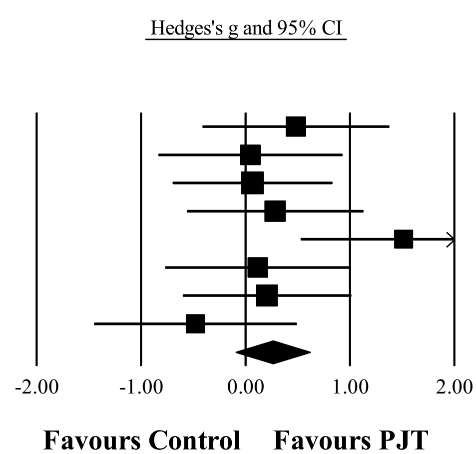

Figure 5. Forest plot of changes in velocity at submaximal intensities (i.e. fixed lactate level) in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Ache-Dias et al	-0.056	0.449	0.202	-0.936	0.824	-0.125	0.901
Hamilton et al.	0.337	0.432	0.186	-0.509	1.183	0.782	0.434
Li et al.	0.338	0.442	0.196	-0.529	1.205	0.764	0.445
Saunders et al.	-0.089	0.487	0.238	-1.044	0.866	-0.183	0.855
	0.147	0.226	0.051	-0.295	0.589	0.651	0.515

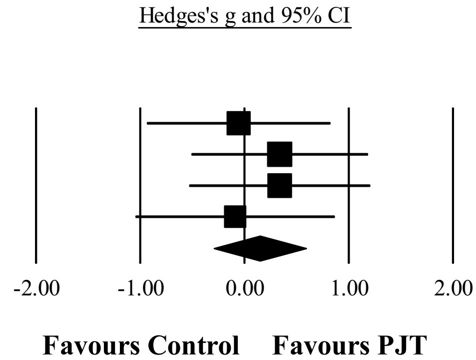

Figure 6. Forest plot of changes in heart rate at submaximal velocities in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Giovanelli et al.	0.000	0.387	0.150	-0.759	0.759	0.000	1.000
Gomez-Molina et al.	0.412	0.394	0.155	-0.360	1.185	1.047	0.295
Saunders et al.	0.053	0.487	0.237	-0.902	1.008	0.108	0.914
	0.166	0.240	0.058	-0.305	0.637	0.692	0.489

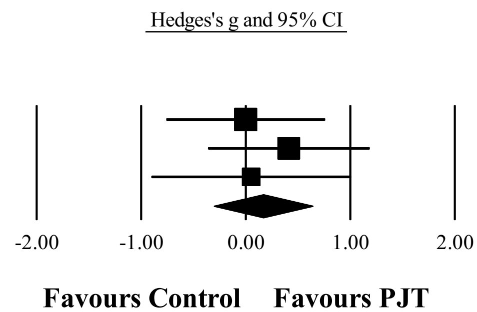

Figure 7. Forest plot of changes in stride rate at submaximal velocities in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Barnes et al. (female)	-0.637	0.451	0.203	-1.521	0.247	-1.412	0.158
Barnes et al. (male)	-0.814	0.447	0.200	-1.691	0.062	-1.820	0.069
Garcia-Pinillos et al.	0.177	0.203	0.041	-0.222	0.575	0.869	0.385
Giovanelli et al.	0.050	0.387	0.150	-0.709	0.809	0.128	0.898
Gomez-Molina et al.	0.464	0.395	0.156	-0.311	1.238	1.173	0.241
Spurrs et al.	0.194	0.462	0.214	-0.713	1.100	0.419	0.675
	-0.027	0.186	0.035	-0.392	0.337	-0.148	0.883

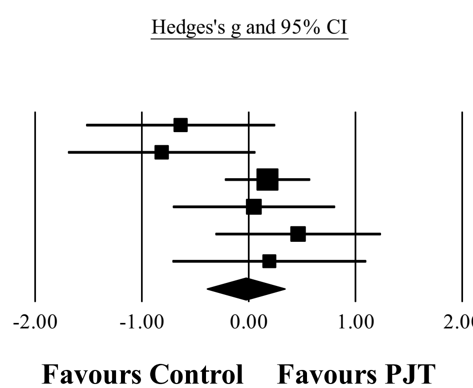

Figure 8. Forest plot of changes in stiffness in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

stride rate, stiffness, or strength performance. Together, these findings suggest that improvements in time-trial performance in endurance runners after JT may be related to explosive force and running economy, which could underpin improvements in high-intensity-related athletic performances.

To our knowledge, this is the first SRMA that analysed the effects of JT on time trial performance among endurance runners. The significant improvement observed after JT could confirm the positive transfer of strength- and power-related adaptations, after JT, to a specific marker of endurance performance such as a time trial test. Of note, improvements were observed between 2 km and 5 km, distances over which running speeds are greater and ground contact times are shorter compared to what is observed over longer distances (García-Pinillos et al., 2019, 2020a). This is an important finding that confirms the specificity of these adaptations to maximal (i.e. > anaerobic threshold), but not submaximal, running intensities thus questioning the usefulness of JT to improve performance of long-distance runners.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Bonacci et al.	-0.122	0.636	0.404	-1.368	1.124	-0.192	0.847
Lundstrom et al. (male)	-0.069	0.583	0.340	-1.212	1.074	-0.118	0.906
Lundstrom et al. (female)	0.206	0.542	0.294	-0.856	1.269	0.380	0.704
Berryman et al.	0.014	0.510	0.260	-0.985	1.014	0.028	0.977
Saunders et al.	0.066	0.487	0.237	-0.889	1.021	0.136	0.892
Taipale et al.	-0.322	0.471	0.222	-1.246	0.601	-0.685	0.494
Spurrs et al.	0.045	0.461	0.213	-0.859	0.949	0.098	0.922
Paavolainen et al	0.273	0.454	0.206	-0.617	1.163	0.601	0.548
Li et al.	0.072	0.439	0.193	-0.788	0.933	0.165	0.869
Hamilton et al.	0.018	0.428	0.183	-0.821	0.858	0.043	0.966
Gomez-Molina et al.	0.015	0.390	0.152	-0.748	0.779	0.039	0.969
Blagrove et al.	0.078	0.387	0.150	-0.682	0.837	0.200	0.841
Ramirez-Campillo et al.	0.110	0.346	0.119	-0.567	0.788	0.319	0.749
	0.042	0.126	0.016	-0.205	0.288	0.331	0.741

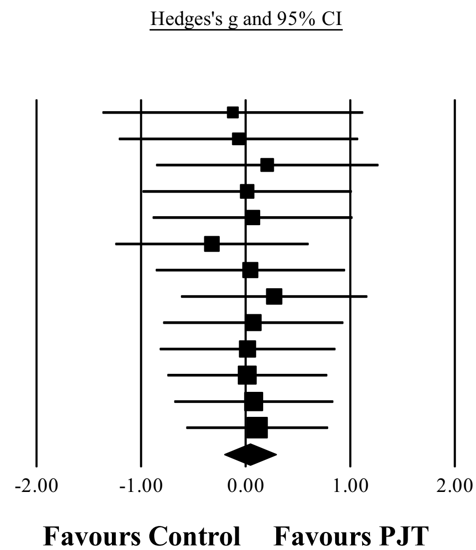

Figure 9. Forest plot of changes in body mass in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Ache-Dias et al	0.251	0.451	0.203	-0.633	1.135	0.557	0.578
Barnes et al. (female)	-0.602	0.450	0.202	-1.483	0.279	-1.339	0.181
Barnes et al. (male)	-0.377	0.432	0.187	-1.225	0.470	-0.873	0.383
Blagrove et al.	0.665	0.462	0.214	-0.242	1.571	1.437	0.151
Li et al.	0.862	0.461	0.212	-0.041	1.764	1.871	0.061
Paavolainen et al	0.840	0.473	0.224	-0.087	1.767	1.776	0.076
Sedano et al.	0.796	0.557	0.310	-0.296	1.888	1.429	0.153
Spurrs et al.	0.001	0.461	0.213	-0.903	0.905	0.002	0.998
Taipale et al. 2010	0.429	0.473	0.224	-0.499	1.357	0.906	0.365
	0.291	0.184	0.034	-0.070	0.651	1.582	0.114

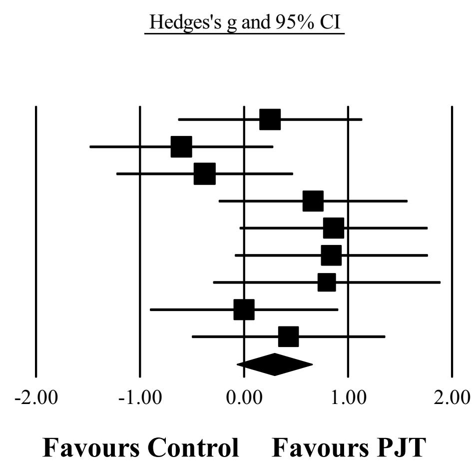

Figure 10. Forest plot of changes in strength performance in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Further studies should more specifically attempt to examine the extent of the positive influence of JT on endurance running at different intensities.

4.1. Maximal oxygen consumption and velocity at maximal oxygen consumption

There was a non-significant effect of JT on VO_2max levels. Previous studies consistently reported such a trend after JT (Andrade et al., 2018; Barnes & Kilding, 2015; Yamamoto et al., 2008), probably due to the lack of influence of this training type on central (e.g. cardiac output) and peripheral (e.g. muscle capillary) mechanisms that influence VO_2 max (Coyle, 1995). Moreover, there was a non-significant effect of JT on vVO_2max performance. This finding was somewhat surprising, considering that this parameter depends on both VO_2max and running economy, the latter having being shown to be enhanced after the performance of JT (Balsalobre-Fernández et al., 2016; Barnes & Kilding, 2015; Denadai et al., 2017). Of note, among the studies that provided data for vVO_2max performance, seven (out of nine) studies used ramp protocols with 0.25–1.0 km.h^{-1} treadmill velocity increments every 0.5–1.0 minute until volitional exhaustion, while the other two studies used 1.0 km.h^{-1} treadmill velocity increments every 3 min until volitional exhaustion. As vVO_2max is protocol-dependent and considering that higher running velocities are more dependent on muscular power and anaerobic contribution, *a posteriori* we tested separately if the vVO_2max of ramp protocols would reveal a significant effect. Indeed, a near significant effect was noted (ES = 0.27; p = 0.097) compared to the vVO_2max of non-ramp protocols (ES = −0.13; p = 0.739). Therefore, for researchers assessing the effects of JT on vVO2max, a ramp protocol would be

Study name	Statistics for each study						
	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Ache-Dias et al	0.392	0.454	0.206	-0.498	1.281	0.863	0.388
Berryman et al.	0.250	0.512	0.262	-0.753	1.253	0.489	0.625
Blagrove et al.	0.000	0.449	0.202	-0.880	0.880	0.000	1.000
Chelly et al.	0.323	0.376	0.141	-0.414	1.060	0.859	0.390
Garcia-Pinillos et al.	0.480	0.206	0.042	0.077	0.884	2.333	0.020
Giovanelli et al.	0.275	0.389	0.151	-0.488	1.037	0.706	0.480
Gomez-Molina et al.	0.000	0.390	0.152	-0.764	0.764	0.000	1.000
Li et al.	0.628	0.451	0.203	-0.255	1.511	1.395	0.163
Lundstrom et al. (female)	-0.195	0.542	0.294	-1.257	0.868	-0.359	0.720
Lundstrom et al. (male)	0.278	0.586	0.344	-0.872	1.427	0.474	0.636
Paavolainen et al	1.067	0.486	0.236	0.116	2.019	2.198	0.028
Pellegrino et al.	0.670	0.422	0.178	-0.158	1.498	1.585	0.113
Ramirez-Campillo et al.	0.129	0.346	0.120	-0.548	0.807	0.374	0.708
Sedano et al.	0.923	0.565	0.320	-0.185	2.031	1.633	0.102
Spurrs et al.	0.813	0.482	0.232	-0.131	1.757	1.687	0.092
Taipale et al.	-0.205	0.469	0.220	-1.124	0.714	-0.437	0.662
Turner et al.	0.224	0.421	0.177	-0.600	1.049	0.533	0.594
	0.360	0.098	0.010	0.168	0.551	3.679	0.000

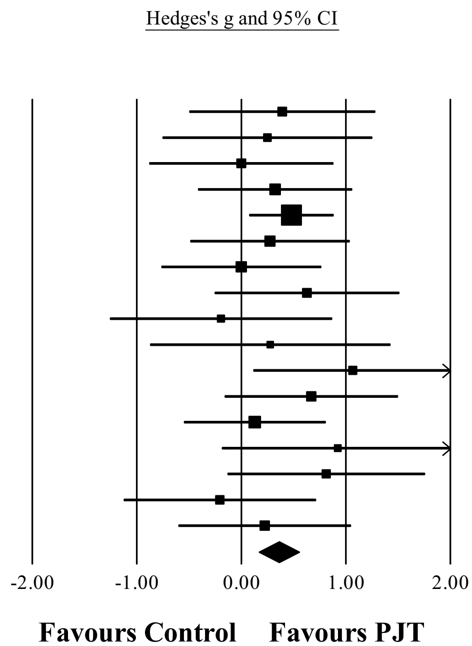

Figure 11. Forest plot of changes in jump performance in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Study name	Statistics for each study						
	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Ache-Dias et al	0.553	0.458	0.210	-0.345	1.452	1.207	0.227
Saunders et al.	0.581	0.499	0.249	-0.396	1.558	1.166	0.244
Spurrs et al.	0.736	0.478	0.229	-0.201	1.673	1.540	0.124
	0.623	0.276	0.076	0.082	1.163	2.258	0.024

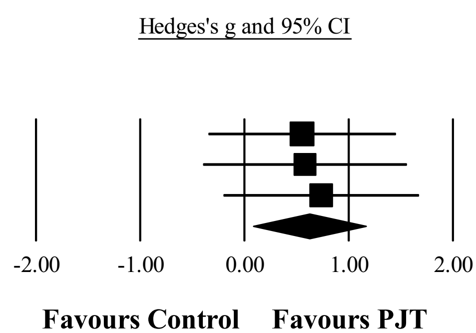

Figure 12. Forest plot of changes in rate of force development in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

recommended to more specifically reflect the underlying factors associated with adaptations induced by JT.

4.2. Velocity at submaximal intensities and heart rate at submaximal velocities

Although there was a small magnitude (ES = 0.26) improvement in velocities at submaximal lactate levels (e.g., 4 mmol.l^{-1}) after JT, this effect was non-significant. Considering the improvement in time-trial performance previously discussed, and given that lactate threshold and critical power are important determinants of endurance running performance (Poole et al., 2016), the lack of an effect due to JT was somewhat surprising. However, time-trial performances among the included studies involved distances of 5 km or less, distances which are traversed by a runner at intensities over and above the lactate threshold (Abe et al., 1999) and, thus, involve anaerobic metabolism. Moreover, there was a non-significant effect of JT on heart rate at submaximal velocities. Although running economy at submaximal velocities may be improved after JT (Balsalobre-Fernández et al., 2016; Barnes & Kilding, 2015; Denadai et al., 2017), probably due to the enhancement of the elastic mechanisms that govern locomotion (Da Rosa et al., 2019), such improvements may not be related to a reduced chronotropic response of the heart and could therefore limit the usefulness of this parameter to monitor such adaptations. Further, although an improvement in running economy after JT may relate to enhanced elastic mechanisms (Da Rosa et al., 2019), future studies must clarify this and other factors with a view to uncoupling the independent effects associated with concomitant responses to JT and endurance exercise. In particular, the role of changes in running economy, neuromuscular adaptation and elastic mechanism (Da Rosa et al., 2019), and how these factors interact after long-term JT interventions, with respect to the varying programming parameters (e.g., intensity, type of drills), in athletes with different characteristics (e.g., competitive level; sex; age), should be further explored.

Study name	Std diff in means	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Lundstrom et al. (male)	0.734	0.666	0.444	-0.571	2.040	1.103	0.270
Lundstrom et al. (female)	0.142	0.586	0.344	-1.007	1.291	0.242	0.809
Paavolainen et al	1.035	0.505	0.255	0.046	2.025	2.051	0.040
Blagrove et al.	0.379	0.476	0.226	-0.553	1.311	0.797	0.425
Li et al.	0.445	0.465	0.216	-0.467	1.356	0.956	0.339
Chelly et al.	0.163	0.386	0.149	-0.593	0.920	0.423	0.672
Ramirez-Campillo et al.	0.171	0.355	0.126	-0.524	0.867	0.483	0.629
	0.376	0.175	0.030	0.033	0.718	2.152	0.031

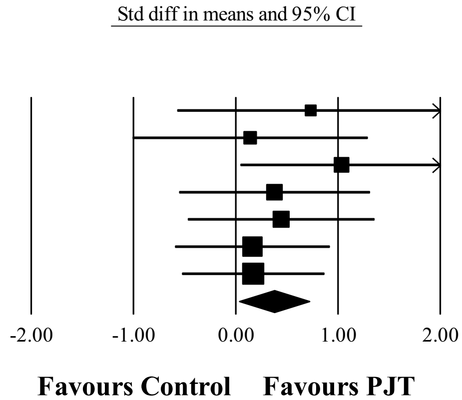

Figure 13. Forest plot of changes in sprint performance in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Barnes et al. (female)	0.861	0.461	0.212	-0.042	1.764	1.870	0.062
Barnes et al. (male)	0.678	0.442	0.195	-0.187	1.543	1.536	0.125
Chelly et al.	1.455	0.423	0.179	0.626	2.283	3.441	0.001
Garcia-Pinillos et al.	0.573	0.207	0.043	0.167	0.979	2.768	0.006
Gomez-Molina et al.	0.484	0.396	0.156	-0.292	1.259	1.222	0.222
Li et al.	0.742	0.455	0.207	-0.150	1.634	1.630	0.103
Ramirez-Campillo et al.	0.728	0.357	0.128	0.029	1.428	2.040	0.041
Saunders et al.	1.158	0.531	0.282	0.118	2.199	2.181	0.029
Sedano et al.	0.462	0.541	0.293	-0.599	1.522	0.853	0.394
	0.727	0.124	0.015	0.484	0.971	5.853	0.000

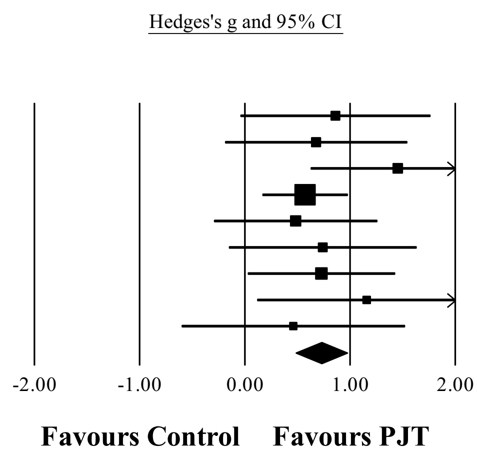

Figure 14. Forest plot of changes in reactive strength performance in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

Study name	**Hedges's g**	**Standard error**	**Variance**	**Lower limit**	**Upper limit**	**Z-Value**	**p-Value**
Ache-Dias et al. 2016	0.047	0.449	0.202	-0.833	0.928	0.106	0.916
Berryman et al. 2010	0.925	0.536	0.287	-0.124	1.975	1.728	0.084
Blagrove et al. 2018	0.324	0.452	0.204	-0.563	1.210	0.716	0.474
Gomez-Molina. 2018	0.235	0.391	0.153	-0.532	1.001	0.600	0.548
Li et al. 2019	2.160	0.562	0.315	1.059	3.260	3.846	0.000
Lundstrom et al. 2017 (females)	-0.185	0.542	0.294	-1.247	0.877	-0.342	0.732
Lundstrom et al. 2017 (males)	-0.331	0.588	0.345	-1.483	0.821	-0.563	0.574
Pellegrino et al. 2016	1.203	0.448	0.201	0.324	2.082	2.681	0.007
Sedano et al. 2013	0.955	0.567	0.322	-0.158	2.067	1.682	0.093
Spurrs et al. 2003	0.344	0.465	0.216	-0.567	1.256	0.740	0.459
	0.551	0.219	0.048	0.122	0.980	2.518	0.012

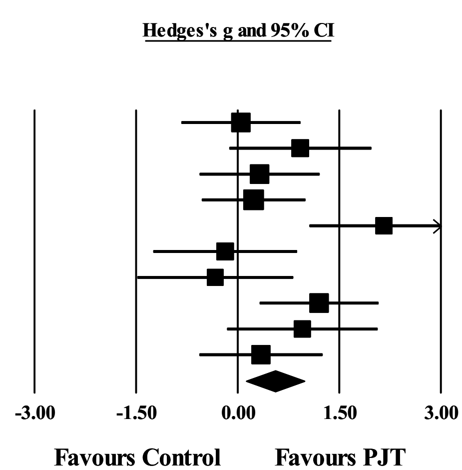

Figure 15. Forest plot of changes in running economy in endurance runners participating in programmes of jump training (PJT) compared to controls. Values shown are effect sizes (Hedges's g) with 95% confidence intervals (CI). The size of the plotted squares reflects the statistical weight of the study.

4.3. Stride rate at submaximal velocities

There was a non-significant effect of JT on stride rate. Although both stride length and stride frequency may affect running performance (Coyle, 1995), increases in running speed are usually achieved through increased stride length as opposed to stride frequency (García-Pinillos et al., 2019, 2020a). In this way, it is not surprising that JT may improve time trial performance with no discernible change in stride rate performance. However, data for stride length were only available from two studies (Giovanelli et al., 2017; Paavolainen et al., 1999), precluding their inclusion in the current meta-analysis. Of note, none of the aforementioned studies observed significant changes in stride length after JT compared to control participants. However, considering that only three studies provided data for stride rate at submaximal velocities, and only two for stride length, future studies are warranted to further investigate how different JT configurations could affect both stride length and frequency and how these parameters may be related to time trial performances and proxies of athletic performance as stiffness.

4.4. Stiffness

The term "stiffness" relates to the potential of an elastic body to resist deformation when subjected to the application of force (Latash & Zatsiorsky, 2016). Lower-limb stiffness is a relevant parameter when assessing and monitoring long-distance runners given its direct effect on running economy (Li, Newton, et al., 2019a). The stiffer the leg, the greater the storage and release of energy and this could result in enhanced running economy (Moore, 2016). Lower-limb stiffness has been suggested as an integral underpinning factor for the storage and reutilisation of elastic energy in long-distance running (Moore, 2016). Importantly, for this purpose, JT has been proposed as an effective training stimulus for increasing the ability of the lower limbs to store and release this elastic energy (Fouré et al., 2009). Likewise, the authors of an intervention study included in this SRMA (García-Pinillos et al., 2020b), concluded that the execution of 5 min of jump-rope drills, in the form of a warm up exercise, was effective in improving the RSI and foot arch stiffness of endurance runners and, consequently, subsequent running performance (i.e., 3 km time trial). Short ground contact times (<0.2 s) are recommended as an important programming parameter for coaches who are prescribing plyometric exercises as this timeframe is equivalent to that which is experienced during ground contact in running activity (Giovanelli et al., 2017). Accordingly, this promotes the execution of fast SSC sequences, thus enhancing the lower-limb stiffness of the athlete (Giovanelli et al., 2017; Spurrs et al., 2003). Contrary to our expectations, and after analysing the results from five different studies with stiffness measurements, we did not find a significant effect of JT on this measure (Figure 8). However, a lack of consistency in the methods utilised across studies (e.g., different stiffness measurements and/or different JT characteristics) could be a moderating factor on the effects of the training programme on this particular outcome. On this, a posteriori-analysis revealed a significant sub-group difference (between-group, $p = 0.041$) when JT interventions were combined with RT (ES = −0.43) compared to JT programmes performed in isolation (ES = 0.23). However, such analysis must be interpreted with caution because the parameter of the programme was calculated irrespective of between-parameter interactions (e.g., no meta-regression was performed) (Moran et al., 2018). Future studies should clarify how different types of JT drills, in combination with other training methods, could affect distinct stiffness measures (e.g. tendon stiffness, muscle stiffness; lower limb behavioural stiffness [leg stiffness; vertical stiffness; joint stiffness]) (Latash & Zatsiorsky, 2016). Furthermore, studies should control the ground contact times of the applied *plyometric* (i.e. <250 ms) and *hopping* (i.e. >250 ms) exercises, the former being a more specific form of exercise for the development of stiffness (Bobbert, 1990; Bobbert et al., 1987a; Markovic & Mikulic, 2010).

Expanding on our analysis on stiffness, the lack of improvement in this quality, which contrasts with the improvements seen in running economy and time-trial performance, may indicate a relatively less influential role of stiffness compared with the broader concept of the elastic mechanism (or rebound system) (Da Rosa et al., 2019). Accordingly, while stiffness is commonly associated with the effectiveness of the elastic mechanism (Moore, 2016), previous studies have also shown that this elastic mechanism can be altered independent of changes in stiffness, thus suggesting that their occurrence is correlated, but not causative (Cavagna et al., 2008a, 2008b). Meanwhile, concentric performance during the SSC can be acutely enhanced despite reduced force in the eccentric phase with post-activation potentiation seeming to be a plausible explanation for this phenomenon (D. A. Boullosa et al., 2011). On this basis, it could be reasonable to suggest that the long-term adaptations of the elastic mechanism may also be associated with changes in potentiation mechanisms and a concomitant resistance to the associated fatigue related with repeated muscle actions (D. Boullosa et al., 2018; Del Rosso et al., 2016, 2021). Accordingly, *stiffness* should be considered as another variable of the elastic mechanism amongst others that can influence performance (Da Rosa et al., 2019) and, because of this, be manipulated by coaches. Future studies should elucidate the role of the factors associated with the storage and release of elastic energy including both stiffness and post-activation performance enhancement mechanisms, and how JT might influence them, and affect endurance performance.

4.5. Body mass

Data revealed a non-significant effect of JT on body mass. Increases in force-generating capabilities that are independent of changes in body mass may yield a greater power-to-weight ratio (i.e. relative power), resulting enhanced running performance (Barnes & Kilding, 2015; Coyle, 1995; Markovic & Mikulic, 2010). However, how body composition changes (e.g. body fat decreases and muscle mass increases) might affect endurance performance is unclear. A recent review indicated that JT may increase muscle mass in untrained or recreationally trained participants (Grgic et al., 2020). Moreover, some evidence indicates significant reductions in body fat after JT was combined with HIIT in obese females (Racil et al., 2015). Furthermore, a cross-sectional study revealed that high jumping frequency resulted in important metabolic activation during exercise (e.g., ≥90% of VO_2max) (Ducrocq et al., 2020). On this basis, JT interventions that are characterised by a high jumping frequency might be especially effective in stimulating neuromuscular measures of physical fitness, as well as having the potential to induce significant metabolic stimulation (Ducrocq et al., 2020). Moreover, JT may also have a role in influencing cardiovascular and metabolic responses to exercise (Arazi et al., 2014; Barillas et al., 2017; Brown et al., 2010; Ramirez-Campillo et al., 2016). As most JT studies published so far have involved jump efforts with a low frequency (e.g., one jump repetition, followed by a recovery of 15 s before the next jump repetition) (Ramirez-Campillo, Alvarez, Garcia-Hermoso, et al., 2018), the potential effect of some forms of JT on body fat-related measures may seemingly remain unclear. However, diet control is very rare in JT studies and this serves as a further confounding factor that prevents more definitive conclusions being made (Grgic et al., 2020; Ramirez-Campillo, Alvarez, Garcia-Hermoso, et al., 2018; Ramirez-Campillo, Moran, et al., 2020). Because of this, a direct causal relationship cannot be established between JT and any potential changes in body mass or body composition. Accordingly, if JT could affect endurance runners' body composition further investigations, that incorporate nutritional controls are warranted.

4.6. Strength performance

Changes in maximal strength after JT were not significant (Figure 10). However, this finding may be related to the results of one highly influential study (Barnes et al., 2013) because as its the removal in our sensitivity analysis significantly affected the results (ES = 0.53; p = 0.003). Despite this, in comparison to maximal strength, it is likely that increases in RFD may play a more relevant role in endurance running as athletes need to apply high forces during short ground contact times to generate adequate propulsive forces (Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2018). Indeed, to the best of our knowledge, there are no studies associating maximum strength levels with endurance running performance, a trend which could be due to the longer duration required for achieving true maximum force values during the process of testing (Güllich & Schmidtbleicher, 2001). Meanwhile, further studies could simultaneously evaluate different RFD measures and maximum strength levels to identify the influence of different jumping exercises on these complementary parameters.

4.7. Jump performances

Unsurprisingly, we observed a significant effect of JT on jump performance. According to previous studies (Markovic, 2007; De Villarreal et al., 2009), and according to the training principle of specificity, such improvements were to be expected. Improved jumping ability may be related to increased neural drive to the agonist muscles, improved intermuscular coordination, changes in muscle size and architecture and changes in single-fibre mechanics, among others neuro-mechanical factors (Markovic & Mikulic, 2010; Radnor et al., 2017b; Taube et al., 2012). In particular, these jump improvements probably reflect a significant increase in explosive-strength performance requiring slow SSC actions, as most of the applied tests in the analysed studies (CMJ [n = 10], CMJA [n = 4)], SJ [n = 2], bounding for distance [n = 1]), were of this nature (Güllich & Schmidtbleicher, 2001; Komi, 2003; Komi & Gollhofer, 1997). The relationship between jumping performance and running endurance performance has previously been established (Hudgins et al., 2013). Indeed, the current findings also show a significant improvement in time trial performance (from 2 km up to 5 km) after JT. Although the influence of JT on endurance running may be particularly important over shorter distances, its relevance for middle- and long-distance runners should also be considered in the design of training programmes (Hudgins et al., 2013). A common myth regarding JT is related to the perceived notion that high jump volumes are necessary to induce significant improvements in performance. On the contrary, a relatively low volume of jumps (i.e. 50–60 jumps per session) may be highly effective (Ramirez-Campillo et al., 2014; De Villarreal et al., 2009), even among athletes with extensive experience in jumping actions (i.e. volleyball players) (Ramirez-Campillo, Andrade, et al., 2020). Moreover, a recent study found that 2.5 min of jump rope activity, applied two to four times per week, may be an adequate strategy to improve jumping performance and physical fitness in endurance runners (García-Pinillos et al., 2020b). Furthermore, an excessive jump volumes may increase the risk of acute or overuse injury (Brumitt et al., 2016, 2018) and it is thus particularly important to control training loads in endurance athletes with an already high load placed on the joints and surrounding musculature. Considering the individualised responses to JT (Meylan & Malatesta, 2009; Radnor, Lloyd, et al., 2017a; Ramirez-Campillo, Alvarez, Gentil, et al., 2018), and in order to avoid an excessive volume of jumps, some approaches have been recently proposed (Jiménez-Reyes et al., 2017; Jimenez-Reyes et al., 2019; Ramirez-Campillo, Alvarez, García-Pinillos, et al., 2018). If such approaches (such as the consideration of force-velocity profiling in the programming of JT) can optimise the prescription of JT interventions, we encourage researchers to engage in future research that evaluates which type of jump exercise (e.g. vertical, vs. horizontal, slow SSC vs. fast SSC) is most efficient and effective in enhancing endurance running performance.

4.8. Rate of force development

Rate of force development has been defined as the speed with which the neuromuscular system can increase contractile force during muscle activation (Rodríguez-Rosell et al., 2018), also commonly termed *explosive* force (Turner et al., 2020). The RFD is considered a key muscle strength parameter in sports requiring high-speed actions such as running (Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2018). This SRMA included three studies which were focused on the effect of JT on the RFD of endurance runners (Ache-Dias et al., 2016; Saunders et al., 2006; Spurrs et al., 2003). The current findings seem to be consistent with those studies reporting significant improvements in RFD after JT programmes, with a duration of 4 weeks (Ache-Dias et al., 2016), 6 weeks (Spurrs et al., 2003) and 9 weeks (Saunders et al., 2006) (Figure 12). Of note, improvements were observed even when different measures of RFD were used in the included studies, these comprising such measures as rate of torque development of knee extensors (Ache-Dias et al., 2016), RFD while jumping (Saunders et al., 2006), and RFD of the ankle extensors. Such results might suggest that JT could induce significant fast force generating capabilities in the lower-limb joints. The ankle, knee and hip are the main joints involved while jumping (Bobbert et al., 1987a; Komi, 2003; Lees et al., 2004) and adaptations to RFD each of these joints would be of practical benefit for athletes running on various ground gradients (i.e. uphill; down-hill; level-ground) (Vernillo et al., 2017). Moreover, depending on a runner's individual needs (e.g. relatively week hip-joint muscles), JT could be individualised to prioritise the development of one joint over another (Bobbert et al., 1987a; Komi, 2003; Lees et al., 2004).

4.9. Sprint

We found significant improvements in sprint performance in response to JT. Sprinting speed may have a crucial role in endurance event competition, particularly during decisive moments of a race, such as when a sprint finish occurs. The neuromechanical adaptations induced by JT (e.g., enhanced neural drive to agonist muscles) (Markovic & Mikulic, 2010) may improve SSC efficiency and, by extension, could facilitate the generation of a greater level of force within a given unit of time (i.e., greater RFD). This force can be reutilised in sequential concentric phases of a movement following a rapid eccentric muscle action (Komi & Gollhofer, 1997; Markovic & Mikulic, 2010; Radnor, et al., 2017b), a key requirement for better sprint performance already discussed elsewhere in this work (Bishop & Girard, 2013). Furthermore, improved neuromechanical properties after JT may enhance different ground reaction force (GRF) characteristics (e.g., impulse; peak force) (Markovic & Mikulic, 2010), which, in turn, may contribute to faster sprint accelerations (Lockie et al., 2014). Specifically, JT may primarily improve step length (Lockie et al., 2014) as opposed to step frequency, since the latter is known to reach a plateau after four to five steps during sprinting actions (Girard, Brocherie, Morin, Degache, et al., 2015; Girard, Brocherie, Morin, Millet, et al., 2015; Girard et al., 2011). Arguably, a higher load of horizontal JT may lead to larger improvements in performance during the early acceleration phase of a sprint (horizontal GRF; push-off phase) (Dello Iacono et al., 2017; Morin et al., 2012; Ramirez-Campillo et al., 2015); while, in contrast, JT with a greater emphasis on vertical force production and displacement may induce larger improvements when approaching top speed (vertical GRF) (Dello Iacono et al., 2017; Morin et al., 2012; Ramirez-Campillo et al., 2015). When interpreting the findings of this SRMA, it is important to consider: (i) 16 out of 21 included studies involved mixed JT programmes that combined both horizontal and vertical drills; and, (ii) sprinting tests comprised mostly of sprint distances ranging from 20 m up to 50 m, with one study including a 200 m sprint. On the whole, this suggests that more favourable horizontal GRF characteristics induced by JT would primarily be responsible for the improvements in sprinting observed (Moran et al., 2021). Considering the potential relevance of the force-velocity profile to both optimise JT approaches and to better assess the different components (force-velocity spectrum) of the sprinting ability of endurance runners (Jiménez-Reyes et al., 2017; Jimenez-Reyes et al., 2019; Ramirez-Campillo, Alvarez, García-Pinillos, et al., 2018), future studies may include these approaches during JT programmes.

4.10. Reactive strength performance

The observed improvements in reactive strength indices were an expected finding of this SRMA. Surprisingly, however, this outcome is in contradiction to the absence of an effect of JT on stiffness measures, as reactive strength indices are supposedly proxies of neuromuscular stiffness (Dallas et al., 2020; Flanagan & Comyns, 2008; García-Pinillos et al., 2020b; Li, Newton, et al., 2019a; Markovic & Mikulic, 2010). This finding may be related to the limited number of studies which included different measures of stiffness (five vs. eight studies for stiffness and reactive strength, respectively), and the variety of methods and indices used. In this way, it could be expected that a lower signal-to-noise ratio for stiffness measures vs. reactive strength measures would be observed. For instance, although reactive strength has been calculated with methods using both multiple vertical jumps (Barnes et al., 2013; Gomez-Molina et al., 2018; Saunders et al., 2006; Sedano et al., 2013) and single drop jumps from different heights (Chelly et al., 2015; García-Pinillos et al., 2020b; Li et al., 2019a; Ramirez-Campillo et al., 2014), the calculation of reactive strength index (RSI) only requires the flight (or jump height) and ground contact time. This reduces the sources of technical error when compared to stiffness measures derived from force-time measures and this differential could have exerted a disproportionate effect on our results. Meanwhile, it remains to be determined which measure of RSI represents the optimal method to measure effects on running performance whilst the most efficacious form of JT, in terms of ground contact time (e.g. >250 ms), has also eluded definitive conclusion (Bobbert, 1990; Bobbert et al., 1987a, 1987b; Pedley et al., 2017). Considering that competitive running events (i.e. >16 $km.h^{-1}$) are characterised by ground contact times of less than 250 ms (García-Pinillos et al., 2019, 2020a), it could be hypothesised that improvements in reactive strength by means of reduced contact time, rather than jumping height may be particularly relevant for endurance runners.

4.11. Running economy

The analyses of the nine studies evaluating running economy after JT confirms previous evidence on the positive effect of different programmes on running economy (Balsalobre-Fernández et al., 2016; Barnes & Kilding, 2015; Yamamoto et al., 2008). As previously commented, this finding is in contradiction to the results for vVO_2max, and HR and velocity at submaximal intensities. These different findings may be the result of methodological discrepancies or the intensities used between studies analysing different outcomes in runners of various levels and training history. Further studies should investigate these issues while simultaneously evaluating submaximal and maximal physiological responses to confirm the supposedly positive influence of running economy on specific and non-specific running intensities (Helgerud et al., 2010).

Meanwhile, the specific influence of jumping exercises with a slow or fast SSC on these specific adaptations should also be considered.

4.12. Practical applications

Based on the characteristics of the participants included in the 21 studies analysed in our SRMA, both youth and adult male and female endurance runners, at recreational and high-competitive levels, may benefit from the execution of a JT programme. Regarding the characteristics of effective JT interventions for endurance runners, a total duration of between four and twelve weeks, with one to four JT sessions per week (depending on volume and intensity of the sessions) should be undertaken. These sessions should usually involving high or maximal-intensity drills (e.g., minimal ground contact time; maximal RSI), and should involve a combination of plyometric jumps that are both unilateral and bilateral, in both horizontal and vertical planes. Depending on the type of drill, the volume may be prescribed as repetitions, distance or time, and, depending on the total duration and frequency of the JT programme, the total volume may vary between 240 and 2,880 jump repetitions, 540–2,700 m, 320–4,800 seconds, or a combination of these. The recovery between jump efforts was poorly reported among the included studies, but it seems that <15 seconds would seem an adequate recovery, and ~120 seconds between sets. However, coaches must be aware that when recovery time is taken between jumps, the reutilisation of kinetic energy via the elasticity of the musculotendinous unit is compromised. Regarding inter-day recovery, although 24 hours may be adequate after lower dose JT sessions, most studies incorporated a recovery of ≥48 hours. Most JT programmes followed a progressive overload, considering the volume, intensity, difficulty of the drill or a combination of these factors. Regarding the type of performance surface, most studies did not report this information, although a number of different surfaces types (e.g., grass; synthetic) were utilised across studies. Of note, most of the studies included in our SRMA recruited endurance runners without systematic experience in JT. Therefore, extrapolation of the current findings to endurance runners with extensive experience in JT must be done with caution.

We recommend that coaches and endurance runners assess the potential incorporation of an individualised JT programme into their holistic preparation programme. Moreover, JT can also be effective even when done in place of a portion of regular endurance-training, thus negating the need for additional training time and reducing the risk of excessive loading. Indeed, if an athlete's schedule is congested, the use of horizontal jumps only is an acceptable strategy for performance and the reader is, therefore, encouraged to seek out a recent work (Moran et al., 2021) for a comprehensive comparison of the benefits of adopting such a strategy. Moreover, JT drills may be performed without the need for external or expensive equipment and may be performed in a small physical space. These are practical elements of great relevance, particularly during pandemic times when athletes may be confined to their homes. Further, JT sessions as short as 5 min might offer significant benefits for endurance runners.

5. Conclusion

This SRMA confirms the positive effect of different JT regimens on middle distance running up to 5 km. The observed improvements were accompanied by small-to-moderate enhancements of jump performance, RFD, sprint performance, reactive strength, and running economy, thus confirming the positive effect of JT on the force-producing capabilities of endurance athletes and, therefore, on endurance running at high intensities. Further studies are required to identify the best JT exercises and periodisation schemes to enhance endurance running performance and to determine if these improvements may be extended to longer distances.

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