Sports Med (2017) 47:545–554
DOI 10.1007/s40279-016-0604-z

SYSTEMATIC REVIEW

Explosive Training and Heavy Weight Training are Effective for Improving Running Economy in Endurance Athletes: A Systematic Review and Meta-Analysis

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Abstract

Background Several strategies have been used to improve running economy (RE). Defined as the oxygen uptake required at a given submaximal running velocity, it has been considered a key aerobic parameter related to endurance running performance. In this context, concurrent strength and endurance training has been considered an effective method, although conclusions on the optimal concurrent training cannot yet be drawn.

Objective To evaluate the effect of concurrent training on RE in endurance running athletes and identify the effects of subject characteristics and concurrent training variables on the magnitude of RE improvement.

Methods We conducted a computerized search of the PubMed and Web of Science databases, and references of original studies were searched for further relevant studies. The analysis comprised 20 effects in 16 relevant studies published up to August 2015. The outcomes were calculated as the difference in percentage change between control and experimental groups (% change) and data were presented as mean ± 95 % confidence limit. Meta-analyses were performed using a random-effects model and, in addition, simple and multiple meta-regression analyses were used to identify effects of age, training status, number of sessions per week, training duration, type of strength training, and neuromuscular performance on % change in RE.

Results The concurrent training program had a small beneficial effect on RE (% change = -3.93 ± 1.19 %; $p < 0.001$). In addition, explosive (% change = -4.83 ± 1.53; $p < 0.001$) and heavy weight (% change = -3.65 ± 2.74; $p = 0.009$) training programs produced similar improvements in RE, while isometric training (% change = -2.20 ± 4.37; $p = 0.324$) in selected studies did not induce a significant effect. The multiple linear meta-regression analysis showed that all the differences between % changes could be explained by including the above-mentioned characteristics of subjects and weight training program elements. This model showed that the magnitude of the % change in RE was larger for longer training duration ($\beta = -0.83 \pm 0.72$, $p = 0.02$).

Conclusion Explosive training and heavy weight training are effective concurrent training methods aiming to improve RE within a few weeks. However, long-term training programs seem to be necessary when the largest possible improvement in RE is desired.

Key Points

During short-to-medium concurrent training periods, explosive training and heavy weight training seem to have similar positive effects on running economy (RE) of endurance athletes.

RE may be improved by adding a low weekly volume of explosive and heavy weight training to endurance training in endurance runners with different training statuses.

Although RE can be improved after 6–8 weeks of concurrent training, a larger effect seems to be present after a longer period of training.

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1 Introduction

Running economy (RE), defined as the oxygen uptake required at a given submaximal running velocity, has been considered a key aerobic parameter of endurance performance of well-trained endurance athletes [1]. Indeed, some studies have shown that RE is an important predictor of endurance running performance, particularly in elite runners who have similar maximal oxygen uptake (VO_{2max}) values [2]. Additionally, there can be high inter-individual variability (>15 %) in RE among highly trained athletes with similar VO_{2max} values [2, 3]. Thus, RE is a multifactorial measure, which seems to be influenced by different aspects such as anthropometric (e.g., distribution of segment mass), morphological (e.g., fiber-type distribution), neuromuscular (e.g., neural input, muscular strength, and stiffness), and biomechanical (stride length and frequency, mechanical and morphological properties of ankle and knee muscles) factors. In addition, different interventions (training, altitude, muscle damage) might also influence RE [4, 5].

Submaximal endurance training can improve RE of well-trained athletes [6, 7]. It is important to note that a relatively long period of submaximal endurance training (typically 14–20 weeks) seems to be necessary to produce a measurable improvement in RE, especially among trained individuals [1, 6, 7]. Furthermore, a high weekly volume of training has been also associated with better RE [8]. However, a relatively short period of endurance training (3 weeks) combined with sleeping at a simulated altitude of 2000–3100 m led to an improvement of RE in elite runners (3–4 %) [9]. Although this intervention seems to accelerate training-induced changes in endurance performance, it is not easy to implement during real-world endurance training.

Alternatively, many studies have shown that explosive or heavy weight training (EXP or HWT) added to regular endurance training (i.e., concurrent training) enhances both RE and endurance performance after 4–6 weeks [10, 11]. Thus, concurrent training seems to be a practical and efficient intervention for improving RE of endurance athletes. Indeed, previous systematic reviews have provided evidence that concurrent training has a positive effect on endurance running performance and RE of endurance athletes [12, 13]. However, exercise prescription parameters used during strength training varied considerably across studies. Thus, it is necessary to determine (1) subject characteristics; (2) training characteristics (i.e., type, intensity, and duration); and (3) training-induced changes in neuromuscular performance (i.e., countermovement jump [CMJ] and lower-limb strength). This could improve the understanding of the underlying determinants of concurrent training-induced improvements in RE, thereby allowing optimization of training prescription. Therefore, the purposes of the present study were to (1) systematically review the results of the published peer-reviewed articles on the effect of concurrent training on RE in endurance running athletes and (2) use a meta-analysis to obtain estimates of contributions of the above-cited factors to the magnitude of RE improvement.

2 Methods

2.1 Literature Search

A systematic search of randomized controlled trials of the effects of concurrent strength training and endurance training on RE was conducted. The search included all peer-reviewed studies published up to August 15, 2015. We performed a computerized search of the PubMed and Web of Science databases using the terms ‘running economy’ and ‘weight training’, ‘resistance training’, ‘strength training’, ‘explosive training’, ‘concurrent training’, or ‘plyometric training’. Reference lists of retrieved studies were also reviewed. Attempts were also made to contact the authors of the selected articles to request any missing relevant information.

2.2 Inclusion and Exclusion Criteria

Studies meeting the following inclusion criteria were considered for review: (1) available in English; (2) randomized controlled trials; and (3) studies where the RE test was conducted before and after training. Studies were excluded for the following reasons: (1) assessment included only endurance performance and/or VO_{2max} measurements and (2) participants were non-endurance runners. No further restrictions (e.g., period of intervention and experience level) were imposed at the search stage.

2.3 Study Selection

The search of the electronic databases and examination of the reference lists revealed 119 relevant studies (Fig. 1). Seventy-nine articles were excluded based on the review of the title or abstract. Forty full-text articles were evaluated and 16 were included in the meta-analysis. All 16 studies were assessed for quality on the basis of the Physiotherapy Evidence-Based Database (PEDro) scale independently by at least two authors of the present study. The maximal total score is 11 points, with more points corresponding to higher quality [14].

When a study used multiple strength training programs, multiple effects were calculated and included separately.

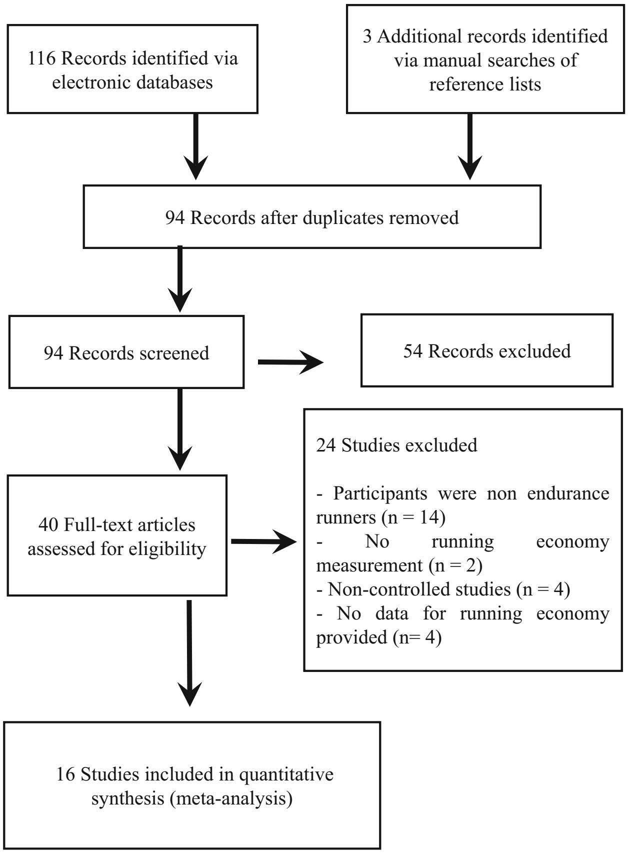

Fig. 1 Flow chart of study selection

Independent variables that can affect training efficiency were grouped into the following categories:

(1) Subject characteristics: age and training status. Training status was expressed as recreationally trained ($\text{VO}_{2\text{max}} \le 55$ mL kg^{-1} min^{-1}), well trained ($\text{VO}_{2\text{max}}$ between 55 and 65 mL kg^{-1} min^{-1}), and highly trained ($\text{VO}_{2\text{max}} > 65$ mL kg^{-1} min^{-1}). If $\text{VO}_{2\text{max}}$ values were not provided [15, 16], the training status was determined based on the classification adopted in each study.

(2) Strength training program elements: number of sessions per week, program duration, and type of strength training (HWT, isometric [IST], EXP, or endurance strength) (Table 1). HWT training was defined as an exercise using $\le$10 repetitions and a load $\ge$70 %1 repetition maximum (RM); endurance-strength training was defined as a exercise using $\ge$15 repetitions and a load $\le$50 %1RM; IST was defined as an exercise using isometric contraction; EXP was defined as an exercise with a low load ($\le$40 %1RM), performing the concentric phase as fast as possible (i.e., high-velocity movements), and/or exaggerating the stretch-shorten cycle (i.e., plyometric movements).

(3) Outcome measurements: RE, 1RM for lower limbs, CMJ. Outcome measures were extracted for both experimental and control conditions in the forms of (a) pre- and post-training intervention means and standard deviations (SDs); (b) difference in means before and after training and SD of the difference in means; and (c) sample sizes. Mean effects on RE, 1RM for lower limbs, and CMJ were converted to percentage changes. Importantly, when several stages of an incremental test were used for assessing RE, only the second and third stages were used in the meta-analysis.

2.4 Study Characteristics

Twenty training effects were collected from 16 studies included in the meta-analysis; their characteristics are summarized in Table 1. A total of 311 subjects were included in the 16 studies: 133 and 178 in the control and experimental training groups, respectively. The participants were recreational, well-trained, and highly trained athletes in six, six, and four studies, respectively. There were eight, two, and eight training effects, respectively, of HWT, IST, and EXP. The other two training effects were extracted from the Sedano et al. [27] study that used endurance-strength training or mixed training (i.e., heavy weight exercises following by plyometric movements). Because only one study presented these training effects, they were not included in the analysis of the type of strength training. The RE measurement primarily involved absolute intensity, though three studies used relative intensity. Finally, only two studies used athletes with prior experience with HWT in the previous 6 months [21, 22].

2.5 Analysis and Interpretation of Results

Statistical analyses were performed using Comprehensive Meta-Analysis, version 3.0 (Englewood, NJ, USA), with the level of statistical significance set at $p < 0.05$. Unless otherwise noted, all data are reported as mean ± 95 % confidence limit (CL). To estimate the magnitude of impact of concurrent training on outcome measures, the difference in percentage change between the control and experimental groups (i.e., % change) was calculated [31]. Importantly, the RE improvement means a reduced oxygen cost, thereby giving rise to the negative % change. For the % change in RE, standard errors (SEs) were calculated to determine the level of imprecision. The weight of each study was obtained as inverse variance of the net % change in RE. Standard errors were directly calculated from the reported Δ SE or SD of the percentage change in RE of both groups. Missing variances were calculated from exact F values or,

Table 1 Characteristics of studies examining the effect of concurrent training on running economy

Study	*n*	Sex	Fitness level	Training type (*n*)	Amount of exercise per session[a]	Number of sessions per week	Training duration (weeks)
Albracht and Arampatzis [15]	26	M	Recreational	IST (13)	1 ISE	4	14
Piacentini et al. [16]	16	FM	Well trained	HWT (6)	5 HW	2	6
				HWT (5)	6 HW		
Damasceno et al. [17]	18	M	Recreational	HWT (9)	4 HW	2	8
Ferrauti et al. [18]	22	FM	Recreational	HWT (11)	5 HW	1	8
Fletcher et al. [19]	12	M	Highly trained	IST (6)	1 ISE	3	8
Johnston et al. [20]	12	F	Recreational	HWT (6)	4 HW, 1 RE, 1 ME	3	10
Mikkola et al. [21]	25	FM	Well trained	EXP (13)	8 EXE	3	8
Mikkola et al. [22]	27	M	Recreational	HWT (11)	2 HW	2	8
				EXP (10)	5 EXE	2	8
Millet et al. [23]	15	M	Highly trained	HWT (7)	6 HW	2	14
Pellegrino et al. [24]	22	FM	Recreational	EXP (11)	4 EXE	2–3	6
Berryman et al. [25]	28	M	Well trained	EXP (12)	1 EXE	1	8
				EXP (11)	1 EXE	1	8
Saunders et al. [26]	15	M	Highly trained	EXP (7)	[c]	2–3	9
Sedano et al. [27][b]	18	M	Highly trained	HWT and EXP (6)	4 HW with EXE	2	12
				EST (6)	4 ESE	2	12
Skovgaard et al. [28]	21	M	Well trained	EXP (12)	3 EXE	2	8
Spurrs et al. [29]	17	M	Well trained	EXP (8)	4 EXE	2–3	6
Storen et al. [30]	17	FM	Well trained	HWT (8)	1 HW	3	8

ESE endurance-strength exercise, *EST* endurance-strength training, *EXE* explosive exercises, *EXP* explosive training, *F* female only, *FM* female and male, *HW* heavy weight exercises, *HWT* heavy weight training, *ISE* isometric exercises, *IST* isometric training, *M* male only, *RE* resistance exercise (exercise using 11–14 repetitions)

[a] Exercises focused on lower-limb muscles

[b] Although this training contributed to the overall % change, it was excluded from the training group analysis

[c] In this study, different amounts of exercises were performed in each session but with a predominance of EXE

in the absence of exact values, from the mean inter-trial correlation between the RE measurements before and after training. It was possible to calculate the inter-trial correlation for five studies [16, 17, 20, 21, 29], resulting in a mean value of 0.78.

The overall % change was calculated using a random-effects model that accounted for true inter-study variations in effects as well as for random errors within each study [32]. A random-effects model was chosen over a fixed-effect model because of the wide variation in experimental factor levels in the reviewed studies. The effect of publication bias on the primary meta-analyses was addressed by combining a funnel plot assessment with Duval and Tweedie's trim and fill correction [33]. Statistical heterogeneity, which refers to the percentage of variability between studies owing to clinical and methodological heterogeneity rather than sampling error, was assessed by the I^2 statistic [32]. According to Higgins et al. [34], I^2 values of 25, 50, and 75 % represented low, medium, and high heterogeneity, respectively. In addition, we calculated the SD of true value of the % change between studies (T).

To determine the influence of moderating variables on % change in RE, random-effects meta-regression analyses were performed using an a priori identified variable. While a simple meta-regression analysis (i.e., only one covariate) was performed for all independent variables, a multiple meta-regression analysis was performed for the characteristics of subject (i.e., age and training status) and weight training program elements (i.e., number of sessions per week, program duration, and type of strength training) characterized a priori. A multiple meta-regression analysis with more than one covariate yields a set of statistics for each covariate, as well as a set of statistics for the model. The statistics for each covariate reflect the impact of that covariate partialing out the effects of all other covariates in the model. The statistics for the full model reflect the combined impact of all covariates.

A scale based upon the one proposed by Hopkins et al. [35] was used to evaluate the relative magnitude of the training-induced changes. Accordingly, the inferences were based on the standardized thresholds for small, moderate, and large changes of 0.2, 0.6, and 1.2 SDs, respectively, and derived by averaging appropriate between-subject variances for baseline RE. Therefore, the magnitude thresholds for RE were 1.66, 4.98, and 9.96 % in the present meta-analysis.

3 Results

The % change of the studies ranged from −12.52 to 0.72 % (Fig. 2). Seventeen of the twenty concurrent training effects exhibited an improvement in RE. Overall, concurrent training had a small but significant beneficial effect in terms of RE (% change = −3.93 ± 1.19 %; $p < 0.001$) (Table 2). The PEDro quality scores for the 16 studies were good and very similar, ranging from 8 to 6 points. In the funnel plot, a disproportionate number of studies were located to the right of the overall % change. Five studies required adjustments using Duval and Tweedie's trim and fill correction to produce symmetrical funnel plot around the mean % change. After this correction, the overall % change was −4.84 ± 1.31 % ($p < 0.001$), confirming the small but significant beneficial effect. The significant improvement in RE following concurrent training was homogenous ($Q = 26.30$; $p = 0.122$) with low-to-medium inconsistency of effects ($I^2 = 27.74$ %; $T = 1.37$ %).

The results of the simple meta-regression analysis were not significant for any categorical and continuous covariates (Table 3), although training status ($I^2 = 27.74$ to 19.46 %; $T = 1.37$ to 1.12 %), age ($I^2 = 27.74$ to 24.50 %; $T = 1.37$ to 1.26 %), and CMJ ($I^2 = 20.12$ to 15.50 %; $T = 1.22$ to 1.06 %) reduced the inconsistency in % change. In addition, Table 3 shows that the % change did not differ between subgroups for categorical variables, although only HWT and EXP presented a % change significantly lower than zero when moderated by training types.

In an attempt to reduce confounding effects, we also performed a meta-regression analysis using the characteristics of the subjects and weight training program elements. This multiple meta-regression analysis reduced the inconsistency of % change to zero (Table 4), indicating that all the variability in % change estimates between studies was reduced to within-studies sampling errors only. In addition, the impact of each covariate partialing out the effects of the other covariates was only significant for training duration

Reference	% Change	p-Value
Millet et al. 2002 [23]	-12.515	0.001
Berryman et al. 2010 ^{1} [25]	-7.070	0.000
Spurrs et al. 2003 [29]	-6.905	0.000
Storen et al. 2008 [30]	-6.790	0.003
Sedano et al. 2013 ^{1} [27]	-5.030	0.002
Johnston et al. 1997 [20]	-4.770	0.000
Mikkola et al. 2007 [21]	-4.450	0.142
Albracht and Arampatzis 2013 [15]	-4.225	0.025
Berryman et al. 2010 ^{2} [25]	-4.100	0.105
Skovgaard et al. 2014 [28]	-3.990	0.006
Pellegrino et al. 2015 [24]	-3.735	0.190
Saunders et al. 2006 [26]	-3.625	0.397
Piacentini et al. 2013 ^{1} [16]	-2.870	0.433
Sedano et al. 2013 ^{2} [27]	-2.270	0.161
Ferrauti et al. 2010 [18]	-1.750	0.558
Piacentini et al. 2013 ^{2} [16]	-1.635	0.769
Mikkola et al. 2011 ^{1} [22]	-0.220	0.938
Fletcher et al. 2010 [19]	0.255	0.913
Damasceno et al. 2015 [17]	0.500	0.892
Mikkola et al. 2011 ^{2} [22]	0.715	0.735
Overall effect	-3.933	0.000

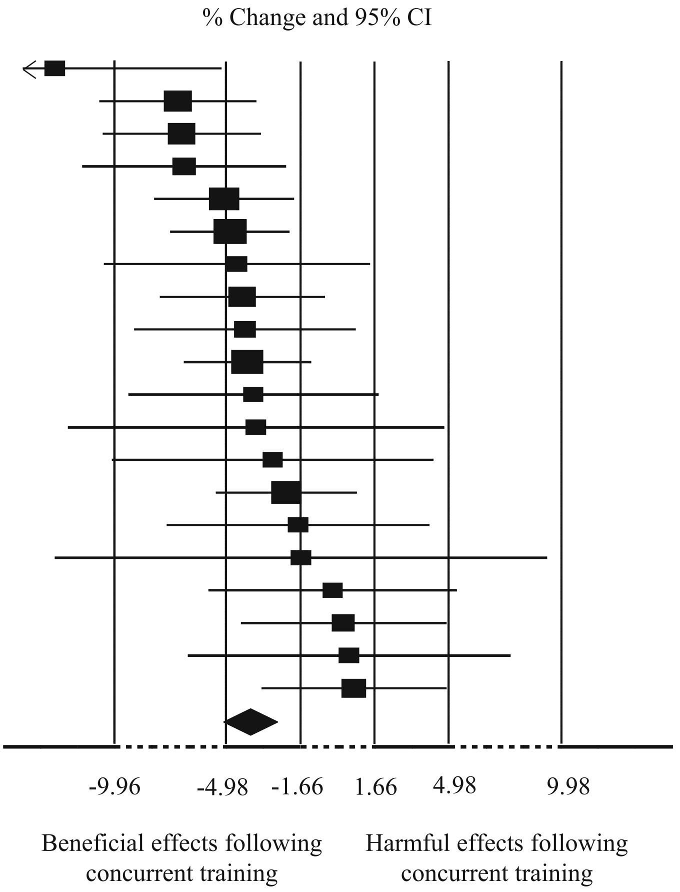

Fig. 2 Forest plot of running economy effect size ($n = 20$). Each *point* represents a running economy effect size and 95 % CI. The *vertical line* indicates the standardized thresholds for trivial, small, moderate, and large changes. The *superscript numbers* in column 1 refer to different strength training programs assessed in the same study. *CI* confidence interval

Table 2 Analysis of studies included in the meta-analysis

Study	Training group	Running economy		1RM assessment		Countermovement jump
		Intensities	Overall % change ± 95 % CL	Exercises	Overall % change	Overall % change
Albracht and Arampatzis [15]	IST	10.8 and 12.6 km h^{-1}	-4.23 ± 3.70			
Piacentini et al. [16]	HWT	9.75 and 10.75 km h^{-1}	-2.87 ± 7.17	Leg press	22.11	-4.31
	HWT		-1.64 ± 10.93		16.04	-4.58
Damasceno et al. [17]	HWT	12.0 km h^{-1}	0.50 ± -7.19	Half-squat	23.58	15.34
Ferrauti et al. [18]	HWT	8.64 and 10.08 km h^{-1}	-1.75 ± 5.86	Leg extension	30.97	
Fletcher et al. [19]	IST	75, 85, and 95 % LT	0.26 ± 4.59			
Johnston et al. [20]	HWT	12.8 and 13.8 km h^{-1}	-4.77 ± 2.68	Parallel squat, knee flexion	38.52	
Mikkola et al. [21]	EXP	12.0 and 13.0 km h^{-1}	-4.45 ± 5.94	Leg extension	Insufficient data	Insufficient data
Mikkola et al. [22]	HWT	10 and 12 km h^{-1}	-0.22 ± 5.55	Leg press	3.97	Insufficient data
	EXP		0.72 ± 4.14		3.87	
Millet et al. [23]	HWT	75 %VO$_{2\max}$ and Δ25 %	-12.52 ± 7.43	Half-squat, heel raise	22.22	15.37
Pellegrino et al. [24]	EXP	9.18 and 10.62 km h^{-1}	-3.74 ± 5.59			6.09
Berryman et al. [25]	EXP	12.0 km h^{-1}	-4.10 ± 4.95	Squat	15.47	1.57
	EXP		-7.07 ± 3.53		3.78	3.08
Saunders et al. [26]	EXP	16.0 and 18.0 km h^{-1}	-3.63 ± 8.38			7.75
Sedano et al. [27][a]	HWT and EXP	14.0 km h^{-1}	-5.03 ± 3.15	Leg extension, barbell squat, seated calf raises, lying leg curl	5.24	13.13
	EST		-2.27 ± 3.17		9.91	3.13
Skovgaard et al. [28]	EXP	12.0 km h^{-1}	-3.99 ± 2.87	Squat, leg press	8.85	
Spurrs et al. [29]	EXP	12.0 and 14.0 km h^{-1}	-6.91 ± 3.55	Seated calf raise machine	16.19	16.19
Storen et al. [30]	HWT	70 % VO$_{2\max}$	-6.79 ± 4.56	Half-squat	27.12	

Cells with no entries indicate that the respective outcome was not investigated

CL confidence limit, *EXP* explosive training, *EST* endurance-strength training, *HWT* heavy weight training, *IST* isometric training, *LT* lactate threshold, *1RM* one repetition maximum, VO_{2max} maximal oxygen uptake, *Δ25%* velocity associated with the second ventilatory threshold plus 25 % of the difference between the second ventilatory threshold and VO$_{2\max}$

[a] Although this training contributed to the overall % change, it was excluded from the training group analysis

(Table 4; Fig. 3), indicating a higher RE improvement with longer training duration. It is worthwhile to mention that the meta-regression analysis including only four covariates, (1) training duration, (2) training type, (3) session per week, and (4) age or training level, also reduced I^2 to zero %, further indicating a significant impact of both age and training level. This suggests that age and training level were confounded, making it difficult to isolate the individual impact of each [36].

4 Discussion

The purpose of this meta-analysis was to evaluate the effects of concurrent training on RE of endurance athletes. Our data revealed that, when compared with only endurance training or light resistance training, concurrent training has a small beneficial effect (~4 %) on RE. To assess the variability between studies, meta-regression analyses considering the effects of different domains such as characteristics of subjects, training variables, and concurrent training modality were performed. The meta-regression analyses including training duration, type of strength training, age, training level, and number of sessions per week accounted for all of the variance between the effects of the analyzed studies. In addition, this model showed that the improvements in RE were significantly greater for longer periods of training. Therefore, long-term muscular adaptations found after concurrent training seem to be important in inducing large changes in RE.

Our meta-analysis revealed for the first time that short and medium periods (6–14 weeks) of concurrent training

Table 3 Effects of concurrent training on running economy according to categorical and continuous covariates

Moderator	*n*	% Change ± 95 CL	*p* value
Categorical variables			
Training status			
Highly trained athletes	5	−3.94 ± 3.27	0.018
Well trained athletes	8	−5.37 ± 1.85	0.000
Recreational athletes	7	−2.64 ± 1.53	0.005
Concurrent training program			
Explosive training	8	−4.83 ± 1.53	<0.001
Heavy weight training	8	−3.65 ± 2.74	0.009
Isometric training	2	−2.20 ± 4.37	0.324
Continuous variables			
Age	20	0.154 ± 0.203	0.137
Body mass	20	0.079 ± 0.182	0.395
Training duration	20	−0.181 ± 0.517	0.492
Sessions per week	20	−0.237 ± 1.570	0.767
Exercises per session	20	−0.047 ± 0.521	0.861
Exercises per week	20	−0.053 ± 0.195	0.597
CMJ	11	−0.155 ± 0.248	0.221
1RM	15	−0.046 ± 0.129	0.499

CL confidence limit, *CMJ* countermovement jump, *1RM* one repetition maximum

Table 4 Multiple meta-regression analysis including training duration, age, concurrent training program, fitness level, and number of sessions per week

	% Change ± 95 % CL	*p* value
Intercept	1.36 ± 16.61	0.872
Training duration	−0.83 ± 0.72	0.023
Age	0.14 ± 0.35	0.425
Sessions per week	−0.66 ± 2.19	0.552
Concurrent training program[a]		0.090
EXP × HWT	0.10 ± 3.52	
EXP × IST	5.18 ± 5.84	
Fitness level[a]		0.120
Recreational × well trained	−1.28 ± 5.32	
Recreational × highly trained	−3.33 ± 3.21	

CL confidence limit, *EXP* explosive training, *HWT* heavy weight training, *IST* isometric training

[a] When IST and well-trained athletes were chosen as the reference groups, the estimates for the comparison between IST and HWT and well-trained and highly trained athletes were −5.07 ± 95 % CL 4.53 % and 2.05 ± 95 % CL 5.05 %, respectively

were effective in improving RE of endurance runners. Conversely, both a relatively long period (14–20 weeks) and a high weekly volume of endurance training seemed to be necessary to enhance RE of highly trained individuals [1, 6–8]. Thus, there appears to be a difference in the time courses of RE improvements induced by concurrent training and endurance training only. Furthermore, the beneficial effect increased gradually with time (Fig. 3), such that the improvements in RE were relatively small after 6–8 weeks of concurrent training, whereas moderate-to-large effects were observed after 12–14 weeks. While a direct relation between training duration and training effect was apparent, the lack of a relationship between RE improvements and training volume (i.e., number of sessions per week) in the analyzed studies suggests that a high weekly volume of strength-based exercises during concurrent training does not seem to induce greater RE improvements. These findings may have practical applications because higher volumes of strength training would likely impact/reduce the volume of endurance training. However, this result needs to be interpreted with caution because the vast majority of studies included in the present meta-analysis used similar training frequencies (two to three times per week), limiting the generalizability of this conclusion to all concurrent training programs.

In individuals with no experience in strength training, the time courses of neural and morphological adaptations are potentially different. During short programs (up to 8 weeks), increased neural activation and decreased relative proportion of fast-type IIX fibers are the main neuromuscular adaptations, while radial or longitudinal hypertrophy and increased muscle-tendon unit stiffness (MTS) are expected to be found during long-term programs [37–39]. Muscle hypertrophy can be observed after a period of concurrent training (8–21 weeks) [40, 41]. However, Williams and Cavanagh [42] reported an inverse relationship between maximal thigh circumference and submaximal VO_2 ($r = -0.58$), suggesting that a increased body mass after strength training, particularly in the legs, may reduce RE. In contrast, increased MTS and triceps surae force after strength training could improve elastic energy storage during the early stance phase, thus decreasing work related to fascicle shortening during propulsion [43]. Indeed, Arampatzis et al. [43] confirmed, based on analysis of endurance runners at submaximal speeds, that individuals with the highest RE possessed greater plantar flexor muscle strength and greater tendon-aponeurosis stiffness in the triceps surae. Thus, increased MTS seems to be an important factor contributing to the long-term improvement in RE after concurrent training.

Elite distance runners have better RE than less experienced runners, suggesting that they could be less responsive to a similar training program in terms of RE improvement. Indeed, short-to-medium endurance training periods have been shown to improve RE only in untrained and moderately trained individuals [1]. However, this seems not to be the case for concurrent training because the studies analyzed in this present meta-analysis showed that the RE improvement after concurrent training was similar

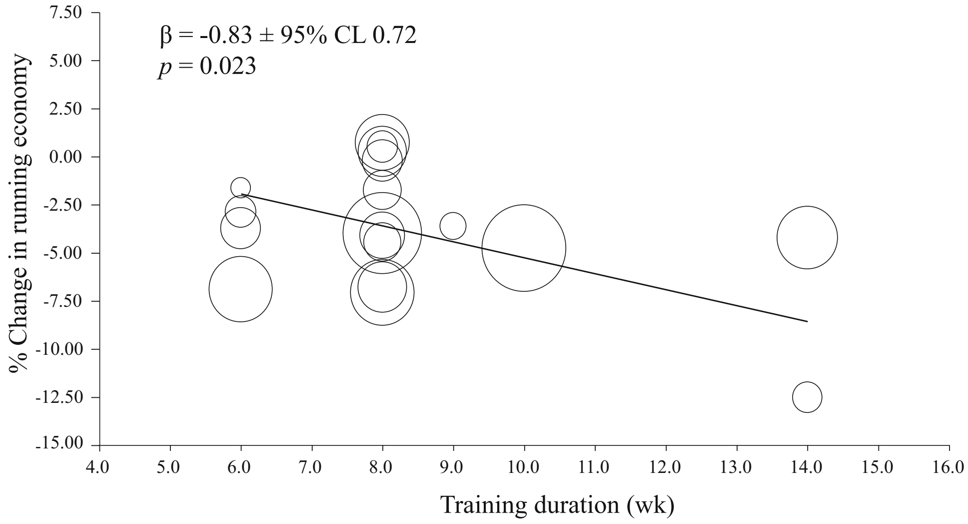

Fig. 3 Meta-regression analysis for the effect of training duration on percentage of change in running economy partialing out the effects of all other covariates in the model (i.e., age, training status, number of sessions per week, and type of strength training). *CL* confidence limit

in individuals of different training levels and similar for the amount of training required for achieving this improvement (i.e., number of sessions per week). Collectively, these data support the notion that the putative mechanisms for improved RE after endurance and concurrent training are possibly different. Endurance training is likely to enhance the metabolic and cardiorespiratory factors linked to RE, which could be less responsive in elite endurance athletes requiring higher training loads and/or longer training periods [1, 6, 7]. However, a short period of EXP and/or HWT training, with low weekly volume added to endurance running training seems to enhance the neuromuscular and mechanical factors specific to running and to induce changes in muscle recruitment [43], improving RE even in elite runners.

Different strength training programs have been employed to enhance RE of endurance runners. EXP (i.e., exercises with high-velocity movements, jumps, squat jumps, drops jumps, hops, bounds, and sprints) and HWT impose different training stimuli on the neuromuscular system. Indeed, some studies have demonstrated that changes in neural activation, force-velocity relationship, and jump mechanics are specific to these different training stimuli [45]. However, in non-experienced individuals, neuromuscular performance improvement (e.g., strength, power, speed, and jump height) can be similar after a short- to medium-term program involving EXP or HWT [45]. The present meta-analysis revealed that both EXP and HWT training have similar positive effects on RE of endurance athletes in similar conditions (i.e., inexperienced individuals and a short-to-medium program). Hypothetically, a different scenario would be found in athletes with superior strength training background and/or after a long-term period of concurrent training [46, 47]. In these conditions, EXP or mixed training (i.e., heavy weight exercise followed by jump movements) may be more effective in endurance athletes in terms of RE improvement. This hypothesis seems to be supported by the results of a single study that used a model of mixed training and detected a moderate beneficial effect (% change = 5.03) following 12 weeks of training [27]. IST has been suggested as another concurrent training method effective in improving RE. However, our meta-analysis failed to show a significant effect of IST after a short-to-medium period of concurrent training, suggesting that the lack of specificity of this training mode could attenuate the improvement of RE in endurance athletes. It should, however, be pointed out that so far only two studies used IST and, in addition, such a training method only appears to be effective in improving both MTS and RE after a long period of training [15, 19, 48].

An important goal of the present meta-analysis was to relate % change in RE with the change in parameters of neuromuscular performance (i.e., 1RM and CMJ). The meta-regression analysis revealed that the effect of concurrent training on RE was not significantly different when moderated by both 1RM and CMJ. However, it was possible to explain the between study in changes in RE of 24 % based on % change in CMJ. While improvements in CMJ reflect different qualities of the muscular-tendinous locomotor apparatus, some strength tests assess only a small part of the locomotor apparatus, precluding any reduction of the inconsistency of % change in RE when moderated by 1RM. Moreover, the technique is less likely to play a large role in CMJ results compared with some strength tests (e.g., squat). Some mechanisms determining CMJ improvement could be responsible for RE enhancement after a concurrent training program. As discussed above, changes in MTS, which has been associated with improvements in CMJ performance [49], seem to explain partly the improvement in RE after concurrent training. Indeed, Spurrs et al. [29] found a significant correlation between changes in MTS and RE following 6 weeks of plyometric training. Other potential mechanisms that could explain the improvements in RE are changes in movement mechanics and the stretch-shorten cycle (SSC) function during jumping. Strength training can improve both peak performance parameters and the shape of the power-, force-, velocity-, and displacement-time curves of CMJ [45]. These changes can optimize SSC function and improve the mechanical factors specific to running. However, the limited number of studies included in the present meta-analysis precludes drawing a firm conclusion regarding the influence of changes in CMJ on the improvement of RE after a period of concurrent training.

4.1 Limitations

The present meta-analysis identified various sets of potentially confounding or contaminating variables, and the regression was used in an attempt to control as much of the unwanted variability as possible. However, if there are strong confounding effects among some or all of the independent variables, none of them will have a substantial effect on the dependent variable, and estimates for individual predictors will be invalid [36]. In the present meta-analysis, there appeared to be a high confounding effect between age and training level because the recreational athletes were older than the well-trained and highly trained athletes. Therefore, it is difficult to draw conclusions about training level and age because the important reduction in variability of the % change in RE could be owing to both or either of the predictors.

Few studies in the present meta-analysis used exclusively plyometric (i.e., aimed at exaggerating the SSC) or high-velocity exercises (e.g., squat jumps, dynamic weight exercises with concentric phase performed as fast as possible). Therefore, the present meta-analysis did not separate these exercise types because both exercises are explosive in nature. Although both types of explosive exercise seem to induce improvements in the parameters responsible for RE enhancement after concurrent training [13, 44], more detailed studies separating these two types of exercise are still warranted.

4.2 Future Directions

We propose several topics for future research to analyze the effects of concurrent training using a more complex approach. Future studies using a randomized controlled trial design should address the long-term effects of concurrent training as well as establish the time course of the adaptations to clarify whether the effects primarily occur during the first few weeks of training. Furthermore, future investigations should compare the effects of different concurrent training modalities (i.e., traditional weight training vs. plyometric training vs. mixed training) using different types of periodization models (i.e., linear and daily undulating). More studies investigating SSC function and the morphological (hypertrophy, muscle fiber type, and MTS) effects of concurrent training are also warranted. Finally, a review of studies investigating the effect of concurrent training on movement economy in other sports such as cycling (a non-weight-bearing activity) could also produce interesting implications for training prescription in this field.

5 Conclusion

Different strength training modalities have been added to endurance training in an attempt to improve RE and aerobic performance of endurance runners. The present meta-analysis shows that concurrent training has a significant beneficial effect on RE of endurance runners and that this effect increases gradually with duration of training. EXP and HWT seem to have similar positive effects on RE of endurance athletes after a short-to-medium training period. Because RE improvements were dependent on training duration, concurrent training should be based on longer training periods, especially when a large benefit is desired.

Compliance with Ethical Standards

Funding The authors thank Fundação de Amparo à Pesquisa do Estado de São Paulo for financial support provided (Process 2013/23585-4). No other sources of funding were used to assist in the preparation of this article.

Conflict of interest Benedito Sérgio Denadai, Rafael Alves de Aguiar, Leonardo Coelho Rabello de Lima, Camila Coelho Greco, and Fabrizio Caputo declare that they have no conflicts of interest relevant to the content of this review.

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