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***TITLE**: THE EFFECTS OF STRENGTH TRAINING ON RUNNING ECONOMY IN HIGHLY TRAINED RUNNERS: A SYSTEMATIC REVIEW WITH META-ANALYSIS OF CONTROLLED TRIALS*

***BRIEF RUNNING HEAD**: META-ANALYSIS: STRENGTH TRAINING&RUNNING ECONOMY*

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ABSTRACT

The purpose of this study was to perform a systematic review and meta-analysis of controlled trials to determine the effect of strength-training programs on the running economy (RE) of high-level middle- and long-distance runners. Four electronic databases were searched in September 2015 (Pubmed, SPORTDiscus, MEDLINE and CINAHL) for original research articles. After analyzing 699 resultant original articles, studies were included if the following criteria were met: (a) participants were competitive middle- and/or long-distance runners; (b) participants had a VO_{2max} > 60mL·kg^{-1-}·min^{-1}; (c) studies were controlled trials published in peer-reviewed journals; (d) studies analyzed the effects of strength-training programs with a duration greater than 4 weeks; (e) RE was measured before and after the strength-training intervention. Five studies met the inclusion criteria, resulting in a total sample size of 93 competitive, high-level middle- and long-distance runners. Four out of five of the included studies used low to moderate training intensities (40-70% one-repetition maximum), and all of them used low to moderate training volume (2-4 resistance lower-body exercises plus up to 200 jumps and 5-10 short sprints) 2-3 per week for 8-12 weeks. The meta-analyzed effect of strength training programs on RE in high-level middle- and long-distance runners showed a large, beneficial effect (standardized mean difference [95%Confidence Interval] = -1.42 [-2.23, -0.60]). In conclusion, a strength-training program including low to high intensity resistance exercises and plyometric exercises performed 2-3 times per week for 8-12 weeks is an appropriate strategy to improve RE in highly training middle- and long-distance runners.

KEYWORDS: elite athletes; distance running; performance; resistance training; plyometrics

INTRODUCTION

Sustained running performance is reliant on a complex interaction of factors that lead to efficient muscular work and should result in fast and effective running gait (25). Among the factors that may predict middle- and long-distance running performance, running economy (RE), commonly defined as the steady-state VO_2 required at a given submaximal speed, has garnered the most attention over the last decade, although it is often still referred to as "*being relatively ignored in the scientific literature*" (12).

Traditionally, biomechanical factors (30,50), muscle fiber distribution (7,38), age (28), sex (8) and anthropometric factors (32), have been found to account for inter-individual variability in RE. However, RE is also largely influenced by training strategies, including a wide range of forms of strength training such as low-resistance training, high-resistance training, explosive training and plyometric training(3). These different strength-training modalities have been reported to improve RE not only in recreational, but also in moderately trained and highly trained runners (3,4,58).

RE improvements consequence of strength-training interventions have been attributed to improved lower limb coordination and muscle co-activation, which would ultimately increase muscle stiffness and decrease ground contact times (37). Similarly, strength-training interventions have been suggested to increase type I and type II fibers' strength (53), resulting in less motor unit activation to produce a given force (3). This increase in strength may also improve biomechanical efficiency and muscle recruitment patterns (43), thus allowing a runner to run more efficiently at a given running speed.

However, despite the body of evidence supporting the use of strength training to improve RE, it has been traditionally overlooked by long-distance runners and their coaches to the extent that runners competing in the 2008 US Olympic Marathon trials "*included little strength training in their training programmes… and nearly half the runners did no strength training at all*" (26). This may be a consequence of long-distance runners and their coaches being unaware of the potential benefits of strength training to improve RE and thus, performance.

Previous review articles on the effects of strength-training programs on RE did not perform a meta-analysis as they only summarised the available data (3,4,58). Thus, the aim of this study was to systematically review the body of scientific literature for original research and perform a meta-analysis addressing the effects of strength training on RE in highly-trained runners.

METHODS

Experimental approach to the problem

A literature search was conducted on 25 September 2015. The following databases were searched: Pubmed, SPORTDiscus, Medline and CINAHL (Cumulative Index to Nursing and Allied Health Literature). Databases were searched from inception up to September 2015, with no language limitation. Abstracts and citations from scientific conferences were excluded.

Literature search

In each database the title, abstract and keywords search fields were searched. The following keywords, combined with Boolean operators (AND, OR), were used: “running economy”, “cost of running”, “strength training”, “resistance training”, “weight training”, “weight lifting”, “plyometric”, “sled training”, “resisted sprints” and “jump”. No additional filters or search limitations were used.

Inclusion criteria

Studies were eligible for further analysis if the following inclusion criteria were met: (a) participants were middle- and/or long- distance runners (studies with triathletes or any other kind of athletes were excluded); (b) participants had a VO_{2max} value > 60mL·kg^{-1}·min^{-1}; (c) studies were controlled trials published in peer-reviewed journals; (d) studies analyzed strength-training programs with a duration greater than 4 weeks; (e) RE was measured before and after the strength-training intervention.

Two independent observers reviewed the studies and then individually decided whether inclusion was appropriate. In the event of a disagreement, a third observer was consulted to determine the inclusion of the study. A flow chart of the search strategy and study selection is shown in Figure 1.

****FIGURE 1 ABOUT HERE****

Quality assessment

The Physiotherapy Evidence Database (PEDro) scale (34) and Oxford’s levels of evidence (36) were used by two independent observers in order to assess the methodological quality of the articles included in the meta-analysis. Oxford’s level of evidence ranges from 1a to 5, with 1a being systematic reviews of high-quality randomized controlled trials and 5 being expert opinions. The PEDro scale consists of 11 different items related to scientific rigor. Items 2-11 can be rated with 0 or 1, so the highest rate in the PEDro scale is 10, and the lowest, 0.

Statistical analyses

Standardized mean difference (SMD) with 95% Confidence Intervals (CI) between strength training and control conditions were calculated with RevMan 5.3.5 for Mac using a random effects model. Mean and standard deviations for the outcome measures were present in each original article and it was not necessary to contact the authors for further data. Significance for an overall effect was set at $p<0.05$. Heterogeneity of the analyzed studies was assessed using an I-squared test, setting the significance level at $p<0.01$. If heterogeneity was significant, further analysis (removing studies to detect the potential source of heterogeneity) was performed. Also, the contribution (%) of each study to the overall combined effect of the intervention was computed as an inverse proportion of the within-study variance (20). Finally, effects of the interventions (strength-training programs) were qualitatively assessed using the following threshold for the standardized mean difference, which was specifically designed for high-level athletes (40): <0.25, trivial; 0.25-0.50, small; 0.50-1.0, moderate; >1.0, large.

RESULTS

Studies selected

Search strategy yielded 699 total citations as presented in Figure 1. After removing duplicates and reviewing the resultant 174 full-text articles, 5 studies met the inclusion criteria (33,37,51,52,54). Excluded studies had at least one of the following characteristics: (a) participants had VO_{2max} values < 60 $ml \cdot kg^{-1} \cdot min^{-1}$; (b) participants were not middle and/or long distance runners; (c) lack of a control group; (d) strength-training interventions lasted less than 4 weeks; (e) RE was not measured. Thus, the overall sample for the present meta-analysis resulted in 93 high-level middle- and long-distance runners with VO_{2max} > 60 ml·kg^{-1}·min^{-1}.

Level of evidence and quality of the studies

Three of the 5 included studies had a level of evidence 1b (high quality randomized controlled trials). The two remaining studies had a level of evidence 2b as participants were not randomly allocated into the intervention or control groups. Also, mean score in the PEDro scale was 5.4, with values ranging from 5 to 6 (Table 1).

Characteristics of the participants

A summary of participants' characteristics is presented in Table 2. The total number of participants was 93 (78 males and 15 females) with an age ranging from 17.3 to 29.8 years. Participants' VO_{2max} ranged between 61.2-71.1 ml·kg^{-1}·min^{-1}. All participants competed in middle- and long-distance running events at national and/or international level.

Characteristics of the training programs

The characteristics of the training programs of each study are depicted in Table 3. Three studies (51,52,54) randomly allocated the participants into the intervention or control groups, while the other two (33,37) matched the groups for age and training level in a non-randomized way. Training interventions ranged from 8 to 12 weeks: 2 studies used 8-week programs (33,54), 2 studies used 9-week programs (37,51) and 1 study used a 12-week program (52). Participants trained 3 times per week in 4 studies (33,37,51,54), and 2 times per week in the other study (52). Training duration ranged from 15 to 90 minutes, with 4 of the 5 studies having sessions longer than 30 minutes (33,37,51,52). One study (54) used high loads (85% of one-repetition maximum, 1-RM) and just the half squat exercise for the intervention group. In contrast, four studies (33,37,51,52) used 4 resistance-exercises with 1-3 sets of 4-10 repetitions at low and moderate intensities (40-70% 1RM) in combination with 2-6 unloaded plyometric exercises for a total of 30-200 jumps and/or 5-10 repetitions of 20-150 m sprints.

Effects of strength training on running economy

The average RE change was -2.32 ± 2.07 and 0.57 ± 2.48 $ml \cdot kg^{-1} \cdot min^{-1}$ for the intervention and control group, respectively. The meta-analysis demonstrated an overall, significant, large beneficial effect of the strength-training interventions on RE when compared to the control group (SMD [95%CI] = -1.43 [-2.23, -0.64], Z = 3.53, $p<0.001$). Four studies showed a large effect of the intervention (SMD >1.0) and another one showed a moderate effect. See Figure 2.

****FIGURE 2 ABOUT HERE****

The I-squared test showed a significant heterogeneity among the included studies (I^2=61%, p=0.03). However, further analysis showed that the removal of the study by Paavolainen et al. (37) reduced the heterogeneity to 0 (I^2 = 0%, p=0.77), indicating that this study was the source of heterogeneity. In addition, the contribution of this particular study was the lowest of the 5 studies (13.5% *vs*. 20.3-24.1%). When removing the aforementioned study, the re-calculated average RE change was -1.88 ± 2.31 and 0.51 ± 2.76 $ml \cdot kg^{-1} \cdot min^{-1}$ for the intervention and control group, respectively. This resulted in an overall large, beneficial and significant effect of the strength-training interventions (SMD [95%CI] = -1.06 [-1.56, -0.56], Z = 4.16, p<0.001).

DISCUSSION

The present meta-analysis shows an overall large beneficial effect of the strength training interventions on RE in highly trained middle- and long-distance runners when compared to the control group. Four of the 5 included studies presented an absolute SMD greater than 1, which is considered a large effect when studying high-level athletes (40), and the fifth study showed a moderate to high effect. Moreover, the overall 95% CI ranged from -2.23 to -0.64 SMD, that is, it did not cross 0 or positive values, which would have meant trivial or negative effects of the intervention. Thus, 100% of the studies showed a significant and meaningful beneficial effect of strength-training interventions on RE in highly trained middle- and long-distance runners. Interestingly, one particular study (37) showed a very large SMD, which was greater than those observed in the other studies (i.e., -3.78 *vs.* -1.43 for the overall effect). However, we could not find any particular explanation for the superior benefits of the intervention used in Paavolainen et al. (37) as the number of strength-training sessions conducted (3 sessions), its contents (resistance, plyometrics and sprint exercises), the range of loads used (0-40% 1-RM) and the duration of the intervention (9 weeks) were very similar to those in the other studies.

One of the main concerns when training strength and endurance concurrently is the well-known interference phenomenon, by which the development of one of these capacities is impaired by training the other (15). Thus, finding the right balance between strength- and endurance-training sessions appears to be crucial (1,13,16). It has been previously reported that just one resistance training session per week is not enough to increase muscle strength or power in elite middle- and long-distance runners probably because of the high endurance:strength training ratio (2). In this regard, although every study in this meta-analysis used a different configuration of exercises and training intensities, all included at least 2 strength-training sessions per week during the intervention, with most studies (4/5) having 3 sessions per week (Table 3). Taking into account that runners conducted also 6-9 endurance-training sessions per week, it results in a 6:2-9:3 ratio between weekly endurance:training sessions. All analyzed studies found significant improvements in muscle strength, power output, jump height and RE (33,37,51,52,54); therefore, strength-training sessions being ~30% of the total training sessions might be an valid strategy to improve RE and muscle strength concurrently in highly trained runners according to our analysis.

The most common strength-training programs in the analyzed studies consisted of lower-body resistance exercises such as back squats or leg extensions combined with plyometrics (33,37,51,52,54). Both types of strength-training modalities have been probed, in both an isolated or combined way (11,41,55) to improve several variables related to neuromuscular performance such as maximal strength muscle power output, tendon stiffness and rate of force development (9,11,17,29,42). While these factors have been specially studied in strength or explosive athletes such as weightlifters, rugby players or sprinters (5,18,44), there is a growing body of research that highlights the importance of neuromuscular performance in middle- and long-distance runners (4,10,38,39). For example, a significant correlation has been observed between jumping ability and the time to cover 800, 3000 and 5000 m in highly trained runners (21). Similarly, recent studies describing the muscle-tendon properties of world-class Kenyan runners found that these athletes have higher jumping ability, muscle power and smaller stretch-shortening amplitudes and contact times that national level Japanese athletes (47,48), variables likely related to their more efficient RE (31,35,42).

It has to be noted that most strength-training programs (4 out of 5 of the included studies in the present meta-analysis) used low to moderate training intensities for the resistance exercises (40-70% 1-RM), and all of them used low to moderate training volumes (2-4 resistance lower-body exercises plus up to 200 jumps and 5-10 short sprints, for a total session duration of 30-60 min). Just one study used heavy loads (85% 1-RM), but each strength-training session consisted of just 4 sets of 4 repetitions of back squat for about 15 min. Furthermore, none of the studies used repetitions to failure, a common practice in bodybuilding that seems to maximize muscle hypertrophy (11,45), but that may impair muscular performance and produce an excessive degree of fatigue (19,23,24,57).

Training to failure (reaching the maximal number of repetitions that could be done within a set for a determined load) produces an enormous metabolic and neuromuscular fatigue (19,46) that could lead to a transition to slow-twitch fiber type (14) and reduce the muscle power output (19,23). Therefore, since variables related to muscle power are crucial for distance running performance, a non-to-failure approach aiming the improvement of the neuromuscular performance might be more appropriate for highly-trained middle- and long-distance runners.

The main limitation of the present meta-analysis is the small number of included studies. Although the role of strength training in the improvement of running performance has received a lot of attention during the last decade (4,42,58), the vast majority of the studies recruited amateur-recreational runners instead of highly trained athletes (27,35,38). Considering that highly trained runners have different biomechanical and physiological profiles than non-elite athletes (6,48,49,56), future research analysing elite runners is thus warranted. This may provide valuable information for coaches and applied scientists for the ongoing management of elite running training programmes and may be especially relevant in the context of a multifactorial approach to reach historic milestones such as the sub-2h marathon (22).

PRACTICAL APPLICATIONS

The present meta-analysis shows an overall unanimous, large, beneficial effect of the strength training in the RE of highly trained middle- and long-distance runners when compared to the control group. It appears that a strength-training program consisting of 2-4 resistance exercises at 40-70% 1-RM without reaching failure, plus plyometric exercises performed 2-3 times per week for an overall 3:1 endurance:strength training ratio and lasting 8-12-week is a safe strategy to improve RE. This may help highly trained middle- and long-distance runners to achieve an optimum performance.

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FIGURES LEGENDS

Figure 1. Flow chart of search strategy and selection of articles

Figure 2. Forest plot showing the individual and combined effects of the intervention on running economy (RE). Black square with horizontal lines indicates the standardized mean difference (SMD), with 95% Confidence Interval (CI) between the intervention (experimental) and control groups for each study, while the black diamond represents the overall SMD and CI for all studies in the meta-analysis. Mean and SD represent absolute measures of RE in $ml \cdot kg^{-1} \cdot min^{-1}$.

Table 1. PEDro ratings and evidence levels of the included studies

Study	PEDro ratings*												Evidence levels
	1	2	3	4	5	6	7	8	9	10	11	Total	
Paavolainen et al. 1999	No			1				1	1	1	1	5	2b
Saunders et al. 2006	Yes	1		1				1	1	1	1	6	1b
Mikkola et al. 2007	Yes			1				1	1	1	1	5	2b
Støren et al. 2008	Yes	1						1	1	1	1	5	1b
Sedano et al. 2013	Yes	1		1				1	1	1	1	6	1b

*Items in the PEDro scale: 1 = eligibility criteria were specified; 2 = subjects were randomly allocated to groups; 3 = allocation was concealed; 4 = the groups were similar at baseline regarding the most important prognostic indicators; 5 = blinding of all subjects; 6 = blinding of all therapists who administered the therapy; 7 = blinding of all assessors who measured at least 1 key outcome; 8 = measures of 1 key outcome were obtained from .85% of subjects initially allocated to groups; 9 = all subjects for whom outcome measures were available received the treatment or control condition as allocated or, where this was not the case, data for at least 1 key outcome was analysed by “intention to treat”; 10 = the results of between-group statistical comparisons are reported for at least 1 key outcome; 11 = the study provides both point measures and measures of variability for at least 1 key outcome.

Table 2. Characteristics of the studies and the participants

First author, year	Participants			Study design	
	Number (M/F)	Age (yrs.)	VO_2Max (mL*kg^{-1}*min^{-1})	Randomized: YES/NO	Main outcome*
Paavolainen et al. 1999	18 (18/0)	23.3 ± 3	63.3 ± 2.1	NO	RE at 15km/h; VO_2Max
Saunders et al. 2006	15 (15/0)	24.2 ±2.3	71.1 ± 6.0	YES	RE at 18km/h, VO_2Max
Mikkola et al. 2007	25 (18/7)	17.3 ± 0.5	62.6 ± 3.9	NO	RE at 14km/h, VO_2Max
Støren et al. 2008	17 (9/8)	29.1 ± 6.1	61.2 ± 3.9	YES	RE at 70%VO_2Max, VO_2Max
Sedano et al. 2013	18 (18/0)	23.8 ± 1.2	69.6 ± 2.0	YES	RE at 12km/h, VO_2Max

RE = running economy; M/F = male/female; VO_2Max = maximal oxygen consumption. *RE and VO_2Max values were measured in mL*kg^{-1}*min^{-1}, except in Støren et al (CITA), in which RE was measured in mL*kg$^{-0.75}$*min^{-1}, and in Sauders et al. (CITA), in which RE was measured in L*min^{-1}.

Table 3. Characteristics of the training programs

First author, year	Program type	Program exercises	Range of loads (%BW/RM)*	#weeks of intervention	Sessions/week	Duration (min)	**SMD [95%CI]**
Paavolainen et al. 1999	ST/PLY/RT	ST: (5-10reps of 20-100m); PLY: (alternative jumps, CMJ, jump squats, drop jumps, 30-200 total jumps); RT: (leg extension, leg curl, leg-press, 1set/5-10 rep)	ST/PLY: 0; RT: 40	9	Not reported; 2.7h per week, according to session duration most likely 3	15-90	**-3.78 [-5.45, -2.1]**

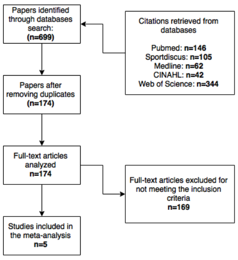
Saunders et al. 2006	PLY/RT	PLY: (alternate leg-bounds, skip for height, single-leg ankle jumps, CMJ, hurdle jumps, scissors jumps, 1-2sets/6-15reps; 36-180 total jumps); RT (leg press, hamstring curls, 1-2sets/6-10reps)	PLY: 0; RT: 60	9	3	30	**-0.54 [-1.58, 0.49]**
Mikkola et al. 2007	ST/PLY/RT	ST: (5-10reps of 30-150m); PLY: (alternative jumps, calf jumps, squat	ST/PLY: 0; RT: Low loads, repetitions	8	3	30-60	**-1.03 [-1.87, -0.18]**

		jumps, hurdle jumps, reps/sets not reported); RT (half-squats, knee extensions, calf raises, abdominal crunches, back extensions, 2-3sets/6-10reps)	NOT until failure, %RM not reported				
Støren et al. 2008	RT	RT: (half squats, 4sets/4reps)	85	8	3	Not reported. Considering number of exercises, sets and reps, about 15min	**-1.45 [-2.56, -0.35]**

Sedano et al. 2013	RT/PLY	RT: (back squat, lying leg curl, seated calf raises, leg extension, 3sets/7reps); PLY: (hurdle jumps, horizontal jumps, 6sets/10reps; 120 total jumps)	RT: 40-70; PLY: 0	12	2	Not reported. Considering number of exercises, sets and reps, about 45-60min	**-1.17 [-2.24, -0.10]**

ST = sprint training. Short sprints performed at maximal intended velocity; PLY = plyometric training; RT = resistance training; BW = body weight; RM =1-repetition maximum; SMD = standardized mean difference between experimental and control groups, bias corrected (Hedge's g) as reported by RevMan 5.3; CI = confidence intervals.

*Range of loads is reported as a percentage of BW for ST and PLY, and as a percentage of RM for RT.


Papers identified through databases search: (n=699)
Citations retrieved from databases
Pubmed: n=146
Sportdiscus: n=105
Medline: n=62
CINAHL: n=42
Web of Science: n=344
Papers after removing duplicates (n=174)
Full-text articles analyzed n=174
Full-text articles excluded for not meeting the inclusion criteria n=169
Studies included in the meta-analysis n=5

	Experimental			Control				Std. Mean Difference	
Study or Subgroup	Mean	SD	Total	Mean	SD	Total	Weight	IV, Random, 95% CI	Year
Paavolainen et al.	−4.1	1.13	10	0.8	1.36	8	13.5%	−3.78 [−5.45, −2.10]	1999
Saunders et al.	−3.1	5.03	7	0.4	5.13	8	21.1%	−0.65 [−1.70, 0.40]	2006
Mikkola et al.	−1.5	2.38	13	1.3	2.9	12	24.3%	−1.03 [−1.87, −0.18]	2007
Storen et al.	−1.22	0.84	8	0.43	1.25	9	20.3%	−1.45 [−2.56, −0.35]	2008
Sedano et al.	−1.7	0.99	12	−0.1	1.8	6	20.8%	−1.17 [−2.25, −0.10]	2013
Total (95% CI)			**50**			**43**	**100.0%**	**−1.43 [−2.23, −0.64]**	

Heterogeneity: $Tau^2 = 0.49$; $Chi^2 = 10.39$, $df = 4$ ($P = 0.03$); $I^2 = 61\%$

Test for overall effect: $Z = 3.53$ ($P = 0.0004$)