Effects of resistance training on running economy: a systematic review and meta-analysis

Efectos del entrenamiento de resistencia en la economía de carrera: una revisión sistemática y un metaanálisis

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How to cite in APA

Zecchin, A., de Lima, L. R. C., F Puggina, E., & Tasinafo-Júnior, M. F. (2025). Effects of resistance training on running economy: a systematic review and meta-analysis. *Retos*, *71*, 275–287. https://doi.org/10.47197/retos.v71.113574

Abstract

Introduction: Running economy (RE) is a key determinant of endurance performance in long-distance runners, influencing their efficiency and energy expenditure. Resistance training has been proposed as a strategy to enhance RE, yet its effectiveness remains debated.
Objective: We aimed to systematically and meta-analytically review manuscripts describing the effects of resistance training on RE in long-distance runners (≥10 km). Methodology: A systematic search of the literature was conducted in the PubMed, Web of Science and Scopus databases for manuscripts with no date restriction other than being published until March 2024.
Results: Out of 895 studies, 8 met the inclusion criteria. Risk of bias was calculated, and standardized mean differences (SMDs) were weighted by inverse variance to calculate the overall effect and its 95% confidence interval (CI) of resistance training on RE. A total of 80 subjects from the included studies were analyzed (age: 36.2 ± 6 yrs; VO2max: 49.2 ± 4 ml.kg.min-1). The mean training intensity was 83% 1RM ± 7.5%. Resistance training improved RE in long-distance runners ($p= 0.003$, $d= 0.47$) while training intensity, race specialty and duration of the training protocol positively modulated such adaptations.
Discussion: These results provide a framework that resistance training evokes positive effects in RE in long-distance runners corroborating with previous studies.
Conclusions: The present study showed that resistance training improves RE. Training structure appears to be the key point, and further studies are required to provide information on the effects of resistance training on RE in long-distance runners.

Keywords

Distance running; oxygen cost; running; strength training.

Resumen

Introducción: La economía de carrera (RE) es un factor determinante en el rendimiento de corredores de larga distancia, al influir en la eficiencia y el gasto energético. El entrenamiento de resistencia ha sido propuesto como estrategia para mejorar la RE, aunque su efectividad aún se debate.
Objetivo: Revisar sistemática y metaanalíticamente estudios que evaluaron los efectos del entrenamiento de resistencia sobre la RE en corredores de larga distancia (≥10 km).
Metodología: Se realizó una búsqueda sistemática en PubMed, Web of Science y Scopus, sin restricción de fecha, hasta marzo de 2024. Se analizaron los manuscritos que cumplieron los criterios de inclusión.
Resultados: De 895 estudios encontrados, 8 fueron incluidos. Se evaluó el riesgo de sesgo y se calcularon las diferencias medias estandarizadas (SMDs), ponderadas por varianza inversa, para estimar el efecto general del entrenamiento de resistencia sobre la RE, con IC del 95%. En total, se analizaron 80 sujetos (edad: 36.2 ± 6 años; VO_2max: 49.2 ± 4 $ml \cdot kg^{-1} \cdot min^{-1}$). La intensidad promedio del entrenamiento fue del 83% de 1RM (±7.5%). El entrenamiento de resistencia mejoró significativamente la RE ($p = 0.003$, $d = 0.47$). La intensidad, la duración del protocolo y la especialidad en la carrera influyeron positivamente en los resultados.
Discusión: Los hallazgos respaldan que el entrenamiento de resistencia mejora la RE en corredores de larga distancia.
Conclusiones: La estructura del entrenamiento influye en los resultados, y se requieren más estudios para profundizar en sus efectos.

Palabras clave

Carrera de larga distancia; costo de oxígeno; correr; entrenamiento de fuerza.

Introduction

Running economy (RE) is commonly defined as the steady-state oxygen uptake (VO2) required to sustain a given submaximal speed and has been widely studied over the past decades (Balsalobre-Fernandez et al., 2016). It has been proposed that athletes with the same VO2max may differ in their fractional VO2 at a given submaximal intensity. RE is the result of a myriad of factors that influence endurance performance (Van Hooren et al., 2024). Although multiple factors might influence RE and, consequently, performance, neuromuscular efficiency and cardiorespiratory capacity have been identified as two of its most important modulators (Berryman et al., 2018; Blagrove et al., 2018).

Previous research has been dedicated to describing the efficacy of resistance training in improving muscle strength and influencing middle- and long-distance running performance (Llanos-Lagos C, 2024). Recently, Eihara et al. (Eihara et al., 2022) explored different types of resistance training protocols aiming to improve RE (without distance distinction). They confirmed and described the efficacy of a combination of plyometrics and isometric training in improving running economy. Additionally, different mechanisms have been suggested to explain the relationship between neuromuscular activation and running performance. It has been proposed that resistance training improves neural function, favoring the utilization of type IIa and IIx muscle fibers. This mechanism allows the optimization of the stretch-shortening cycle (SSC), which has been reported to contribute to RE in middle- and long-distance running (Aagaard et al., 2011; Ramirez-Campillo et al., 2021; Rønnestad & Mujika, 2014).

Despite these claims, the findings in the literature remain controversial regarding the positive effects of resistance training on RE. In previous studies, decrements in aerobic and muscular adaptations were reported when resistance training and endurance training were combined (Balsalobre-Fernandez et al., 2016; Hickson, 1980). This training approach may be counterintuitive, as there is evidence suggesting that muscle hypertrophy is associated with a reduction in mitochondrial density and distribution in muscle fibers (Wilson et al., 2012). In this sense, the configuration of resistance training programs seems to influence RE (Eihara et al., 2022). Previously, Palmer et al. (Palmer & Sleivert, 2001) determined the acute effects of a single high-intensity resistance training session (80% 1RM) on RE in well-trained distance runners (VO2max: 66.6 ± 10.2 ml.kg-1.min-1). RE was impaired up to eight hours after the session and remained so 24 hours thereafter. Contrastingly, Taipale et al. (Taipale et al., 2010) showed that 28 weeks of resistance training improved RE in recreational runners. More recently, a meta-analysis by Berryman et al. (Berryman et al., 2018) described that chronic resistance training positively modulates RE in runners of different performance levels.

Despite growing interest from the scientific community, no meta-analysis to date has specifically focused on the effects of resistance training on running economy in long-distance runners (≥10 km), who present distinct physiological demands compared to middle-distance athletes. In contrast to previous meta-analyses that grouped middle- and long-distance runners together, the present study focuses exclusively on long-distance runners (≥10 km), a subgroup with unique physiological and biomechanical demands often overlooked in prior syntheses. Variables such as intensity, running specialization, and the type of exercises used represent existing gaps in the literature (Berryman et al., 2018; Denadai et al., 2017; Llanos-Lagos C, 2024). Furthermore, earlier reviews often failed to analyze specific resistance training protocols (e.g., plyometric vs. isometric) or account for training status, limiting their applicability to specialized athlete populations. Recent systematic reviews (e.g., Eihara et al., 2022 (Eihara et al., 2022); Llanos-Lagos et al., 2024 (Llanos-Lagos C, 2024)) have started to differentiate between heavy-load, plyometric, submaximal, and combined methods, and to evaluate their effectiveness across training-status subgroups, reinforcing the need for our more targeted meta-analysis.

Thus, the present study aimed to describe the effects of resistance training on RE in long-distance runners (i.e., those who compete in events ≥ 10 km). In particular, we evaluated how different training protocols—such as heavy-load strength training (≥80% 1RM), plyometric exercises, and combined methods—affect running economy based on intervention duration and training background. Based on previous studies (Berryman et al., 2018; Denadai et al., 2017; Van Hooren et al., 2024), we hypothesized that high-intensity resistance training (e.g., heavy or combined plyometric/strength protocols) performed over a minimum of eight weeks would yield greater improvements in running economy than low-load or short-term interventions.

Method

Experimental Approach to the problem

The current systematic review and meta-analysis comprised a comprehensive synthesis quantifying effectiveness of resistance training on running economy in long-distance runners (≥10 km). Primary analyses investigated the athlete demographic (e.g., running specialty, training level, training type) and training dose (e.g., frequency, volume and intensity). The secondary analyses investigated relationships between changes in running economy and the application of resistance training. The studies were classified by The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009). The selected studies were analyzed to assess the effects of resistance training on RE, and the risk of bias was calculated. Egger's regression intercept test and visual inspection of the funnel plot were applied to detect the potential of publication bias. The methodological quality of the included studies was assessed using the Physiotherapy Evidence Database (PEDro) scale (de Morton, 2009).

Registration of systematic review protocol

A systematic search of randomized controlled trials investigating the effects of resistance training on RE was conducted. Before the research began, the study project was registered at the International prospective register of systematic reviews (PROSPERO nº: CRD42022339621).

Search strategy

After PROSPERO approval, searches were conducted in the PubMed, Scopus and Web of Science databases. Included studies were published with no date restriction up to March 2024. The keywords used to identify the studies were similar to those used in a study on the use of different training methods to investigate RE in endurance athletes (Denadai et al., 2017). The search terms were: "running economy" and "weight training" OR "resistance training" OR "strength training". The systematic search was carried out by two independent researchers. In case of disagreement between the two independent researchers, a third researcher was consulted. Disagreements were resolved using the eligibility criteria. If there was any remaining doubt, the corresponding author was contacted to clarify discrepancies. If the corresponding author did not return the contact, the paper was excluded to avoid the risk of bias. Papers were initially screened based on their title, abstract or key-words, and only articles in the English language were included for further analysis. All analyses were performed in the Rayyan® website. When data were missing or incomplete, study authors were contacted for clarification. If data remained unavailable, the respective outcome was excluded from the quantitative synthesis.

Eligibility criteria

The PICOS (problem, intervention, comparison, outcome and study design) approach was used to rate studies for eligibility (Liberati et al., 2009). Only runners who ran track or road modalities were included. Trail and cross-country running were excluded because these modalities involve uneven terrain, variable environmental conditions, and elevation changes that significantly affect running economy (RE) independently of physiological adaptations. Including such studies would introduce considerable heterogeneity, limiting the ability to compare results across standardized resistance training interventions. Therefore, to ensure methodological consistency and comparability, only studies involving road or track running on relatively flat and controlled surfaces were included (Tjelta & Enoksen, 2010). We utilized the resistance training definition by Faigenbaum et al. (Faigenbaum & Myer, 2010). "The term resistance training refers to a specialized method of physical conditioning that involves the progressive use of a wide range of resistive loads, different movement velocities and a variety of training modalities including weight machines, free weights (barbells and dumbbells), elastic bands, medicine balls and plyometrics". Table 1a shows the inclusion eligibility criteria.

Table 1a. Inclusion criteria following PICOS recommendation.

Inclusion	
P	Participants: males and females performing road or track long-distance running (10 km or more); at least three years of endurance training experience.
I	Intervention: Resistance training (weight machines, free weight, barbells and dumbbells, plyometrics, isoinertial, isometric, body weight, elastic bands, medicine ball).
C	Comparison: Healthy control group (sedentary and/or no resistance and/or endurance training intervention).
O	Outcome: Running economy, pre- and post-analysis (VO_2).
S	Study design: Parallel and RCTs.

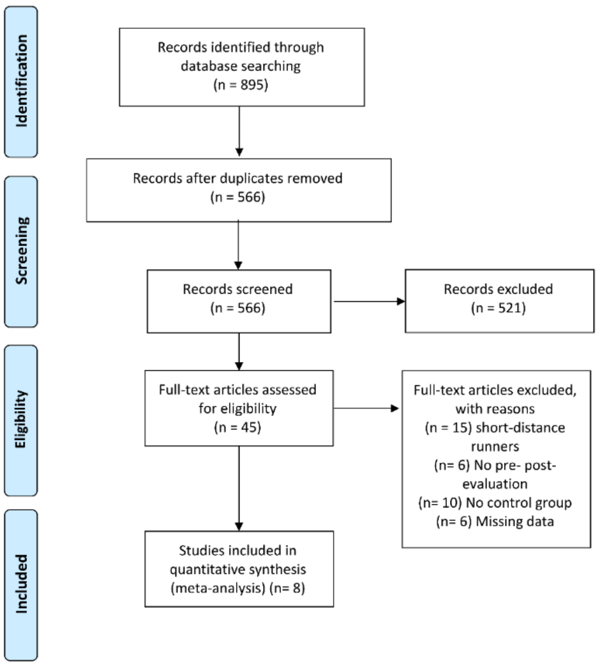
Table 1b shows the exclusion eligibility criteria:

Table 1b. Exclusion criteria following PICOS recommendation.

Exclusion	
P	Participants: Running any distance up to 9.99km. Trail or cross country running.
I	Intervention: Whole body vibration, electrostimulation.
C	Comparison: Other than running economy (i.e., max. vel.); analysis through resistance training.
O	Outcome: Utilization of any variable other than VO_{2max} (lactate, velocity, neuromuscular efficiency, heart rate, substrate utilization, core temperature, fatigue, biomechanics) as a surrogate of running economy.
S	Study design: Cross-sectional, review of literature, case reports, special communication, letters to the editor, invited commentaries, errata.

This systematic review and meta-analysis was performed in accordance with The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (figure 1) (Moher et al., 2009).

Figure 1. Flowchart of the study selection.



Data extraction

Participant characteristics, sample size, study design, intervention characteristics (i.e., level of training, race distance, number of exercises per session, weeks of intervention, exercises included in intervention, outcomes), and characteristic of the tests to determine RE were extracted from the included papers.

Risk of bias assessment

Egger's regression intercept test and visual inspection of the funnel plot were applied to detect the potential of publication bias. The methodological quality of the included studies was assessed by at least two independent researchers using the Physiotherapy Evidence Database (PEDro) scale (de Morton, 2009). The PEDro scale consists of 11 items related to methodological quality. Items 2–11 are scored as either “0” (criterion not met) or “1” (criterion met), resulting in a total score ranging from 0 to 10, with higher scores indicating better quality (Vorup et al., 2016). In the present review, two independent researchers evaluated the methodological quality of each study using the PEDro scale. In cases of disagreement, a third researcher was consulted, and consensus was reached through discussion. Systematic differences (heterogeneity) were assessed utilizing I^2 statistics, which represent the percentage of heterogeneity of the selected studies. I^2 values of 25%, 50%, and 75% indicate low, moderate and high heterogeneity (Higgins et al., 2003).

Statistical analysis

Statistical analyses were performed using OpenMetaAnalyst® (AHRQ, Maryland, USA) with the level of significance set at $p < 0.05$. Standardized mean differences (SMDs) for each study were calculated using the DerSimonian-Laird random-effects model, which is widely employed in meta-analyses when heterogeneity is expected among studies. This model accounts for both within-study and between-study variance, making it appropriate for the present analysis, which included studies with varying sample sizes, interventions, and outcome measures. SMDs were weighted by the inverse variance to estimate the overall effect size. All the data are reported as mean ± 95% confidence interval (CI). The meta-analysis was performed based on RE improvement, represented by a reduction in oxygen cost at the same absolute intensity, and thus presents a negative SMDs change. The magnitude of difference in RE was calculated using Cohen’s d to interpret the magnitude of SMDs (DerSimonian & Laird, 1986). The ES classification was <0.20, trivial; 0.20 to 0.49, small; 0.50 to 0.79, moderate; and >0.80, large (Cohen, 1988).

Results

From 895 studies obtained in three databases, eight studies met the inclusion criteria for quantitative synthesis. The PEDro scores for the eight studies were good and similar (range: 6-7) (table 2).

Table 2. PEDro ratings of evidence levels of the included studies.

Study	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Total
Spurrs et al. (Spurrs et al., 2003)	1	0	1	0	0	0	1	1	1	1	6
Ferrauti et al. (Ferrauti et al., 2010)	1	1	1	0	0	0	0	1	1	1	6
Albracht et al. (Albracht & Arampatzis, 2013)	0	1	1	0	0	0	1	1	1	1	6
Piacentini et al. (Piacentini et al., 2013)	1	1	1	0	0	0	1	1	1	1	7
Damasceno et al. (Damasceno et al., 2015)	1	1	1	1	0	0	0	1	1	1	7
Vorup et al. (Vorup et al., 2016)	1	0	1	0	0	0	1	1	1	1	6
Giovanelli et al. (Giovanelli et al., 2017)	0	1	1	0	0	0	1	1	1	1	6
Festa et al. (Festa et al., 2018)	1	1	1	1	0	0	0	1	1	1	7
Median score											6

The subjects’ characteristics and the training design are shown in table 3:

Table 3. Main findings of the included studies from the endurance training group added resistance training.

Study	N (sex)	Study population	Racing specialty	Exercises per session (n)	Sessions per week (n)	Training duration (weeks)	Main activity	Results
Spurrs et al. (Spurrs et al., 2003)	8 M	Recreational runners	10 km	4	2	6	Plyometric exercises	Improved RE
Ferrauti et al. (Ferrauti et al., 2010)	9 M 2 FM	Recreational runners	42 km	6	2	8	Gym lower and upper limbs machines	Improved RE
Albracht et al. (Albracht & Arampatzis, 2013)	13 NIG	Recreational runners	10 km	1	4	14	Dynamometer	Improved RE

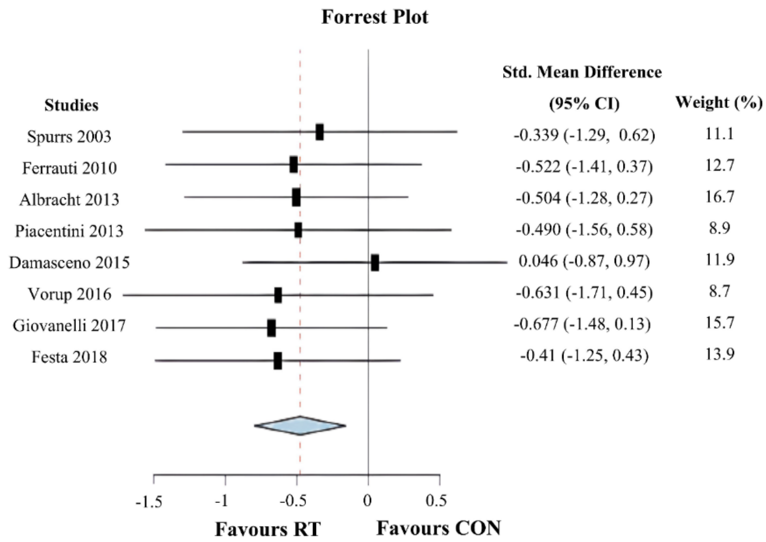
Piacentini et al. (Piacentini et al., 2013)	4 M 2 F	Recreational runners	10-42 km	14	2	6	Gym upper/lower limbs machines/weight exercises	Improved RE
Damasceno et al. (Damasceno et al., 2015)	9 M	Recreational runners	10 km	4	2	8	Gym lower limbs machines	No changes in RE
Vorup et al. (Vorup et al., 2016)	9 M	Trained runners	10-42 km	3	2	8	Gym lower limbs machines/weight barbell	Improved RE
Giovanelli et al. (Giovanelli et al., 2017)	13 M	Well-trained runners	>50 km	5-8	3	12	Body exercises	Improved RE
Festa et al. (Festa et al., 2018)	6 M 5 FM	Recreational runners	21 km	2	1	8	Gym lower limbs machine	Improved RE

Note: NIG, non-informed gender; FM, female; M, male; RE, running economy; w, week.

The pooled sample size across all studies included in this review was 80 participants. Of these, 73% (n = 58) were male and 11% (n = 9) were female. In the remaining 16% (n = 13), the participants' gender was not reported, such as in the study by Albracht and Arampatzis (Albracht & Arampatzis, 2013). The mean age of all subjects was 36.2 ± 6.3 years, and the baseline VO_{2max} was 49.2 ± 4.7ml.kg.min^{-1}. The frequency of sessions per week was 2.3 ± 0.9, composed of an average of 4.6 ± 4.1 exercises per session. The average training intensity of the studies was 83% 1RM. Spurrs et al. (Spurrs et al., 2003) and Giovanelli et al. (Giovanelli et al., 2017) did not report training intensity. Ferrauti et al. (Ferrauti et al., 2010) prescribed their training protocol using 70% 1RM. Albracht et al. (Albracht & Arampatzis, 2013) prescribed the training protocol using a mean intensity of 90% isometric maximum voluntary contraction (MVIC). Piacentini et al. (Piacentini et al., 2013) utilized a mean training intensity of 88% 1RM. The protocol of the Damasceno et al. (Damasceno et al., 2015) study was designed with 80% 1RM, based on the Landers (Landers, 1985) study which associated the percentage of repetition with the number of repetitions. Vorup et al. (Vorup et al., 2016) and Festa et al. (Festa et al., 2018) conducted training protocols with 85% 1RM.

The mean duration of the resistance training protocols was nine (9) weeks. Three quarters (*n*=6) of the included studies were conducted with recreational subjects (Albracht & Arampatzis, 2013; Damasceno et al., 2015; Ferrauti et al., 2010; Festa et al., 2018; Piacentini et al., 2013; Spurrs et al., 2003). The remaining quarter of the studies (n=2) included trained and well-trained subjects (Giovanelli et al., 2017; Vorup et al., 2016). Frequently used gym machines were leg-press (Damasceno et al., 2015; Ferrauti et al., 2010; Piacentini et al., 2013; Vorup et al., 2016), knee extension (Ferrauti et al., 2010), knee flexion (Ferrauti et al., 2010), reverse fly (Ferrauti et al., 2010), and pull down machine (Piacentini et al., 2013). For the free weight/barbell, the most common exercises were bench press (Ferrauti et al., 2010; Piacentini et al., 2013), half squat on the barbell (Damasceno et al., 2015; Vorup et al., 2016), plantar flexion and extension (Ferrauti et al., 2010), hip extension (Ferrauti et al., 2010), trunk extension and rotation (Ferrauti et al., 2010), deadlift (Vorup et al., 2016), weighted lunges (Piacentini et al., 2013), half squat holding dumbbells (Piacentini et al., 2013), and triceps/biceps dumbbell curls (Piacentini et al., 2013). Conversely, Albracht et al. (Albracht & Arampatzis, 2013) used isometric ankle plantar flexion in a dynamometer; Spurrs et al. (Spurrs et al., 2003) applied plyometric training (i.e., squat jump); Festa et al. (Festa et al., 2018) utilized flywheel leg press machine; and Giovanelli et al. (Giovanelli et al., 2017) applied home-based exercises (i.e., body exercises: half squat, step-up). Seven of the studies included in this meta-analysis reported significant improvements in RE following resistance training (Albracht & Arampatzis, 2013; Ferrauti et al., 2010; Festa et al., 2018; Giovanelli et al., 2017; Piacentini et al., 2013; Spurrs et al., 2003; Vorup et al., 2016), and one reported no changes in RE (Damasceno et al., 2015) (figure 2). The effect sizes obtained in the studies which observed improvements in RE following resistance training were: d=-0.33, small, in Spurrs et al. (Spurrs et al., 2003); d=-0.52, moderate, in Ferrauti et al. (Ferrauti et al., 2010); d=-0.50, moderate, in Albracht et al. (Albracht & Arampatzis, 2013); d=-0.49, moderate, in Piacentini et al. (Piacentini et al., 2013); d=-0.63, moderate, in Vorup et al. (Vorup et al., 2016); d=-0.67, moderate, in Giovanelli et al. (Giovanelli et al., 2017); and d=-0.63, moderate, in Festa et al. (Festa et al., 2018). The study in which significant changes in RE were not observed following resistance training (p>0.05) obtained an effect size of d=0.04, trivial (Damasceno et al., 2015). The heterogeneity of the included pooled studies (I^2) was low (0%) (Q[df=7], 1.766; p=0.972). The pooled forest plot results showed improvements in RE after resistance training (p=0.003, d=-0.47, moderate).

Figure 2. Forest plot of running economy (n=8). Note: Favours RT, favours resistance training group; Favours CON, favours control group.



Discussion

Summary of results

We aimed to systematically and meta-analytically review the existing data to determine the effects of resistance training on running economy in long-distance runners (> 10 Km). Confirming previous meta-analyzes describing the effects of resistance training on RE in endurance runners, this study showed an improvement in RE after resistance training (Balsalobre-Fernández et al., 2016; Berryman et al., 2018; Denadai et al., 2017). This is the first meta-analysis in which the effects of resistance training on running economy of long-distance runners (≥10 km) were investigated. Only one study found no improvements on RE in runners from middle and long-distance following resistance training (Damasceno et al., 2015). Our hypothesis was confirmed since we found significant improvements in RE through high-intensity resistance training performed over an average of eight weeks in long-distance runners.

Racing specialty and RE

Most of the studies in this meta-analysis were conducted with recreational runners accustomed to races between 10 and 42 km (Albracht & Arampatzis, 2013; Damasceno et al., 2015; Ferrauti et al., 2010; Festa et al., 2018; Piacentini et al., 2013; Spurrs et al., 2003). While only one study examined well-trained ultra-endurance runners (>50 km) (Giovanelli et al., 2017). From all the included studies, only the one by Damasceno et al. (Damasceno et al., 2015) did not report improvements in RE through resistance training. The authors suggested that the higher intensity and lower training volume applied (3 sets of 10 to 3 reps at ~80% 1 RM) may have been a factor. Interestingly, other studies using a similar high-intensity approach did report improvements in RE (Ferrauti et al., 2010; Festa et al., 2018; Piacentini et al., 2013; Vorup et al., 2016), suggesting that training response may depend on additional factors, including neuromuscular conditioning, baseline fitness, and adaptation time. Notably, the subjects in Damasceno et al.(Damasceno et al., 2015) had no prior experience with resistance training and trained at low aerobic intensities. It is plausible that the training stimulus imposed excessive neuromuscular stress, which limited adaptation (Moritani & deVries, 1979). Short-term resistance training might increase neural activation, but other adaptations (e.g., muscle-tendon stiffness) may require longer interventions (Hortobagyi et al., 2023; Staron et al., 1994).

Endurance performance is primarily associated with aerobic capacity (Rønnestad & Mujika, 2014), but in shorter events (e.g., 800-5000m), neuromuscular components such as power and speed may also play an important role. Resistance training may contribute to performance by improving muscle fiber recruitment efficiency and possibly shifting fiber-type profiles. Although transitions from type IIX to IIA fibers have been suggested (Aagaard et al., 2011), more direct evidence is needed to confirm these effects in runners. While some studies in this review did report the resistance training background of their subjects, contractual information (e.g., master athletes, training abstention prior testing) may suggest previous exposure. Still, we recognize that this assumption cannot be confirmed without direct data.

Overall, the findings of this meta-analysis indicate that certain characteristics of resistance training (e.g., intensity, duration, exercise type) may influence its effectiveness on RE, particularly in trained runners. However, further studies are needed to explore how athletes training background and racing specialty effect responsiveness to resistance training.

The design of resistance training for improving running economy

In all studies included in this meta-analysis, resistance training was executed using gym machines, free weight and free body weight exercises. Piacentini et al. (Piacentini et al., 2013) applied a cluster of gym machines and free weight training, such as foundation strength exercises (i.e., deadlift, back squat, bench press). Considering the biomechanics of running, it is well established that running involves cyclic movements that rely on muscle power, contained in weightlifting (van Oeveren et al., 2021). Thus, we believe that different forms of resistance training, such as weightlifting, ballistic training and powerlifting, could also improve RE in runners. There are no available studies in which the effects of weightlifting were investigated in RE.

Regarding training intensity, it is important to note that the mean intensity of the selected studies was 83% 1RM ± 7.2%. Balsalobre-Fernandez et al. (Balsalobre-Fernández et al., 2016) showed that in most of the included studies in which the effects of resistance training on RE were investigated, the intensity proposed was low to moderate (40-70% 1RM), which resulted in improvements in RE in highly trained subjects. The experimental protocol of selected studies generally was composed by high-intensity resistance training (≥80% 1RM), mostly applied in lower limbs. High-intensity resistance training improves neuromuscular performance, such as maximum strength and power (P O'Shea, 1976). However, a high-intensity resistance training session may lead to metabolic and neuromuscular fatigue (Gorostiaga et al., 2012; Sanchez-Medina & Gonzalez-Badillo, 2011), which is associated with a transition in recruitment from type IIx fibers to type IIa fibers (Fry, 2004), reducing muscle strength and power output during, right after, and hours after the training session (Izquierdo et al., 2006).

It is plausible that athletes who performing high-intensity resistance training may require longer recovery intervals before reassessing their endurance performance, which could partially explain the absence og improvement in RE in Dasmasceno etl al. study (Damasceno et al., 2015). However,, this interpretation remains speculative and should be viewed with caution, that warrants further investigation. While the present meta-analysis showed improvements in RE following high-intensity resistance training, supported by the findings of Denadai et al. (Denadai et al., 2017), Balsalobre-Fernandez et al. (Balsalobre-Fernández et al., 2016) and Berryman et al. (Berryman et al., 2018), the use of low-intensity resistance training to improve RE remains understudied. Historically, Schmolinsky (Schmolinsky, 1981) reported that low-intensity resistance training (<40% 1RM) was commonly employed by runners for injury prevention rather than for direct improvements in performance.

Among the included studies in this meta-analysis, only strength training programs shorter than 24 weeks were considered. Only few studies described the effects of resistance training lasting more than 24 weeks in RE, and none met the inclusion eligibility criteria. Earlier, Denadai et al. (Denadai et al., 2017) reported only a small positive effect (~ 4%) of resistance training on RE in a meta-analysis. These effects were reported to be related to the short resistance time-period (6-8 weeks). Conversely, when resistance training lasted from 12 to 14 weeks, moderate to large effects could be observed. Berryman et al. (Berryman et al., 2018) showed improvements in RE (moderate effect size, d=0.63) in studies in which chronic resistance training was prescribed (> 24 sessions), but only trivial effect sizes for those studies in which acute resistance training was investigated (< 24 sessions, d=0.10). Interestingly, in the present meta-analysis, the period of resistance training was short (range: 6-14 weeks), and the average of the total training sessions was low (21 sessions, range: 8-56). Despite the characteristics of acute resistance training reported here, the pooled effect size was also moderate (d = 0.47).

Resistance training represents a subset of neuromuscular training and comprises a wide range of resistive load and movement forms and velocities (Berryman et al., 2018). Here, exercise types and velocities did not change the effects of RE. Recently, Eihara et al. (Eihara et al., 2022) described in their meta-analysis that high-intensity resistance training (≥ 70% 1RM) was more effective to improve RE than plyometric training. In addition, they reported that heavier loads (≥ 90% 1RM) and longer resistance training periods would lead to greater improvements in RE. These results corroborate to our findings. In the studies included in this meta-analysis, Spurrs et al. (Spurrs et al., 2003) used plyometrics, and among the studies which demonstrated improvements in RE, theirs revealed the smallest magnitude of the effect size and CI (small, d=0.33, CI=-1.29-0.62). Hudgins et al. (Hudgins et al., 2013) suggested that the application of > 10 weeks of plyometric training would maximize power performance. Indeed, Spurrs et al. (Spurrs et al., 2003) applied only six weeks of plyometric training, and this might be a limitation for the magnitude of the effect size.

Strengths and limitations

The present meta-analysis identified the outcomes of the resistance training on RE through the available literature (i.e., running specialty, training intensity, and duration of the resistance training protocol). The findings presented in this study explain the effects of resistance training on RE mainly in recreational runners. The results presented here have limited applicability to high performance runners. The pooled sample size across all included studies was 80 participants. Of these, 73% (n = 58) were male and 11% (n = 9) were female. For the remaining 16% (n = 13), the participants' gender was not specified in the original studies, such as in Albracht and Arampatzis (Albracht & Arampatzis, 2013). This lack of gender reporting may limit the interpretation of gender-specific effects and should be considered when generalizing the findings. The overall mean age of the participants was 36.2 ± 6.3 years. Although the studies included diverse training modalities (e.g., plyometric, isometric, machine-based, free-weight, and home-based exercises) and participant profiles (recreational and trained individuals), the consistency in direction and magnitude of the effect sizes across studies may explain this low heterogeneity. Nevertheless, we acknowledge that the diversity in training approaches and sample characteristics could suggest latent variability not captured in the statistical test, and thus, this finding should be interpreted with caution. It is important to note that some studies displayed wide confidence intervals in their effect estimates (e.g., (Ferrauti et al., 2010; Giovanelli et al., 2017; Spurrs et al., 2003), which reflects limited precision and possibly small sample sizes or large within-group variability. These broad intervals indicate uncertainty around the true effect size and should be taken into account when interpreting the pooled findings. Additionally, variability in study quality and methodological differences, such as differences in training supervision, assessment protocols, or outcome measures may also have influenced the results and should be acknowledged as a potential limitation.

Recommendations for future research

The effects of resistance training on RE in runners have been extensively debated among practitioners. This study corroborates with the metanalysis by Denadai et al. (Denadai et al., 2017), suggesting that further studies are needed to distinguish different resistance training modalities (i.e., plyometric and heavy resistance training). We also agreed with Ronnestad et al. (Rønnestad & Mujika, 2014) who described the difficulty to understand the role between resistance training and RE.

Resistance training involving similar muscle groups involved in running might positively affect the RE. This statement is supported by neural adaptations (i.e., the improvement in motor coordination). Some of the discrepancies in the divergent results seem to be related to the structure of the resistance training. Future studies should therefore investigate other chronic resistance training strategies (i.e., weightlifting, powerlifting) to improve RE in recreational and well-trained long-distance runners. Also, future studies should include a control group with the same total training volume as the experimental group (i.e. light running, stretching).

In the present meta-analysis, we found improvements of RE after resistance training in long-distance running. Future investigation should be dedicated to elucidate the hypothesis of the present review on the improvement of RE by resistance training in long-distance runners. The small sample sizes of the trials and high heterogeneity in methods should be considered when interpreting results.

Conclusions

The findings of this meta-analysis suggest that resistance training may contribute to improvements in running economy (RE), particularly among recreational long-distance runners. While some studies included in this analysis reported benefits from high-intensity resistance training, the current evidence remains limited and heterogeneous, with variable methodological quality and small sample sizes. Therefore, any practical applications should be made cautiously. Coaches and athletes might consider incorporating resistance training as part of a broader training strategy, but further high-quality research is needed to clarify the optimal training parameters and to confirm these preliminary findings.

Acknowledgements

We would like to thank the Brazilian Athletics Confederation.

Financing

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES— Finance Code 001).

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