BRIEF REVIEW

Effects of Strength Training on Running Economy in Highly Trained Runners: A Systematic Review With Meta-Analysis of Controlled Trials

CARLOS BALSALOBRE-FERNÁNDEZ,[1] JORDAN SANTOS-CONCEJERO,[2] AND GERASIMOS V. GRIVAS[3]

[1]*Department of Physical Education, Sport and Human Movement, Autonomous University of Madrid, Madrid, Spain;* [2]*Department of Physical Education and Sport, University of the Basque Country UPV/EHU, Vitoria-Gasteiz, Spain; and* [3]*Department of Physical Education and Sport Science, University of Thessaly, Trikala, Greece*

Abstract

Balsalobre-Fernández, C, Santos-Concejero, J, and Grivas, GV. Effects of strength training on running economy in highly trained runners: a systematic review with meta-analysis of controlled trials. *J Strength Cond Res* 30(8): 2361–2368, 2016–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- or long-distance runners; (b) participants had a $\dot{V}O_2max > 60\ ml \cdot kg^{-1} \cdot min^{-1}$; (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; and (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 of the 5 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 times 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 to −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 trained middle- and long-distance runners.

Key Words 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 a 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 $\dot{V}O_2$ 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 interindividual 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 runners but also in moderately trained and highly trained runners (3,4,58).

Running economy improvements, a consequence of strength training interventions, have been attributed to improved lower-limb coordination and muscle coactivation, 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.

Address correspondence to Carlos Balsalobre-Fernández, carlos.balsalobre@icloud.com.

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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 because they only summarized 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 September 25, 2015. The following databases were searched: PubMed, SPORTDiscus, MEDLINE, and CINAHL (Cumulative Index to Nursing and Allied Health Literature). Databases were searched from inception 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 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- or long-distance runners (studies with triathletes or any other kind of athletes were excluded); (b) participants had a $\dot{V}O_2max$ value >60 $ml \cdot kg^{-1} \cdot min^{-1}$; (c) studies were controlled trials published in peer-reviewed journals; (d) studies analyzed strength training programs with a duration greater than 4 weeks; and (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.

Quality Assessment

The Physiotherapy Evidence Database (PEDro) scale (34) and Oxford's levels of evidence (36) were used by 2 independent observers 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 is 0.

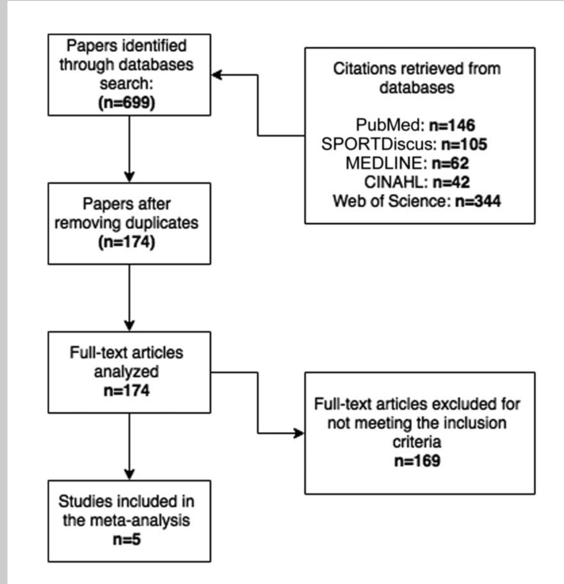

Figure 1. Flow chart of search strategy and selection of articles.

Statistical Analyses

Standardized mean difference (SMD) with 95% confidence intervals (CIs) between strength training and control conditions were calculated with RevMan 5.3.5 for Mac using a random effects model. Mean and SDs for the outcome measures were present in each original article, and it was not necessary to contact the authors for further data. The significance for an overall effect was set at $p \leq 0.05$. 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 values for the SMD, which were specifically designed for high-level athletes (40): <0.25, trivial; 0.25–0.50, small; 0.50–1.0, moderate; and >1.0, large.

Results

Studies Selected

The 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

Table 1. Physiotherapy Evidence Database (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. (37)	No			1				1	1	1	1	5	2b
Saunders et al. (51)	Yes	1		1				1	1	1	1	6	1b
Mikkola et al. (33)	Yes			1				1	1	1	1	5	2b
Støren et al. (54)	Yes	1						1	1	1	1	5	1b
Sedano et al. (52)	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 were analyzed 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.

criteria (33,37,51,52,54). Excluded studies had at least one of the following characteristics: (a) participants had $\dot{V}O_2max$ values <60 $ml\cdot kg^{-1}\cdot min^{-1}$; (b) participants were not middle- or long-distance runners; (c) lack of a control group; (d) strength training interventions lasted less than 4 weeks; and (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 $\dot{V}O_2max >60$ $ml\cdot kg^{-1}\cdot min^{-1}$.

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 2 remaining studies had a level of evidence 2b because participants were not randomly allocated into the intervention group or control group. Also, the 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 men and 15 women) with an age ranging from 17.3 to 29.8 years. Participants' $\dot{V}O_2max$ ranged between 61.2 and 71.1 $ml\cdot kg^{-1}\cdot min^{-1}$. All participants competed in middle- and long-distance running events at national 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 group or control group, whereas the other 2 studies (33,37) matched the groups for age and training level in a nonrandomized way. Training interventions ranged from 8 to 12 weeks: 2 studies used 8-week programs (33,54), 2 studies used 9-week

Table 2. Characteristics of the studies and the participants*.

Study	Participants			Study design	
	Number (M/F)	Age (yrs)	$\dot{V}O_2max$ ($ml\cdot kg^{-1}\cdot min^{-1}$)	Randomized: Yes/No	Main outcome†
Paavolainen et al. (37)	18 (18/0)	23.3 ± 3	63.3 ± 2.1	No	RE at 15 $km\cdot h^{-1}$, $\dot{V}O_2max$
Saunders et al. (51)	15 (15/0)	24.2 ± 2.3	71.1 ± 6.0	Yes	RE at 18 $km\cdot h^{-1}$, $\dot{V}O_2max$
Mikkola et al. (33)	25 (18/7)	17.3 ± 0.5	62.6 ± 3.9	No	RE at 14 $km\cdot h^{-1}$, $\dot{V}O_2max$
Støren et al. (54)	17 (9/8)	29.1 ± 6.1	61.2 ± 3.9	Yes	RE at 70% $\dot{V}O_2max$, $\dot{V}O_2max$
Sedano et al. (52)	18 (18/0)	23.8 ± 1.2	69.6 ± 2.0	Yes	RE at 12 $km\cdot h^{-1}$, $\dot{V}O_2max$

*M/F = male/female; RE = running economy; $\dot{V}O_2max$ = maximal oxygen consumption.
†Running economy and $\dot{V}O_2max$ values were measured in $ml\cdot kg^{-1}\cdot min^{-1}$, except in Støren et al. (CITA), in which RE was measured in $ml\cdot kg^{-0.75}\cdot min^{-1}$, and in Saunders et al. (CITA), in which RE was measured in $L\cdot min^{-1}$.

TABLE 3. Characteristics of the training programs*.

Study	Program type	Program exercises	Range of loads (%BW/RM)†	No. weeks of intervention	Sessions per wk	Duration (min)	SMD (95% CI)
Paavolainen et al. (37)	ST/PLY/RT	ST (5–10 reps of 20–100 m); PLY (alternative jumps, CMJ, jump squats, and drop jumps; 30–200 total jumps); RT (leg extension, leg curl, and leg press; 1 set/5–10 reps)	ST/PLY: 0; RT: 40	9	Not reported; 2.7 h per week, according to session duration most likely 3	15–90	−3.78 (−5.45 to −2.1)
Saunders et al. (51)	PLY/RT	PLY (alternate leg bounds, skip for height, single-leg ankle jumps, CMJ, hurdle jumps, and scissors jumps; 1–2 sets/6–15 reps; 36–180 total jumps); RT (leg press and hamstring curls; 1–2 sets/6–10 reps)	PLY: 0; RT: 60	9	3	30	−0.54 (−1.58 to 0.49)
Mikkola et al. (33)	ST/PLY/RT	ST (5–10 reps of 30–150 m); PLY: (alternative jumps, calf jumps, squat jumps, and hurdle jumps; reps/sets not reported); RT (half squats, knee extensions, calf raises, abdominal crunches, and back extensions; 2–3 sets/6–10 reps)	ST/PLY: 0; RT: low loads, repetitions NOT until failure, %RM not reported	8	3	30–60	−1.03 (−1.87 to −0.18)
Støren et al. (54)	RT	RT: (half squats, 4 sets/4 reps)	85	8	3	Not reported. Considering number of exercises, sets, and reps, about 15 min	−1.45 (−2.56 to −0.35)
Sedano et al. (52)	RT/PLY	RT (back squat, lying leg curl, seated calf raises, and leg extension, 3 sets/7 reps); PLY (hurdle jumps and horizontal jumps; 6 sets/10 reps; 120 total jumps)	RT: 40–70; PLY: 0	12	2	Not reported. Considering number of exercises, sets, and reps, about 45–60 min	−1.17 (−2.24 to −0.10)

*BW = body weight; 1RM = 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; ST = sprint training. Short sprints performed at maximal intended velocity; PLY = plyometric training; RT = resistance training; CMJ = countermovement jumps.

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

Study or Subgroup	Experimental Mean	SD	Total	Control Mean	SD	Total	Weight	Std. Mean Difference 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)

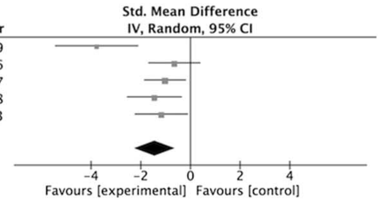

Figure 2. Forest plot showing the individual and combined effects of the intervention on running economy (RE). The black squares with horizontal lines indicate the standardized mean difference (SMD), with 95% confidence interval (CI) between the intervention (experimental) and control groups for each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

programs (37,51), and 1 study used a 12-week program (52). The 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 1 repetition maximum [1RM]) and just the half-squat exercise for the intervention group. In contrast, 4 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 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 group and control group, respectively. The meta-analysis demonstrated an overall, significant, large beneficial effect of the strength training interventions on RE when compared with the control group (SMD [95% CI] = −1.43 [−2.23 to −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 (Figure 2).

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 recalculated average RE change was -1.88 ± 2.31 and 0.51 ± 2.76 $ml \cdot kg^{-1} \cdot min^{-1}$ for the intervention group 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 to −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 with 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 become 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 the study by Paavolainen et al. (37) because the number of strength training sessions conducted (3 sessions), its contents (resistance, plyometrics, and sprint exercises), the range of loads used (0–40% 1RM), 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 seems to be crucial (1,13,16). It has been previously reported that just 1 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 to 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 a 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 and 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). Although 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, 3,000, and 5,000 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 than 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 of the 5 included studies in the present meta-analysis) used low to moderate training intensities for the resistance exercises (40–70% 1RM), 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 minutes). Just one study used heavy loads (85% 1RM), but each strength training session consisted of just 4 sets of 4 repetitions of back squats for about 15 minutes. 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 performed 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, because variables related to muscle power are crucial for distance-running performance, a non-to-failure approach aiming for 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), most 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 nonelite athletes (6,48,49,56), future research analyzing elite runners is thus warranted. This may provide valuable information for coaches and applied scientists for the ongoing management of elite runner training programs and may be especially relevant in the context of a multifactorial approach to reach historic milestones such as the sub–2-hour 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 with the control group. It seems that a strength training program consisting of 2–4 resistance exercises at 40–70% 1RM 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 weeks 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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