EFFECTS OF PLYOMETRIC JUMP TRAINING ON RUNNING ECONOMY IN ENDURANCE RUNNERS: A SYSTEMATIC REVIEW AND META-ANALYSIS

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Review
DOI 10.26582/k.55.2.11

Abstract:

Running economy (RE) has a strong relationship with distance running performance and is defined as the energy demand for a given velocity. Plyometric jump training may improve RE. The present study aimed to assess the effects of plyometric jump training on endurance runners' running economy and to estimate the effectiveness of program duration, training frequency, total sessions, age, training status and velocity. A literature search was performed using PubMed/MEDLINE, Web of Science, and SCOPUS databases. Subgroup and single training factor analyses of program duration, frequency, total sessions, chronological age, training status, and running velocity were performed. A random-effects model for meta-analyses was used. Eighteen studies were selected for the systematic review and 10 for the meta-analysis. A trivial effect was noted for plyometric jump training on running economy (ES=0.19). However, plyometric jump training combined with resistance training revealed a large effect on running economy (ES=1.34). Greater running economy improvements were noted after training interventions with >15 total sessions (ES=1.00), >7 weeks (ES=0.95) and >2 days/week (ES=0.89). The youngest (ES=0.95) and highly trained participants (ES=0.94) with faster velocities (ES=0.95) obtained better results. Our findings highlight the effect of plyometric jump training that may improve running economy, particularly in combination with resistance training, after longer-term interventions (i.e., >15 total sessions, >7 weeks), with greater frequency, and among younger and more highly trained runners, especially during running at higher competitive velocities.

Key words: *running performance, human biomechanics, stretch-shortening cycle, high-intensity interval training, resistance training*

Introduction

Running economy (RE), defined as the oxygen demand (i.e., steady-state oxygen uptake [VO2]) for a given velocity, has a strong relationship with distance running performance (Saunders, Pyne, Telford, & Hawley, 2004). Scientists recommend quantifying RE in aerobic energy cost units over oxygen cost to provide a more accurate reflection of the metabolic demand of running in different ranges of running velocities (Blagrove, Howatson, Pedlar, & Hayes, 2019). Endurance training, resistance training (RT), stretching, environmental conditions for runners, and nutritional factors are among the various modifiable factors that can impact RE (Barnes & Kilding, 2015). RT is one of the training methods that is reported to improve RE (Balsalobre-Fernández, Santos-Concejero, & Grivas, 2016). Improvement in RE after RT may be attributed to enhanced muscle coordination (e.g., co-activation) and leg stiffness that increases kinetic energy storage in tendons that could be used for propulsion (Paavolainen, Hakkinen, Hamalainen, Nummela, &

Rusko, 1999). For instance, the literature demonstrates that traditional RT, which involves heavy loads and slow movement speeds, with 40 weeks of strength training, can significantly improve RE, without concomitant hypertrophy, in competitive distance runners (Beattie, Carson, Lyons, Rossiter, & Kenny 2017).

Plyometric jump training (PJT) focuses on explosive movements and quick stretching and contracting of muscles, aiming to improve power, strength, and neuromuscular efficiency, and due to its similar characteristics with running, the hypothesis that this training methodology could benefit RE seems reasonable (Balsalobre-Fernández, et al., 2016). Indeed, the potential benefits of PJT for athletes' physical fitness, including RE, have been reported to increase exponentially in recent years (Ramirez-Campillo, et al., 2020b).

PJT involves various hopping and jumping exercises typically performed in multiple directions (e.g., unilateral, bilateral, horizontal, and vertical jumps) at high speed and with low or no external loads (Davies, Riemann, & Mankse, 2015; Lum, Tan, Pang, & Barbosa, 2019). The PJT exercises are commonly categorized as *fast* (e.g., drop jump [DJ]) or *slow* (countermovement jump [CMJ]), depending on the ground contact time before the jump (Ramírez-Campillo, Andrade, & Izquierdo, 2013). From a physiological perspective, PJT methods aim to increase the power derived from the stretch-shortening cycle (SSC), which is characterized by an eccentric muscle action immediately followed by a concentric muscle action (Davies, et al., 2015). The immediate succession of eccentric muscle action, such as the descent phase of a jump, with a concentric movement, such as the take-off phase, results in stimulation of a stretch reflex, potentiating performance during the propulsive phase of jumping (Nicol, Avela, & Komi, 2006). The PJT involves different factors that affect RE, mainly SSC enhancing muscle performance by improving neuromuscular efficiency, utilizing elastic energy storage and release, and enhancing strength, power, speed, and jumping ability (Seiberl, Hahn, Power, Fletcher, & Siebert, 2021). Thus, executing at least three sessions per week of PJT effectively enhanced RE in ultra-endurance male runners (Giovanelli, Taboga, Rejc, & Lazzer, 2017). In addition, a similar improvement in RE was found in men distance runners after six weeks of PJT (Spurrs, Murphy, & Watsford, 2003). In contrast, PJT did not improve RE in mixed-sex local club runners running at 4.56 m/s velocity (Pellegrino, Ruby, & Dumke, 2016). Maybe the heterogeneous sample of the study could have given these results.

While PJT appears to be effective for enhancing RE, it is essential to note that not all evidence holds the same weight as per the pyramid-based evidence paradigm, where different levels of evidence indicate varying quality and quantity of available evidence (Murad, Asi, Alsawas, & Alahdab, 2016). The systematic review is the primary quality of evidence; no greater level of knowledge has been generated regarding the effects of PJT training and its impact on endurance runners regarding RE. Further empirical research is still needed to clear the effect of PJT on measures of RE. To the authors' knowledge, no previous systematic review with meta-analysis (SRMA) has been conducted regarding the PJT influence on RE. Furthermore, in an updated scoping review of 420 articles about PJT training, the authors observed that studies tend to include only 10 participants per group (Ramirez-Campillo, et al., 2020b). This problem of underpowered studies may be resolved by conducting a meta-analysis (MA) that allows the analysis of specific results using a macro-sample from several studies.

Given that there has been no SRMA specifically examining the effects of PJT on RE in endurance runners, the significant rise in scientific publications related to PJT training indicates a growing recognition of its importance (Ramirez-Campillo, et al., 2020b). Furthermore, there appear to be conflicting findings regarding the effects of PJT interventions on athletic performance in endurance runners. This study aimed to conduct an SRMA to assess the effects of PJT on RE and to estimate the effectiveness of program duration, training frequency, total sessions, age of participants, training status, and running velocity.

Methods

The systematic review was performed using open access PRISMA® Statement protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Page, et al., 2021). A literature search was conducted in the PubMed/MEDLINE, Web of Science, and SCOPUS electronic databases. The following keywords, combined with Boolean operators (AND, OR) were used: *plyometric training*, *running economy*, *cost of running*, *oxygen cost*, *ballistic*, *complex*, *explosive*, *force-velocity*, *stretch-shortening cycle*, *jump*, *training*, *endurance*, *runners*, and *athletes*. One investigator received automatically generated emails for updates regarding the search terms used. These updates were obtained daily (if available), and the studies were eligible for inclusion until the initiation of the manuscript preparation in June 2022.

Eligibility criteria. The following inclusion criteria were applied (Liberati, et al., 2009): (a) only full-text articles written in English were included in the terms of accessibility, (b) the use of PJT training in interventions for a period of at least four weeks (defined as *lower body unilateral or bilateral bounds, jumps and hops that commonly utilize a pre-stretch or countermovement that incites usage of the stretch-shortening cycle*) (Ramirez-Campillo, et al., 2020c); (c) cohort studies on healthy endurance runners, (d) the assessment of a control group (including active controls), and (e) the measurement of RE. Trials that included PJT combined with RT were also included. The exclusion criteria were: (a) cross-sectional reviews, retrospective and prospective studies, case reports, special communications, repeated-bout effect interventions (interventions where training was repeated and participants became less susceptible to it), letters to the editor, invited commentaries, errata, overtraining studies, or detraining studies; (b) the training-related studies that did not focus on the effects of PJT exercises (e.g., studies examining the effects of upper-body plyometric exercises); (c) studies with ambiguous study protocols, not focused on the effect of PJT exercises or research studies in which PJT was not clearly described; and (d) books, book chapters and abstracts for congresses were not included.

Quality assessment. The Physiotherapy Evidence Database (PEDro) (Morton, 2009) scale was used to assess the methodological quality of the included articles. The PEDro scale is based on 11 items selected by *expert consensus*. The first one was answered Yes or No, and the rest could be rated by either 0 or 1 (0 when the answer is No and 1 when the answer is Yes). These items show a scale where the highest value is 10 (a low risk of bias) and the lowest is 0 (a high risk of bias). The study quality assessment was interpreted using the following 10-point scale: poor quality (≤3 points), moderate quality (4–5 points), and high quality (6–10 points) (Supplementary file 1).

Study selection. Two investigators (EDB and JFL) reviewed the studies and decided whether inclusion was appropriate. Any discrepancies between them were resolved via consensus with the third author (RRC). The Zotero (5.0.96.1) automation tool was used to remove duplicate records (Coar & Sewell, 2010). Figure 1 shows the search strategy and study selection. The eight studies removed from the SR to MA were due to the absence of a control group, specific data, *post-test* values, confusing data, or using control groups involved in training.

Characteristics of the studies included. For the current SRMA, the RE measurements were selected based on a logically defensible rationale. Extracted data included the following information: type of control, type of randomization, number of participants per group, type of a test, unit of measurement of each test and the running velocity of each measurement. In addition, the participants' age (years), sex, and performance level were recorded. Regarding training characteristics, training frequency (days per week), duration of training (weeks), types of PJT-jumps or RT exercises, and sets and repetitions for each exercise were also recorded. The training methods were divided into: PJT method and PJT combined with RT.

Data extraction. The main information (authors, year, objective, sample, measurements, and main findings) was extracted from the included studies. Two investigators verified a suitable process and discussed each item. The articles were divided into three main parts to clarify the information: (1) participants'/athletes' characteristics, (2) training methodology, and (3) velocity to determine RE. The search methodology followed the recommended guidelines in PubMed to identify and address methodological gaps, as advised by experts (Ramirez-Campillo, et al., 2020b).

Data analysis. For the analysis and interpretation of results, meta-analyses were conducted if at least three studies provided baseline and follow-up data for the same parameter (Garcia-Hermoso, Ramírez-Campillo, & Izquierdo, 2019). Means and standard deviations (SD) for each measure of RE *pre-post*-intervention were converted to Hedges's g effect size (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 (Deeks, et al., 2019) and facilitates analysis while accounting for heterogeneity across studies (Kontopantelis, Springate, & Reeves, 2013). In this regard, 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 ES were presented alongside 95% confidence intervals (CIs). The calculated ES were interpreted using the conventions outlined for standardized 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 (Hopkins, Marshall, Batterham, & Hanin, 2009). All analyses were conducted using the Comprehensive Meta-Analysis program (version 2; Biostat, Englewood, NJ, USA).

To gauge the degree of heterogeneity amongst the studies included, the percentage of total variation across the studies due to heterogeneity (Cochran's Q-statistic) (Higgins, Thompson, Deeks, & Altman, 2003) was used to calculate the I^2 statistic. This value represents the proportion of effects due to heterogeneity compared to chance (Page, et al., 2021). Low, moderate and high levels of heterogeneity correspond to I^2 values of <25, 25-75, and >75%, respectively (Higgins, et al., 2003). However, these thresholds are considered tentative (Higgins, et al., 2003). The chi-square test assesses whether any observed result differences are compatible with chance alone. A low *p* value or a large chi-square statistic relative to its degree of freedom provide evidence of heterogeneity of intervention effects beyond those attributed to chance (Deeks, et al., 2019). The risk of bias across studies was assessed using the extended Egger's test (Egger, Smith, Schneider, & Minder, 1997).

Subgroup analyses were performed to assess the potential effects of moderator variables. Using a random-effects model, potential sources of heterogeneity likely influencing training effects were selected *a priori*. As the adaptive responses to PJT programs may be affected by program duration (i.e., ≤7 vs. >7 weeks), training frequency (i.e., ≤2 vs. >2 sessions per week), and total number of training sessions (i.e., ≤15 vs. >15 sessions), these factors were chosen as potential moderator variables (Moran, Clark, Ramirez-Campillo, Davies, & Drury, 2019). In addition, participants' chronological age (i.e., ≤25 years vs. >25 years), training status (i.e., highly trained vs. recreational level) and velocity of tests (i.e., ≤13 km/h vs. >13 km/h) (considering that high running velocities are more competitive) were also considered as potential moderator variables (Ramirez-Campillo, et al., 2020a). Participants were divided using a median split to get a similar sample in the two groups. Meta-analyses stratification by each of these factors was performed, with α value of <.05 considered as the threshold for statistical significance.

Results

Figure 1 provides a graphical schematization of the study selection process carried out using the PRISMA guidelines. Through database searching, 7,024 records were initially identified. Finally, 18 studies were considered in SR and 10 for the MA, involving 24 experimental groups and 24 control groups, with 370 (291 men and 79 women) and 205 (167 men and 38 women) participants, respectively.

Quality of the studies. Supplementary file 1 shows the quality of the studies included in the SRMA. Fourteen out of 18 studies were considered of moderate, three of high, and only one of poor quality. The mode was five points; the mean was 4.8 points for SRMA and 4.9 for the ten articles included in the MA.

Characteristics of the studies included. Table 1 provides a synthesis of the studies included in the SRMA. Eight studies included both male and female athletes, and two of these studies provided data separated according to the sex of the participants. Ten studies included only male athletes.

Regarding training methodologies, eight studies combined PJT with RT and ten used PJT only; interventions lasted between four and 12 weeks with two to three sessions per week, whereas one study used one session per week.

All the tests that measured RE were conducted on a running treadmill, and gas exchange data were collected. The running speed varied from 7.74 km/h to 18 km/h. Most studies used the VO2 of the last minutes of each running stage to calculate RE; one study used the average of different stages, others added the lactate values to the analysis, and another used the greatest value between 60-90% of VO2 max. All studies utilized a treadmill gradient between 0 and 1%.

Main analysis. Ten studies provided data for RE (pooled n =189). Compared to a control condition, there was a moderate effect of interventions on RE (ES =0.60; 95% CI =0.07 to 1.14; p=.027; I^2 =69.8%; Egger's test p=.003; Figure 2). The relative

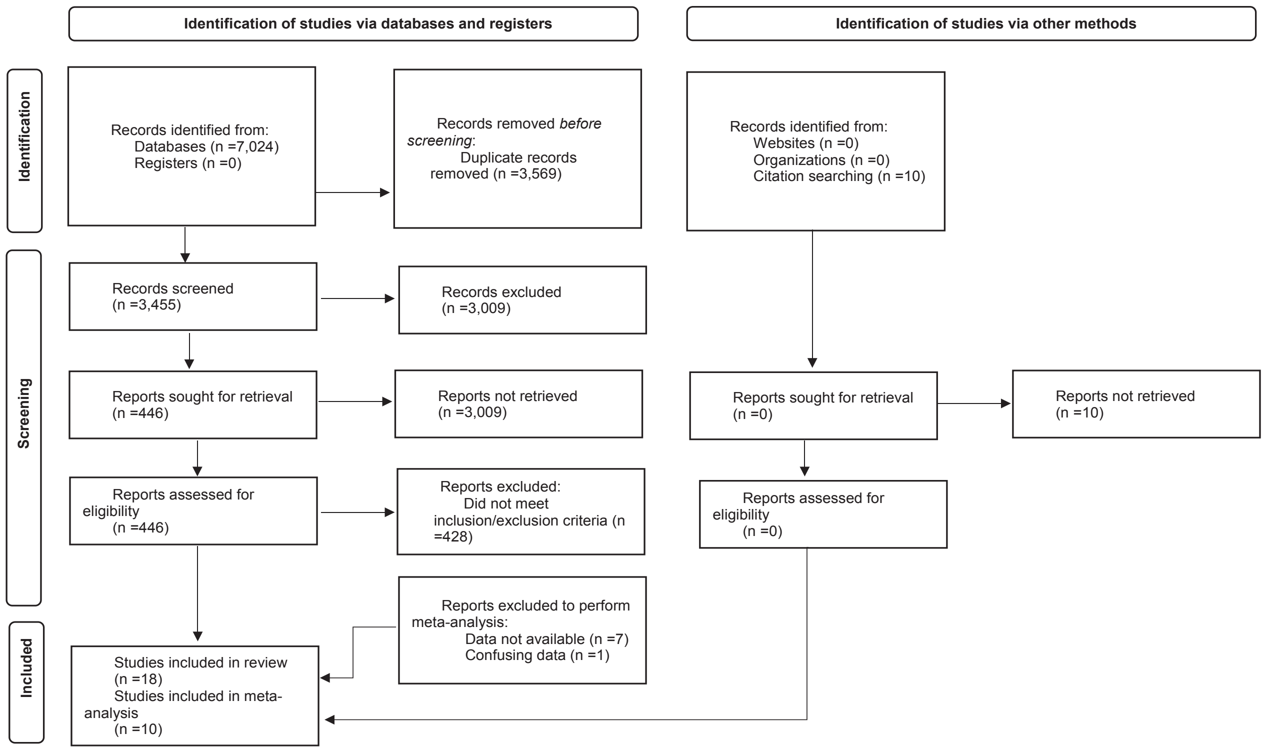

Figure 1. PRISMA flow diagram.

Table 1. Studies included in the SRMA

Authors	Subjects	PLYO training	Duration	Test	Outcome	Effect
Gómez-Molina et al. (2018)	Male (n=25) multi-sport novice athletes average 20.55 y	Different types of jumps, bounds and hops in both horizontal and vertical directions	8 weeks 2 days/week 16 total sessions	Treadmill test (ml/kg/min)	13 km/h	←→
Andrade et al. (2018) *	Male (n=16) and female (n=7) recreational runners average 21.3 y	DJs (30 and 50cm). 3 sets 10 reps each box 2 min rest	4 weeks 3 days/week 12 total sessions	Treadmill test (ml/kg/min)	10 km/h 11 km/h 12 km/h	↑ ←→ ←→
Turner, Owings and Schwane (2003)	Male (n=8) and female (n=10) regular but not highly trained runners average 29 y	Warm-up vertical jumps, double-leg vertical jumps, single-leg vertical jumps with double-leg landing, sub-maximal double-leg vertical springing jumps maximal split-squat jumps and sub-maximal double-leg springing jumps	6 weeks 3 days/week 18 total sessions	Treadmill test (ml/kg/min)	2.68 m/s 3.13 m/s	←→ ↑
Bonacci et al., (2011) *	Male (n=5) and female (n=3) triathletes with altered neuromotor control (age not reported)	CMJs, knee lifts (technical), ankle jumps, back extension squats, hamstring curls, alternate leg bounds, skip for height, single-leg ankle jumps, continuous hurdle jumps and scissor jumps for height	8 weeks 3 days/week 16 total sessions	Treadmill test (ml/kg/min)	12 km/h	←→
Spurrs, Murphy and Watsford (2003)	Male (n=17) distance runners average 25 y (does not specify training status)	20 min dynamic warm-up, squat jumps, split scissor jump, double leg bound, alternate leg bound, single leg forward hop, depth jump, double and single leg hurdle jump	6 weeks 2-3 days/week 15 total sessions	Treadmill test 1% graded (ml/kg/min)	12 km/h 14 km/h 16 km/h	↑ ↑ ↑
Pellegrino, Ruby and Dumke (2016)	Male (n=14) and female (n=8) volunteers from local running clubs average 33.35 y	20 min dynamic warm-up, SJs, split scissor jump, double leg bound, alternate leg bound, single leg forward hops, depth jump, double and single leg hurdle jump	6 weeks 2-3 days/week 15 total sessions	Treadmill test (J/kg/min)	2.15 m/s 2.55 m/s 2.95 m/s 3.36 m/s 3.76 m/s 4.16 m/s 4.56 m/s	←→ ←→ ←→ ←→ ←→ ←→ ←→
Berryman, Maurel and Bosquet (2010)	Well-trained male (n=35) endurance runners average 30 y	DJs (20,40 and 60cm) 3-6 sets 8 reps 3 min rest	8 weeks 1 day/week 7 total sessions	Treadmill test (ml/kg/km)	12 km/h	↑
Ache-Dias et al. (2018)	Male (n=8) and female (n=10) recreational runners average 27.8 y	Continuous maximal jumps 4-6 sets of 30 secs 5 min rest	4 weeks 2 days/week 8 total sessions	Treadmill test (ml/kg/min)	9 km/h	←→
Barnes et al. (2013) *	Male (n=22) and female (n=19) collegiate cross-country runners average 20.13 y	DJs (30 and 50cm) 3 sets 10 reps each box 2 min rest	4 weeks 3 days/week 12 total sessions	Treadmill test (ml/kg/min)	14 km/h	↑
Saunders et al., (2006)	Highly trained male (n=15) distance runners average 24.15 y	RT: back extensions, leg press and CMJ PJT: knee lifts (technical), ankle jumps, hamstring curls, alternate-leg bounds, skip for height, single-leg ankle jumps, continuous hurdle jumps and scissor jumps for height	9 weeks 3 days/week 30 min 27 total sessions	Treadmill test (L/min)	16 km/h 18 km/h	←→ ↑

Authors	Subjects	PLYO training	Duration	Test	Outcome	Effect
Lundstrom et al. (2017) *	Male (n=10) and female (n=12) recreational marathoners average 20.3 y	PJT: sprint exercises, frog hops, alternate leg bounds, unilateral forward hops, forward/ backward cone jumps, SJs, DJs and box to jump (1-3 sets; 8-20 reps or 2-5 reps for sprints)	12 weeks 1 day/week 12 total sessions	Treadmill test (ml/kg/min)	Average of 6 stages velocities	←→
Paavolainen et al. (1999)	Elite male (n=18) cross-country runners average 23.5 y	PJT: sprint exercises, alternative jumps, CMJs, drop and hurdle jumps and unilateral 5 jumps RT: leg press, knee extension and flexion	9 weeks 2-3 days/week	Treadmill test (ml/kg/min)	15 km/h	↑
Taipale et al. (2010) *	Male (n=17) recreational endurance runners average 35.05 y	RT: smith squats and leg press PJT: scissor jumps and SJs	8 weeks 2 days/week 16 total sessions	Treadmill test (ml/kg/min)	10 km/h 12 km/h	←→ ←→
Taipale et al. (2013) *	Male (n=17) recreational endurance runners average 35.1 y	2 groups mixed PJT and RT	8 weeks 1-2 days/week	Treadmill test (ml/kg/min)	10 km/h 12 km/h	←→ ←→
Sedano et al. (2013) *	Male (n=12) well-trained runners average 23.8 y	PJT: 40cm hurdle jumps and horizontal jumps (3 sets of 10 reps) RT: barbell squat, lying leg curl, seated calf raises and leg extension (3 sets of 7 reps)	12 weeks 2 days/week 36 total sessions	Treadmill test (ml/kg/min)	12 km/h 14 km/h 16 km/h	↑ ←→ ↑
Li et al. (2019)	Collegiate long-distance male (n=19) runners average 20.49 y	RT: back squat, Bulgarian squat and Romanian deadlift PJT: 40cm DJs, single leg hops and 50cm double leg hurdle hop (3 sets; 5-6 reps; 4 min rest)	8 weeks 3 days/week 24 total sessions	Treadmill test (ml/kg/min)	12 km/h 14 km/h 16 km/h	←→ ←→ ←→
Giovanelli et al. (2017) *	Well- trained male (n=25) ultra-endurance runners average 38.3 y	RT: plank side plank, superman, single leg half squat, step up, lunges, PLYO: walk on toes, walk on heels, butt kicks, jump rope, high knees, CMJs, split squats (5-8 exercises; 1-3 sets; 6-15 reps)	12 weeks 3 days/week 36 total sessions	Treadmill test (ml/kg/min)	8 km/h 10 km/h 12 km/h 14 km/h	↑ ↑ ↑ ↑
Blagrove et al. (2018)	Male (n=8) and female (n=10) average 17.05 y middle- or long-distance runners from county to international level	PJT: box jump, a-skip, hurdle jump, high knees, sprints, depth jumps and unilateral box jump (3 sets of 6-8 reps or 15-30m) RT: back squats, deadlifts, unilateral leg press and calf raise (2-3 sets of 6-12 reps)	10 weeks 2 days/week 20 total sessions	Treadmill test (kJ·kg -0,67·km-1)	LTP LTP -1km/h LTP -2km/h	←→ ←→ ←→

Note. PJT: plyometric jump training; RT: resistance training; LTP: lactate turn point; DJ: drop jump; CMJ: countermovement jump; SJ: squat jump; *studies not included in the MA; y: years of age; ↑: significantly improved compared to the control group; ←→: no significant difference between the groups; SRMA: systematic review with meta-analysis; MA: meta-analysis.

weight of each study in the analysis ranged from 7.8% to 11.2%.

Six studies analyzed RE after performing a PJT intervention (pooled n =119). There was no significant effect of PJT on RE (ES =0.19; 95% CI =-0.16 to 0.54; p=.295; I^2 =0.0%; Egger's test p=.622; Figure 2). The relative weight of each study in the analysis ranged from 12.3% to 21.1%.

Four studies provided data for RE after PJT combined with RT (pooled n = 70). There was a large effect of PJT combined with RT on RE (ES =1.34; 95% CI =0.09 to 2.59; p=.036; I^2 =82.6%; Egger's test p=.064; Figure 2). The relative weight of each study in the analysis ranged from 23.0% to 26.4%.

Sub-group analysis. The effects of PJT on RE changes are displayed in Table 2.

The statistical calculation revealed no sub-group difference in RE changes (p=.082) between PJT interventions (six experimental groups; ES

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Ache-Dias (2018) 9km/h	0.141	0.450	0.202	-0.740	1.022	0.314	0.754
Berryman (2010) 12km/h	0.325	0.513	0.263	-0.680	1.331	0.634	0.526
Blagrove (2018) 20km/h	0.404	0.454	0.206	-0.486	1.294	0.890	0.373
Gomez-Molina (2018) 13km/h	0.235	0.391	0.153	-0.532	1.001	0.600	0.548
Li (2019) 16km/h	2.160	0.562	0.315	1.059	3.260	3.846	0.000
Paavolainen (1999) 15km/h	2.900	0.662	0.438	1.603	4.197	4.383	0.000
Pellegrino (2016) 16.4km/h	-0.508	0.417	0.174	-1.326	0.310	-1.217	0.224
Saunders (2006) 18km/h	0.138	0.488	0.238	-0.818	1.094	0.284	0.777
Spurrs (2003) 16km/h	0.344	0.465	0.216	-0.567	1.256	0.740	0.459
Turner (2003) 11.3km/h	0.690	0.433	0.187	-0.159	1.538	1.593	0.111
Pooled	0.603	0.273	0.074	0.068	1.137	2.209	0.027

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Saunders (2006) 18km/h	0.138	0.488	0.238	-0.818	1.094	0.284	0.777
Paavolainen (1999) 15km/h	2.900	0.662	0.438	1.603	4.197	4.383	0.000
Li (2019) 16km/h	2.160	0.562	0.315	1.059	3.260	3.846	0.000
Blagrove (2018) 20km/h	0.404	0.454	0.206	-0.486	1.294	0.890	0.373
Pooled	1.342	0.639	0.408	0.090	2.594	2.102	0.036

Study name	Hedges's g	Standard error	Variance	Lower limit	Upper limit	Z-Value	p-Value
Gomez-Molina (2018) 13km/h	0.235	0.391	0.153	-0.532	1.001	0.600	0.548
Turner (2003) 11.3km/h	0.690	0.433	0.187	-0.159	1.538	1.593	0.111
Spurrs (2003) 16km/h	0.344	0.465	0.216	-0.567	1.256	0.740	0.459
Pellegrino (2016) 16.4km/h	-0.508	0.417	0.174	-1.326	0.310	-1.217	0.224
Berryman (2010) 12km/h	0.325	0.513	0.263	-0.680	1.331	0.634	0.526
Ache-Dias (2018) 9km/h	0.141	0.450	0.202	-0.740	1.022	0.314	0.754
Pooled	0.188	0.180	0.032	-0.164	0.540	1.047	0.295

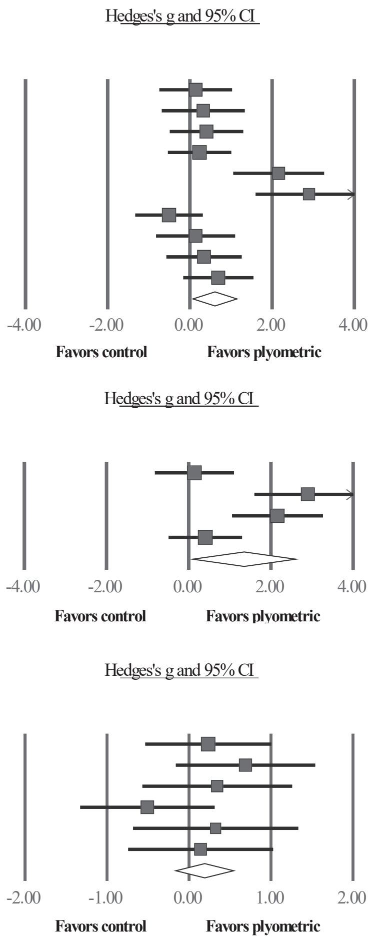

Figure 2. Forest plot of changes in running economy in endurance runners after plyometric jump training and plyometric jump training combined with resistance training compared to control condition (upper panel). Forest plot of changes in running economy in endurance runners after plyometric jump training compared to control condition (middle panel). Forest plot of changes in running economy in endurance runners after plyometric jump training combined with resistance training compared to control condition (lower panel). Values shown are effect sizes with 95% confidence intervals (CI). Black boxes: individual study groups. White diamond: overall result. The relative weight of each study in the analyses is indicated by the size of the plotted box in the figure.

Table 2. Changes in running economy according to training intervention moderators

Subgroups	n	ES	CI 95%	p-value	I2
Type of program				0.082	
PJT	6 groups	0.19			0.0%
PJT + RT	4 groups	0.19			82.6%
Program duration				0.109	
>7 weeks	6 groups	0.95	0.12-1.78		76.7%
≤7 weeks	4 groups	0.15	-0.36-0.67		28.8%
Training frequency				0.242	
>2 days week	6 groups	0.89	-0.05-1.82		82.2%
≤2 days week	4 groups	0.27	-0.17-0.71		0.0%
Total sessions				0.037	
>15 sessions	6 groups	1.00	0.21-1.79		75.8%
≤15 sessions	4 groups	0.03	-0.42-0.48		0.0%
Chronological age				0.104	
>25 years	4 groups	0.14	-0.38-0.66		27.7%
≤25 years	6 groups	0.95	0.13-1.76		76.8%
Training status				0.570	
Highly trained	4 groups	0.94	-0.11-1.98		76.6%
Recreational level	4 groups	0.45	-0.53-1.43		79.8%
Running velocity				0.350	
>13.0 km/h	5 groups	0.95	-0.23-2. 12		85.7%
≤13.0 km/h	4 groups	0.35	-0.09-0.78		0.0%

Note. PJT: plyometric jump training; RT: resistance training.

=0.19; I^2 =0.0%) compared to the interventions that combined PJT and RT (four experimental groups; ES =0.19; I^2 =82.6%).

Similarly, no sub-group difference (p=.350) was found between the PJT programs that assessed RE at velocities <13 km/h (four experimental groups; ES =0.35; 95% CI =-0.09 to 0.78; I^2 =0.0%) compared to those that assessed RE at velocities >13 km/h (five experimental groups; ES =0.95; 95% CI =-0.23 to 2.12; I^2 =85.7%).

Likewise, no sub-group difference (p=.507) was found between PJT programs applied to highly trained runners (four experimental groups; ES =0.94; 95% CI =-0.11 to 1.98; I^2= 76.6%) compared to recreationally trained runners (four experimental groups; ES =0.45; 95% CI= -0.53 to 1.43; I^2 =79.8%).

In addition, no sub-group difference was noted (p=.104) between PJT programs applied to runners with a mean age <25 years (six experimental groups; ES =0.95; 95% CI =0.13 to 1.76; I^2 =76.8%) compared to runners with a mean age >25 years (four experimental groups; ES =0.14; 95% CI =-0.38 to 0.66; I^2 =27.7%).

Moreover, no sub-group difference (p=.242) was found between PJT programs applied <2 sessions per week (four experimental groups; ES =0.27; 95% CI =-0.17 to 0.71; I^2 =0.0%) compared to programs applied >2 sessions per week (six experimental groups; ES =0.89; 95% CI =-0.05 to 1.82; I^2 =82.2%).

In regard to the PJT program duration, no sub-group difference was noted (p=.109) between PJT programs applied during <7 weeks (four experimental groups; ES =0.15; 95% CI =-0.36 to 0.67; I^2 =28.8%) compared to programs applied during >7 weeks (six experimental groups; ES =0.95; 95% CI =0.12 to 1.78; I^2 =76.7%).

However, greater RE improvements (p=.037) were noted after PJT interventions with >15 total sessions (six experimental groups; ES =1.00; 95% CI = 0.21 to 1.79; I^2 =75.8%) compared to <15 total sessions (four experimental groups; ES =0.03; 95% CI =-0.42 to 0.48; I^2 =0.0%).

Discussion and conclusions

This study aimed to evaluate the impact of PJT on RE in endurance runners. Various factors such as program duration, training frequency, total sessions, participants' age, participants' training status, and running velocity were considered. The results did not show a significant effect of PJT training on RE. However, when combined with RT, PJT demonstrated a substantial positive influence on RE. Moderate improvements were observed in ten studies that analyzed PJT and PJT with RT. Notably, a significant difference was observed between studies using PJT alone and those combining PJT with RT. Subgroup analysis indicated that >15 total sessions resulted in significant moderate differences. Although not statistically significant, favorable differences were found for runners >13 km/h, highly trained individuals, athletes <25 years of age, programs with more than two sessions per week, and durations exceeding seven weeks.

The data showed no significant effect (ES =0.19) of PJT on RE compared to the control group/condition. This result could have been affected by the negative effect of PJT reported by Pellegrino, et al. (2016). The authors claim that the type of fibers affects RE in competitive runners and results showed positive in favor of PJT at slower velocities but not at the fastest stage velocities (used in this analysis). However, the other studies included in this SRMA showed a positive effect on RE in favor of experimental groups at faster velocities. Therefore, this study significantly affects this MA due to the low number of studies which measure PJT on RE (Pellegrino, et al., 2016). Contrary to our results, this study showed worse results in RE at higher velocities. Although our MA was not statistically significant, high velocities, >13 km/h (ES =0.95), showed moderate effect, and lower velocities <13 km/h (ES =0.35) showed small effect. Physiological changes induced by PJT, such as muscle-tendon stiffness, might have allowed for reduced ground contact time and reduced energy spent during running (Paavolainen, et al., 1999). For this reason, PJT could have a greater impact on RE at higher velocities in which contact time has more relevance (Cunningham, Hunter, Seeley, & Feland, 2013).

The data showed that PJT with RT had a large effect (ES =1.34) on RE compared to the control group/condition. Supporting these SRMA results, combining both types of training is the best strategy to improve RE (Blagrove, et al., 2018; Giovanelli, et al., 2017; Li, et al., 2019; Lundstrom, Betker, & Ingraham 2017; Paavolainen, et al., 1999; Saunders, et al., 2006; Sedano, Marín, Cuadrado, & Redondo, 2013; Taipale, et al., 2010; Taipale, Mikkola, Vesterinen, Nummela, & Häkkinen, 2013). The data is clear in favor of this strategy, not only in MA results but also in SR studies like that of Giovanelli, et al. (2017), where well-trained ultra-endurance runners improve RE in different steady-stages, from 8 km/h to 14 km/h using PJT with RT. Contrary to the Lum and Barbosa (2019) study results, where endurance-based RT did not have an effect on endurance performance, the study carried out by Giovanelli, et all. (2017) showed that unweighted exercises like lunges or planks combined with PJT enhance RE in well-trained ultra-endurance runners (Giovanelli, et al. 2017). Thus, not much equipment is needed to improve RE, but more scientific evidence is needed to verify this statement. Despite these outcomes, a minimum intensity is probably required to enhance

RE if RT is not combined with PJT (Li, et al., 2019).

The more experienced athletes may have had more time to improve their strength and to test more PJT methodologies throughout their careers. Consequently, these participants could be more familiarized with the stress involved by combining PJT and their usual endurance training (Kraemer, et al., 1995). In contrast, these MA results showed that younger athletes (≤25 years old) got better results in RE (ES =0.14 vs. ES =0.95). This could be because these athletes are not used to new training stimuli or because younger athletes have never used this type of stimulus, which can lead to greater effects (Hawley, 2008). Therefore, >25-year-old athletes could be familiarized with PJT and be more adapted to this training method. Older athletes probably lose reactive strength, and training them could be more difficult. The reactive strength index plays an important role in RE, with the highest impact at high velocities due to the specific demands (Ramirez-Campillo, et al., 2018). It explains, too, the better results at high running velocities, > 13 km/h (ES =0.35 vs. ES =0.95), probably due to fast PJT exercises that take on more relevance. It should be considered that no studies used PJT with RT on subjects over 25 years old and measured at ≤ 13 km/h, so this could be a limitation.

Likewise, the benefits are also related to the athletes' level. The results of this MA showed that highly trained athletes improved more than recreational athletes (ES =0.94 vs. ES =0.45). This could be explained because PJT is well tolerated by high-level athletes (Turner, Owings, & Schwane, 2003) and not so much by lower-level runners (Pellegrino, et al., 2016), which could be due to a minimum of strength needed to start a PJT program as suggested by current concepts (Davies, et al., 2015). Thus, the low training level of recreational athletes, added to the high-impact exercises, could be too aggressive for people without previous experience. The fatigue caused by this training, added to their inexperience in neural adaptations, would be determinant to explain these results. For example, fast SSC exercises like DJ are more aggressive than slow SSC exercises like CMJ (Ramírez-Campillo, et al., 2013). Therefore, low-level athletes might not have enough strength to benefit from activities like DJ and would benefit more from exercises like CMJ. This could be observed in the studies with athletes of different training levels using fast SSC exercise (DJ), where the highly trained ones improved RE at high velocities (12 km/h) (Berryman, Maurel, & Bosquet, 2010) and the poorly trained improved less (Andrade, et al. 2018). In addition, for these reasons, the most experienced athletes benefit more from combining PJT and RT, as shown by this SRMA.

Regarding the program duration, long-term programs (>7 weeks) (ES =0.15 vs. ES =0.95) with more than 15 total sessions are more effective in enhancing RE. A recent MA showed a similar result in favor of PJT with a longer duration to enhance sprint performance (Ramirez-Campillo, et al., 2020a). The study by Sedano, et al. (2013), one of the studies with a high quality on the PEDro scale, used 12 weeks of intervention in well-trained men runners. They observed a RE improvement at 12 and 16 km/h using horizontal and vertical jumps mixed with traditional RT. Likewise, Paavolainen et al. (1999) obtained similar results. Therefore, using a combination of horizontal and vertical jumps with RT could be one of the best methods to enhance RE if these training programs have the necessary duration (Gómez-Molina, Ogueta-Alday, Camara, Stickley, & García-López, 2018; Paavolainen, et al., 1999). Thus, training in specific directions, both horizontal and vertical, can have a significant impact on improving RE. The manipulation of training program variables like duration, frequency and volume are more important than exercise selection to enhance RE, observing these results.

Referring to training frequency, unsurprisingly, a high frequency, >2 days a week (ES =0.27 vs.ES =0.89) (Andrade, et al., 2018; Barnes, Hopkins, Mcguigan, Northuis, & Kilding, 2013; Bonacci, et al., 2011) could help to improve RE. Other performance parameters like CMJ and DJ were also enhanced by PJT when high-volume training was completed (Sedano, et al., 2013). In addition, implementing the PJT program improves performance and reduces the risk of injury (Markovic & Mikulic, 2010).

To the authors' knowledge, this is the first SRMA to assess the effects of PJT on RE in endurance runners. In the current SRMA, 370 experimental and 205 control participants were involved. This could reduce the problem of underpowered sample studies. In addition, the studies included adopted different protocols, so making more complex comparisons could be more challenging. However, regarding sub-group analysis, the sample is not so high, and some results may not be statistically significant due to the small statistical power. Because of this problem, the results should be interpreted with caution. Studies included in the SRMA were executed with endurance-running athletes. Therefore, the results of this study should not be generalized to all sports.

Currently, RE is one of the main concerns for running coaches, researchers, and athletes. This study shows that the best way to improve RE is PJT with RT. This combination has a significant large effect on endurance performance with a better impact on young athletes.

Furthermore, independently computed single factor analyses for different training variables showed significant differences in total training sessions (>15 sessions) which had an advantage in the magnitude of RE improvement. In addition, non-significant benefits are demonstrated in favor of higher compared with lower training volumes (>7 weeks) and frequencies (>2 sessions per week).

Besides, young (<25 years) and highly trained athletes perform better at higher running velocities without significant differences. In addition, PJT may benefit significantly from high running velocity (>13 km/h), where the contact time is more relevant and similar to PJT.

For researchers and practitioners, it is recommended to consider the following:

Further studies should investigate the effects of PJT on RE in endurance runners, aiming for larger sample sizes to enhance statistical power and provide more robust conclusions. To design training programs, coaches and practitioners should prioritize the combination of PJT with RT to optimize RE and improve endurance performance, especially in young athletes. The total training sessions should aim for more than 15 total sessions, as this appears to have a greater impact on RE improvement. Additionally, they should consider longer training durations (>7 weeks) and higher training frequencies (>2 sessions per week) to enhance RE outcomes, and focus on high running velocities (>13 km/h), as PJT may have greater relevance and benefits in terms of contact time, particularly for young (<25 years) and highly trained athletes. While the results of this study highlight the benefits of PJT with RT for endurance runners, caution should be exercised when generalizing these findings to athletes from other sports or populations.

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Submitted: December 20, 2022
Accepted: October 12, 2023
Published Online First: November 17, 2023

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Data availability statement

The review was not registered on PROSPERO; however, following the methods section criteria, everyone can replicate the search strategy. In addition, the datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.