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REVIEW ARTICLE

Strategies to Improve Running Economy

Kyle R. Barnes · Andrew E. Kilding

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Abstract Running economy (RE) represents a complex interplay of physiological and biomechanical factors that is typically defined as the energy demand for a given velocity of submaximal running and expressed as the submaximal oxygen uptake (VO_2) at a given running velocity. This review considered a wide range of acute and chronic interventions that have been investigated with respect to improving economy by augmenting one or more components of the metabolic, cardiorespiratory, biomechanical or neuromuscular systems. Improvements in RE have traditionally been achieved through endurance training. Endurance training in runners leads to a wide range of physiological responses, and it is very likely that these characteristics of running training will influence RE. Training history and training volume have been suggested to be important factors in improving RE, while uphill and level-ground high-intensity interval training represent frequently prescribed forms of training that may elicit further enhancements in economy. More recently, research has demonstrated short-term resistance and plyometric training has resulted in enhanced RE. This improvement in RE has been hypothesized to be a result of enhanced neuromuscular characteristics. Altitude acclimatization results in both central and peripheral adaptations that improve oxygen delivery and utilization, mechanisms that potentially could improve RE. Other strategies, such as stretching should not be discounted as a training modality in order to prevent injuries; however, it appears that there is an optimal degree of flexibility and stiffness required to maximize RE. Several nutritional interventions have also received attention for their effects on reducing oxygen demand during exercise, most notably dietary nitrates and caffeine. It is clear that a range of training and passive interventions may improve RE, and researchers should concentrate their investigative efforts on more fully understanding the types and mechanisms that affect RE and the practicality and extent to which RE can be improved outside the laboratory.

Key Points

A range of training and passive interventions such as endurance training, high-intensity interval training, resistance training, training at altitude, stretching and nutritional interventions may improve running economy.

Improvements in running economy may be made by modifying one or more factors that influence metabolic, biomechanical and/or neuromuscular efficiency.

1 Introduction

The goal in competitive distance running is to run a given distance in the least time, or at least faster than the next best competitor. A number of physiological attributes contribute to successful distance running performance [1, 2], including (i) both a high cardiac output and a high rate

K. R. Barnes (✉) · A. E. Kilding
Sports Performance Research Institute New Zealand, Auckland University of Technology, Level 2, AUT-Millennium Campus, 17 Antares Place, Mairangi Bay, Auckland, New Zealand
e-mail: kyle.barnes@yahoo.com; barnesk@gvsu.edu

K. R. Barnes
Department of Movement Science, Grand Valley State University, Allendale, MI, USA

of oxygen delivery to working muscles, which leads to a large capacity for aerobic adenosine triphosphate (ATP) regeneration [i.e., a high maximal oxygen uptake (VO_{2max})] [3, 4]; (ii) the ability to sustain a high percentage of VO_{2max} for long periods of time (i.e., fractional utilization of VO_{2max}, relative intensity) [5]; and (iii) the ability to move efficiently [running economy (RE)] [6–8]. Maximal aerobic capacity and fractional utilization of VO_{2max} have been widely studied as determinants of running performance; however, RE has been relatively ignored until the past decade or so despite awareness of its importance since at least the 1970s [3].

The steady-state oxygen consumption (VO_2) at a given running velocity, which is often referred to as RE [8–10], reflects the energy demand of running at a constant submaximal speed. Trained runners have superior RE to lesser-trained or untrained runners [11–13], indicating positive adaptations occur in response to habitual training [14, 15]. While a given athlete may be genetically predisposed to having 'good' RE [16], various strategies can potentially further improve an individual's RE through augmenting metabolic, cardiorespiratory, biomechanical and/or neuromuscular responses and adaptations. Given RE has been identified as a critical factor contributing to distance running performance [4, 5, 7, 9, 15, 17–21], effective legal and practical strategies to improve RE are sought after by coaches, athletes and sports scientists. To date, a wide range of acute and chronic interventions have been investigated with respect to improving economy, including various forms of resistance training [22–31], high-intensity interval training (HIT) [32–36], altitude exposure [37–44], stretching [45–50], as well as nutritional supplements (Fig. 1) [51–55]. Therefore, the purpose of this narrative review is to examine various training strategies that have attempted to improve RE, discuss the feasibility of strategies previously identified but yet to be explored in the literature, and discuss potential areas for future research.

2 Endurance Training in Runners

A range of physiological responses occur in response to endurance training in runners, and it is likely that the characteristics of training influence RE. Endurance training leads to increases in the morphology and functionality of skeletal muscle mitochondria [10, 56]. Specifically, an increase in the oxidative muscle capacity allows trained runners to use less oxygen per mitochondrial respiratory chain during submaximal running [57]. Furthermore, adaptations such as improved skeletal muscle buffer capacity [58] and hematological changes [40, 59] (i.e., increased red cell mass) have been observed following various training modalities. These adaptations could also invoke improvements in oxygen delivery and utilization that could improve an athlete's RE.

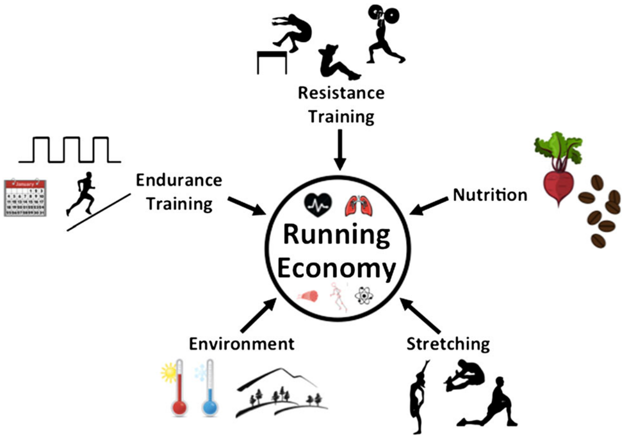

Fig. 1 Schematic of strategies to improve running economy

While training has been suggested to elicit a range of central and peripheral adaptations that improve the metabolic and cardiorespiratory efficiency of a runner [60], many of these adaptations are largely governed by the training load, which can be manipulated for a given athlete by increasing the volume or intensity of running over time.

2.1 Training History

Successful endurance runners typically undergo several years of training to enhance the physiological characteristics important to determining success in distance running events. Indeed, the number of years of running experience and high training volumes have been suggested to be important to RE [61, 62]. Unfortunately, the few longitudinal studies that have examined this question have yielded little consensus, with findings indicating no change [63, 64], a slight increase [65], and varying degrees of reductions (1–15 %) in submaximal VO_2 among trained and untrained runners engaging in different combinations of years, distance, interval and uphill training [36, 66–68]. For example, in moderately trained runners, Mayhew et al. [69] found that years of training was significantly correlated ($r = 0.62$) with RE. In support, Midgley et al. [70] has suggested that the most important factor in improving RE may be the cumulative distance a runner has run over years of training and not short-term (several weeks to month) bouts of high training volume per se. This may be due to continued long-term adaptations in metabolic, biomechanical and neuromuscular efficiency [62, 70]. Case study data from world-class runners also suggests that RE improves over several years of training [17, 21, 71–73]; however, the role played by the interaction between training volume and consistency of training in such improvements over several years of training remains unclear.

2.2 Training Volume

The influence of training volume on RE is not well discussed in the literature, and unfortunately, no training studies to date have examined the implications of increased training volume while controlling for potential confounding variables like training intensity. This makes it difficult to ascertain the effects of manipulating training volume [70]. However, in a cross-sectional investigation, Pate et al. [74] reported that training volume was not associated with better RE. Nevertheless, the importance of training volume should not be downplayed, as high-volume training plays a major role in inducing adaptations important to distance running success [75]. Clearly, there is a need for longitudinal examinations of the relationship between RE and training history, including how subtle changes in volume, intensity, and cumulative volume interact, before conclusions about their effect on RE can be made.

2.3 High-Intensity Interval Training (HIT)

Studies that have incorporated flat overground HIT into the training programs of distance runners have reported equivocal results in relation to improving RE (Table 1). Jones and Carter [76] suggested that runners are typically most economical at the running velocities at which they habitually train; however, no training study to date has investigated the specificity of training velocity on RE. HIT at 93–120 % velocity at VO_{2max} (vVO_{2max}) [32, 35, 36, 77–79] and continuous running at velocity at the onset of blood lactate accumulation (vOBLA) [32, 33, 36, 77] have both been shown to improve RE by ~1–7 % (Table 1). Other studies using similar training intensities have reported no significant improvement [35, 77, 80, 81]. Morgan et al. [82] suggested that the type of run training exerts a negligible effect on improving RE, based on the observation that several studies reported no differences in changes in RE despite the runners engaging in different interval training programs.

Whereas VO_{2max} has been shown to increase significantly during the transition between the off-season and precompetitive period, during which training intensity is increased [17, 64, 83, 84], the same studies reported either a significant improvement [17, 84] or no change [64, 83] in RE. Franch et al. [35] compared interval training at 94, 106 and 132 % vVO_{2max} and found that RE significantly improved in the 94 and 106 % groups, but not in the group that trained at 132 % vVO_{2max}. This suggests that very high-intensity running is not effective in improving RE, possibly because of a loss of running form at very high running velocities, or an inability to complete a sufficient training volume to elicit a training effect [70].

Biomechanical changes could improve exercise efficiency following HIT. However, Lake and Cavanagh [85] investigated the effects of 6 weeks of HIT on various biomechanical variables in a group of moderately trained runners and found no relationship between changes in performance, VO_{2max}, RE and biomechanical variables. The authors concluded that improvements in performance following HIT were more likely to be caused by physiological rather than biomechanical factors.

2.3.1 Uphill Interval Training

Uphill running represents a frequently prescribed form of HIT in periodized training programs for distance runners. For example, a survey of teams competing in a collegiate cross-country national championship race verified its widespread use as a training method and revealed that faster team times were correlated with inclusion of uphill training [86]. Moreover, references to its potential effectiveness as a movement-specific form of resistance training have appeared in several reviews [10, 70, 87]; however, only anecdotal reports and limited research investigations [77, 88, 89] exist concerning the physiological responses and potential improvements in performance to such training. Unlike other modes of resistance training, where a transfer of learning would need to occur to improve RE, uphill running is movement specific and the mechanisms for improving RE are likely to directly affect one or more of the metabolic, biomechanical and neuromuscular systems.

2.4 Summary

It appears that further research is required to establish the relative efficacy of HIT for improving the RE of long-distance runners and to establish whether improvements in RE can be derived from uphill and flat interval training through variations in the frequency, duration, volume and periodization of training.

3 Resistance Training

3.1 Heavy and Strength-Endurance Resistance Training

Understandably, running makes up a significant proportion of a runners training. However, other forms of training are undertaken to bring about specific physiological adaptations that could directly or indirectly (i.e., reduce injury risk) improve performance. A common training method often utilized by distance runners is resistance training. Various forms of resistance training can be adopted, and several have been shown to improve RE in recreational [29, 90, 91], moderately trained [22, 23, 28, 92–95], and

Table 1 Comparison of effects on running economy and performance following adaptation to various high-intensity interval training interventions

References	Subjects	Volume	Frequency and duration	Control	Results (%)	
					Running economy	Performance (distance)
Interval training						
Sjodin et al. [36]	8 highly trained male runners	20 min at vOBLA (vOBLA = 85 % vVO_{2max})	1 day/week for 14 weeks	No control	↑ 2.8	n/a
Yoshida et al. [81]	6 recreational female runners	20 min at vOBLA (vOBLA = 91 % vVO_{2max})	6 days/week for 8 weeks	Endurance training	↑ 2.8	n/a
Franch et al. [35]	12 recreational male runners	Continuous at 94 % vVO_{2max}	3 days/week for 6 weeks	No control	↑ 3.1	↑ 94 (time to exhaustion at 87 % VO_{2max})
	12 recreational male runners	4–6 × 4 min at 106 % vVO_{2max}	3 days/week for 6 weeks	No control	↑ 3.0	↑ 67 (time to exhaustion at 87 % VO_{2max})
	12 recreational male runners	30–40 × 15 s at 132 % vVO_{2max}	3 days/week for 6 weeks	No control	↑ 0.9	↑ 65 (time to exhaustion at 87 % VO_{2max})
Billat et al. [32]	8 highly trained male runners	4 weeks: 5 × 3 min at 100 % vVO_{2max}; 2 × 20 min vOBLA (vOBLA = 85 % vVO_{2max}) 4 weeks: 3 × (5 × 3 min at 100 % vVO_{2max}); 2 × 20 min vOBLA (vOBLA = 85 % vVO_{2max})	2 days/week for 4 weeks + 4 days/week for 4 weeks	No control	↑ 6.1 ↑ 7.7	↔ (time to exhaustion at MAS)
Slawinski et al. [79]	6 moderately trained runners	2 × vΔ50 intervals; 3 × continuous at 60–70 % vVO_{2max} (vΔ50 = 93 % vVO_{2max})	2 days/week for 8 weeks	No control	↑ 3.6	↑ 17.3 (time to exhaustion at 17 km h^{-1})
Laffite et al. [78]	7 moderately trained male runners	2 × vΔ50 intervals (vΔ50 = 93 % vVO_{2max})	2 days/week for 8 weeks	No control	↑ 5.4	n/a
Smith et al. [181]	18 moderately trained runners	6 × 2 min vVO_{2max} + 1 × continuous at 60 % vVO_{2max}	2 days/week for 4 weeks	Endurance training	↑ 3.3	↑ 2.8 (3-km) ↑ 2.3 (5-km)
	18 moderately trained runners	5 × 2.5 min vVO_{2max} + 1× continuous at 70 % vVO_{2max}	2 days/week for 4 weeks	Endurance training	↔	↑ 1.0 (3-km) ↔ (5-km)
Denadai et al. [33]	9 moderately trained male runners	4 × 60 % t_{lim} at 95 % vVO_{2max}; 2 × 20 min vOBLA	2 days/week for 4 weeks	No control	↑ 2.6	↔(1,500-m) ↑ 1.5 (5-km)
	8 moderately trained male runners	5 × 60 % t_{lim} at 100 % vVO_{2max}; 2 × 20 min vOBLA	2 days/week for 4 weeks	No control	↑ 6.7	↑ 2.0 (1,500-m) ↑ 1.4 (5-km)
Enoksen et al. [34]	10 highly trained male runners	13 % of total training volume at 82–92 % HR_{max}	1 day/week for 10 weeks	No control	↑ 4.1	n/a
	9 highly trained male runners	33 % of total training volume at 82–92 % HR_{max}	3 days/week for 10 weeks	No control	↑ 2.6	n/a

Table 1 continued

References	Subjects	Volume	Frequency and duration	Control	Results (%)	
					Running economy	Performance (distance)
Barnes et al. [77]	5 moderately trained runners	12–24 × 8–12 s 120 % vVO_{2max} (uphill) in addition to endurance training	2 days/week for 6 weeks	No control	↑ 2.4	↑ 2.1 (5-km)
	5 moderately trained runners	8–16 × 30–45 s 110 % vVO_{2max} (uphill) in addition to endurance training	2 days/week for 6 weeks	No control	↑ 0.6	↑ 2.0 (5-km)
	5 moderately trained runners	5–9 × 2–2.5 min 100 % vVO_{2max} (uphill) in addition to endurance training	2 days/week for 6 weeks	No control	↓ 1.2	↑ 2.0 (5-km)
	4 moderately trained runners	4–7 × 4–5 min 90 % vVO_{2max} (uphill) in addition to endurance training	2 days/week for 6 weeks	No control	↓ 2.4	↑ 2.1 (5-km)
	3 moderately trained runners	1–3 × 10–25 min 80 % vVO_{2max} (uphill) in addition to endurance training	2 days/week for 6 weeks	No control	↓ 3.2	↑ 2.2 (5-km)

Highly trained national/international level and VO_{2max} >65 ml kg^{-1} min^{-1}, *moderately trained* weekly running volume >30 km $week^{-1}$, *recreational* weekly running volume <30 km $week^{-1}$, *HR_{max}* maximal heart rate, *MAS* maximal aerobic speed, *n/a* indicates not measured, *t_{lim}* time limit, *vΔ50* velocity midway between vLT and vVO_{2max}, *vLT* velocity at the lactate threshold, *VO_{2max}* maximal aerobic capacity, *vOBLA* velocity at the onset of blood lactate accumulation, *vVO_{2max}* velocity at VO_{2max}, ↑ indicates increase, ↔ indicates no change, ↓ indicates decrease

highly trained runners [26, 96] (Table 2). To date, resistance training interventions have been designed specifically to increase muscular strength, power, muscular endurance, and/or promote neural adaptations. For the purposes of this review, and in keeping with use of resistance methods in the literature (Table 2), the term 'resistance training' will refer to any training that uses a resistance to the force of muscular contraction at a low velocity, while 'heavy resistance training' will refer to those studies that utilize loads <6 repetition maximum (RM) (1–6 RM), and 'strength-endurance resistance training' will refer to studies utilizing loads ≥6 RM.

3.1.1 Mechanisms of Improvement Following Heavy or Strength-Endurance Resistance Training

Resistance training may improve RE through several mechanisms. Kyrolainen et al. [97] proposed that resistance training may improve RE through improved lower limb coordination and co-activation of muscles, thereby increasing leg stiffness and decreasing stance phase contact times, allowing a faster transition from the braking to the propulsive phase through elastic recoil [24, 97–101]. Heavy resistance training may primarily cause hypertrophy of type IIA and IIB (fast twitch) fibers, but also type I (slow twitch) fibers [102, 103], resulting in less motor unit activation to produce a given force [104]. Unfortunately, increases in body mass are an undesirable side effect to increases in muscle strength from resistance training that could be counter-productive to distance running performance. However, increased muscular strength might primarily come from neural adaptations without observable muscle hypertrophy [105] since most studies reported little or no changes in body mass, fat free mass, percentage body fat or girth measurements following heavy resistance training. Sale [100] states that heavy resistance training induces changes in the nervous system which allow an athlete to increase the activation of the working muscles, thus producing a greater net force with each stride. An increase in strength following heavy resistance training as a result of increased motor unit recruitment and motor unit synchronization may improve mechanical efficiency and motor recruitment patterns [100, 106]. Greater muscular strength following heavy or strength-endurance resistance training has previously been shown to delay muscular fatigue, resulting in a smaller increase in oxygen consumption (decreased RE) at any given speed during sustained endurance exercise [107]. It is well documented that initial performance gains following heavy resistance training are a result of neuromuscular adaptations rather than within muscle adaptations (e.g., hypertrophy) [100, 106]. Several studies [22, 28, 29, 96] have reported concomitant improvements in RE and maximal strength following heavy resistance training, indicating positive neuromuscular adaptations. Other studies [26, 93, 95, 101, 108] have demonstrated that the combination of strength-endurance resistance training and endurance training improves running performance and enhances RE in moderately and highly trained runners (Table 2). Regardless of whether strength gains occur at the muscular level, neural level, or both, the available evidence suggests if a more efficient recruitment pattern is induced, decreases in oxygen consumption at a given speed are likely to occur [11, 67]; however, more research is necessary to support these assertions.

Improved RE may also be due to increases in strength that cause positive changes in mechanical aspects of running style (i.e., improved biomechanical efficiency) [23], thus allowing a runner to do less work at a given running speed. A number of biomechanical variables have been identified that relate to RE, thereby providing support for the hypothesis that mechanical aspects of running style have an influence on RE [109]. Another possible explanation for improved RE following heavy resistance training could involve muscle fiber-type conversion from less efficient fast twitch fibers (type IIB) to more efficient oxidative fibers (type IIA and type I), though existing data in athletes are conflicting [102, 103, 110, 111]. For example, Staron et al. [102, 103, 110] found a concomitant decrease in submaximal VO_2 and decrease in type IIB fibers, with a simultaneous increase in type IIA fibers following a heavy-resistance low-velocity lower body resistance training program in untrained men [102] and women [102, 103, 110]. Conversely, Coyle et al. [111] reported that VO_2 remained unchanged for the same absolute submaximal intensity throughout a detraining period, despite a large shift from type IIA to IIB fibers when studying seven endurance-trained subjects 12, 21, 56 and 84 days after cessation of training, suggesting that muscle fiber conversion has little or no impact on RE.

3.1.2 Heavy Versus Strength-Endurance Resistance Training

Several studies have attempted to determine which form of concurrent endurance and resistance training might be the most effective at improving running performance in highly trained runners. Sedano et al. [26] prescribed 18 well-trained male runners with 12 weeks of either heavy resistance training or strength-endurance resistance training in addition to their normal running training. The heavy-resistance group elicited substantially greater improvements in RE (5 vs. 1.6 %) and 3-km run performance (1.2 % vs. no change) compared with the strength-endurance resistance training group [26]. Similarly, Berryman et al. [93] found that 8 weeks of strength-endurance resistance training (purely concentric semi-squats on a guided squat rack allowing only vertical movements) improved RE by 4 % in 17 moderately trained male runners. The improvement in economy, along with a substantial increase in peak power, resulted in a (mean) 4.3 % improvement in 3-km running time, without an increase in VO_{2max}, with gains attributed to changes in neuromuscular characteristics [93]. Taipale et al. [29] also reported significant improvements in RE (mean 8 %) and vVO_{2max} (mean 10 %) along with improvements in neuromuscular performance (1 RM maximal strength and electromyographic (EMG) vastus lateralis activity) after 8 weeks of heavy resistance training in recreation runners. However, heavy resistance training was performed in addition to a significant increase in endurance training volume; therefore, the improvements in RE may be related to the increased volume of training rather than the resistance training itself since the subjects in this study were recreational runners [29]. The only study [23] to examine any form of resistance training in females found that 10 weeks of strength-endurance resistance training combined with endurance training significantly improved RE (4 %) without any changes in VO_{2max}.

The available data involving athletes suggest RE can be improved with simultaneous resistance and endurance training, with no chronic deleterious effect on VO_{2max} or running performance [10]. Examination of the acute effects of resistance and endurance training sequence on RE shows that running performance is impaired to a greater degree the day following the resistance training then run sequence compared with the run then resistance training sequence [112]. The combination of improved biomechanical efficiency along with greater motor unit recruitment and muscle coordination may allow for a reduction in relative workload, thereby reducing oxygen consumption [113]. Most of the studies discussed here showed improvements in RE in 10 weeks or less; however, more studies are needed to determine if improvements can be made in shorter periods or what the time course of changes in RE are. Most studies demonstrating improvement in RE following resistance training cite enhancements in neuromuscular characteristics as the mechanism for improvement; however, most studies only make indirect measures of neuromuscular activity. Therefore, more direct measures such as EMG analysis may allow researchers to identify if a transfer of learning from resistance training to running performance occurs. Additionally, each of these studies employed different modes of resistance training; therefore, more research is required to determine which mode of resistance training might be most effective at improving RE and performance in well-trained athletes.

Table 2 Comparison of effects on running economy and performance following adaptation to various resistance training, plyometric and explosive resistance training interventions

References	Subjects	Volume	Frequency and duration	Control	Results (%)	
					Running economy	Performance (distance)
Resistance training						
Johnston et al. [23]	12 moderately trained female runners	2–3 sets of 6–20 RM in addition to endurance training	3 days/week for 10 weeks	Endurance running	↑ 4	n/a
Millet et al. [96]	15 highly trained male triathletes	3–5 sets of 3–5 RM in addition to endurance training	2 days/week for 14 weeks	Endurance training (swim, cycle, run)	↑ 5.6–7	↑ 2.6 (3-km)
Storen et al. [28]	17 moderately trained male/female runners	4 sets of 4 RM in addition to endurance training	8 weeks	Endurance running	↑ 5	↑ 21.3 (time to exhaustion at MAS)
Guglielmo et al. [22]	7 moderately trained runners	3–5 sets of 6 RM in addition to endurance training	2 days/week for 4 weeks	No control	↑ 6.2	n/a
Taipale et al. [29]	18 recreational male runners	2–3 sets of 4–15 RM in addition to endurance training	2 days/week for 8 weeks	Circuit + endurance running	↑ 8	↑ 10
Ferrauti et al. [182]	22 recreational male/female runners	4 sets of 3–5 RM or 3 sets of 20–25 RM in addition to endurance training	2 days/week for 8 weeks	Endurance training	↔	n/a
Mikkola et al. [183]	11 moderately trained male runners	3 sets of 4–6 RM in addition to endurance training	2 days/week for 8 weeks	No control	↔	n/a
	6 moderately trained male runners	3 sets of 40–50 reps in addition to endurance training	2 days/week for 8 weeks	No control	↔	n/a
Berryman et al. [93]	17 moderately trained male runners	3–6 sets of 8 reps in addition to endurance training	1 day/week for 8 weeks	Endurance running	↑ 4	↑ 4.3 (3-km)
Cheng et al. [101]	24 recreational male runners	10 sets of 60 s whole body vibration semi squats	3 days/week for 8 weeks	Placebo resistance training + endurance training	↑ 7.8	n/a
Francesca et al. [95]	16 moderately trained male runners	4 sets of 3–4 at 85–90 % 1 RM in addition to endurance training	2 days/week for 6 weeks	Endurance training	↑ 6.2	n/a
	16 moderately trained male runners	3 sets of 10 reps at 70 % 1 RM in addition to endurance training	2 days/week for 6 weeks	Endurance training	↔	n/a
Albracht and Arampatzis [94]	26 recreational male runners	5 sets of 4 reps in addition to endurance training	4 days/week for 14 weeks	Endurance running	↑ 4	n/a
Barnes et al. [92]	13 moderately trained male runners	1–4 sets of 4–12 RM in addition to endurance training	2 days/week for 10–13 weeks	No control	↑ 1.7	↔ 0.1 (8-km)
	9 moderately trained female runners	1–4 sets of 4–12 RM in addition to endurance training	2 days/week for 10–13 weeks	No control	↑ 3.4	↑ 1.4 (6-km)
Sedano et al. [26]	12 highly trained male runners	3 sets of 7–10 reps in addition to endurance training	2 days/week for 12 weeks	Circuit + endurance running	↑ 5	↑ 1.2 (3-km)
	12 highly trained male runners	3 sets of 20 reps in addition to endurance training	2 days/week for 12 weeks	Circuit + endurance running	↑ 1.6	↔ (3-km)
Taipale et al. [91]	18 recreational male runners	2–3 sets of 4–6 reps in addition to endurance training	1–2 days/week for 8 weeks	Endurance training	↔	n/a

Table 2 continued

References	Subjects	Volume	Frequency and duration	Control	Results (%)	
					Running economy	Performance (distance)
Plyometric/explosive resistance training						
Paavolainen et al. [24]	22 moderately trained male runners	15–90 min/session in addition to endurance training	9 weeks	Endurance running and circuit training	↑ 24.4–33.8	↑ 3.1 (5-km)
Spurrs et al. [27]	17 moderately trained male runners	2–3 sets of 8–15 reps in addition to endurance training	2–3 days/week for 6 weeks	Endurance running	↑ 5.7	↑ 2.7 (3-km)
Turner et al. [31]	18 recreational male/female runners	1 set of 5–25 reps in addition to endurance training	3 days/week for 6 weeks	Endurance running	↑ 2–3	n/a
Saunders et al. [25]	15 highly trained male runners	30 min/session in addition to endurance training	3 days/week for 9 weeks	Endurance running	↑ 4	n/a
Mikkola et al. [120]	25 moderately trained male/female runners	30–60 min session in addition to endurance training	3 days/week for 8 weeks	Endurance running	↑ 3	↔ (peak running speed)
Guglielmo et al. [22]	9 moderately trained runners	3–5 sets of 12 RM in addition to endurance training	2 days/week for 4 weeks	No control	↑ 1.9	n/a
Taipale et al. [29]	17 recreational male runners	2–3 sets of 5–10 reps in addition to endurance training	2 days/week for 8 weeks	Circuit + endurance running	↑ 4	↑ 6
Berryman et al. [93]	16 moderately trained male runners	3–6 sets of 8 reps in addition to endurance training	1 day/week for 8 weeks	Endurance running	↑ 7	↑ 5.1 (3-km)
Mikkola et al. [183]	10 moderately trained male runners	3 sets of 6 reps in addition to endurance training	2 days/week for 8 weeks	No control	↔	n/a
Barnes et al. [92]	10 moderately trained male runners	1–3 sets of 6–12 reps in addition to endurance training	2 days/week for 10–13 weeks	No control	↑ 0.2	↔ 0.8 (8-km)
	10 moderately trained female runners	1–3 sets of 6–12 reps in addition to endurance training	2 days/week for 10–13 weeks	No control	↑ 1.0	↑ 1.1 (6-km)
Taipale et al. [91]	17 recreational male runners	2–3 sets of 5–10 reps in addition to endurance training	1–2 days/week for 8 weeks	Endurance training	↔	n/a
	16 recreational male runners	2–3 sets of 4–10 reps in addition to endurance training	1–2 days/week for 8 weeks	Endurance training	↔	n/a
Barnes et al. [121]	11 moderately trained male runners	1 set of 6 × 10-s strides with weighted vest	Acute	Endurance training	↑ 6.0	↑ 2.9 (peak running speed)

Highly trained national/international level and VO_{2max} >65 ml kg^{-1} min^{-1}, *moderately trained* weekly running volume >30 km $week^{-1}$, *recreational* weekly running volume <30 km $week^{-1}$, *MAS* maximal aerobic speed, *n/a* indicates not measured, *reps* repetitions, *RM* repetition maximum, VO_{2max} maximal aerobic capacity, ↑ indicates increase, ↔ indicates no change

3.2 Plyometrics and Explosive Resistance Training

The concept of movement specificity suggests that the type of resistance training used by runners should closely simulate the movement that will be performed during training and competition [114]. Plyometrics and explosive resistance training are specific forms of strength training that aim to enhance the ability of muscles to generate power by exaggerating the stretch shortening cycle (SSC), using explosive exercises such as jumping, hopping and bounding [31].

3.2.1 *Mechanisms of Improvement Following Plyometric or Explosive Resistance Training*

Plyometric training has the potential to increase the stiffness of the muscle-tendon system, which allows the body to store and utilize elastic energy more efficiently, resulting in decreased ground contact time and reduced energy expenditure [27, 109, 115–117]. Paavolainen et al. [24] indicated that 9 weeks of explosive resistance training improved 5-km run performance (mean 3.1 %) and RE (mean 8.1 %) with no changes in VO_{2max} in 22 moderately trained male runners. Furthermore, significant improvements in velocity over a 20-m sprint (mean 3.4 %), distance jumped (mean 4.6 %), along with a concurrent decrease in stance phase contact times were observed [24]. These variables are thought to represent indirect measures of the neuromuscular system's ability to repeatedly produce rapid force during intense exercise, and the capability to store and utilize elastic energy [24, 98, 99]. The authors suggested that the improved performance was a result of enhanced neuromuscular characteristics and biomechanical efficiency that were transferred into improved muscle power and RE [24].

The importance of the neuromuscular characteristics in determining RE and thereby running performance has also been pointed out previously [27, 118]. Dalleau et al. [118] showed that the energy demand during running is significantly related to the stiffness of the propulsive leg. Similarly, Spurrs et al. [27] demonstrated 6 weeks of plyometric training significantly improved RE, muscle-tendon stiffness, maximal isometric force, rate of force development, jump height, five jump distance and 3-km time trial performance. Plyometric training consisted of 2–3 sessions per week of various unloaded jumps, bounds, and hops. Several other studies (Table 2) have provided support that simultaneous plyometric or explosive resistance training and endurance training improves RE in recreational [29, 31, 91], moderately trained [22, 24, 27, 92, 93, 119, 120], and highly trained runners [25]. Saunders et al. [25] examined the effects of 9 weeks of plyometric training on RE in highly trained runners using loaded and unloaded exercises 3 times per week. The subjects were tested for RE at 14, 16 and 18 km h^{-1} at weeks 5 and 9; however, significant improvements were only found at week 9 for the 18 km h^{-1} test. Other studies have shown improvements in RE after 8 weeks of plyometric training in moderately trained runners with no change in VO_{2max}, [93, 120], with the former study showing a (mean) 7 % improvement in RE and (mean) 5.1 % in 3-km run performance. Proposed explanations for the improvements include increased lower limb stiffness and elastic energy return, enhanced muscle strength and power, or enhanced running mechanics. Recent evidence has also suggested RE can be improved (mean 6.0 %) acutely following a series of warm-up strides with a weighted vest, and this was consistent with improved lower limb stiffness [121]. Turner et al. [31], however, reported no change in four indirect measures of the ability of the muscles to store and return elastic energy despite a (mean) 3 % improvement in RE following 6 weeks of plyometric training in recreational runners. These findings suggest that either more direct measures of potential mechanisms that could improve RE need to be made in future research or other factors are yet to be elucidated as potential mechanisms for enhancing RE following plyometric training.

3.3 Resistance Training Versus Plyometric or Explosive Resistance Training

Paavolainen et al. [24] stated that explosive training, mimicking the eccentric phase of running, is most likely to improve the use of stored elastic energy and motor unit synchronization which increases the ability of the lower-limb joints to act more stiffly on ground contact. Moreover, Millet et al. [96] stated that explosive-strength training leads to different muscular adaptations than does typical heavy weight training; for example, a greater increase in the rate of activation of the motor units. The available data (Table 2), however, suggest that of the six studies [22, 29, 91–93] that included a resistance training and plyometric or explosive resistance training group, four [22, 29, 91, 92] demonstrated greater improvements in RE following traditional resistance training, while one [91] showed no changes in economy in either type of training.

According to Guglielmo et al. [22] when comparing heavy resistance training to explosive resistance training performed on the same equipment, heavy weight training seems to be the more effective mode of training to improve RE. Similarly, Barnes et al. [108] and Sedano et al. [26] have found that a heavy resistance training program was superior to a low-resistance high-speed weight training program at improving RE. Paton and Hopkins [122] came to the same conclusion when reviewing the effects of high-intensity training on performance and physiology in endurance athletes. This is assuming that each of these studies' resistance training programs were matched for volume load and the subjects in each group were matched for training history and ability level.

3.4 Summary

It is reasonable to assume that there are individual responses to various modes of resistance training. However, until more data are collected to describe subject or training characteristics that may identify responders and non-responders to these different modes of resistance training, the current data suggest that traditional resistance training may be superior to plyometric training, but any type of resistance may have a positive effect on RE [114].

While the exact mechanisms responsible for the improved RE following plyometric or explosive resistance training are unclear, the findings to date indicate that improved neuromuscular function likely plays a role in the enhancement in RE and performance. However, this premise is based on indirect measures of neuromuscular function and elastic energy return such as contact times and vertical jump height. Enhancements in strength and power development during isolated tasks (e.g., vertical and forward jumps) may reflect neuromuscular adaptations, but this has not been confirmed by more direct measurements of muscle recruitment, such as EMG activity. Thus it is not possible to infer that these adaptations translate into more efficient muscle recruitment patterns during running or that they are responsible for the enhanced RE following plyometric training. Alternatively, changes in running style that result in more efficient gait patterns, kinematics and kinetics may also improve the economy of runners following plyometric or explosive resistance training. However, the majority of research into kinetics and kinematics of running has been descriptive and changes in biomechanical efficiency may be a result of improved neuromuscular efficiency. Finally, significant improvements in work economy found in cross-country skiers [113, 123–125] and cyclist [126, 127] performing movement specific modes of resistance training may provide evidence that these forms of training may be most beneficial to improving RE and performance; therefore, future studies should examine movement-specific forms of resistance training such as hill running, hypergravity running or running through sand.

4 Altitude Exposure

Interventions to improve RE besides endurance and resistance training are constantly sought after by athletes, coaches and sports scientists; however, there is a paucity of data regarding environmental strategies. Training at altitude offers one potential strategy. Despite altitude exposure being reasonably well-researched over the past few decades, there is still limited data in regard to improving RE; other strategies such as training in heat, cold or humid environments are yet to be examined.

Many athletes undertake some form of altitude training to gain small improvements in physiology and performance. Results from a recent meta-analysis indicate ~1–4 % performance enhancements following various protocols using natural and artificial altitude exposure in highly and moderately trained athletes [128]. Improvements in performance have been primarily attributed to increased hematological parameters leading to an increase in maximal aerobic capacity [40, 129–131]; however, hypoxia-induced enhancements in muscle buffering capacity [58] and RE [42, 43] have also been suggested.

4.1 Altitude Versus Sea-level Natives

Several descriptive, cross-sectional and intervention studies have been conducted in an attempt to highlight differences in RE between altitude natives and individuals residing at sea level with equivocal results. While reporting the physiological characteristics of Kenyan runners living and training at altitude and the Scandinavian runners at sea level, Saltin et al. [132] found that Kenyan runners had 5–15 % lower VO_2 at submaximal running speeds ranging from 10 to 16 km h^{-1} and did not accumulate lactate during running until near peak training intensities. Similarly, Weston et al. [133] reported Kenyan runners had better economy and higher resistance to fatigue while running at the same percentage of VO_{2max} than Caucasian runners. Differences in RE that do exist between various ethnic groups could be related to differences in body mass and mass distribution. Therefore, in running, it has been shown that allometric scaling body mass to the power of 0.67 or 0.75 (e.g., ml $kg^{-0.67}$ min^{-1} or ml $kg^{-0.75}$ min^{-1}) may be more appropriate when comparing RE between individuals with varying body mass [19, 134–144].

One study [145] examining changes in physiological and performance parameters following 46 weeks of training at 2,210 m altitude in sea-level and altitude natives suggested that changes in former sea-level residents may require longer periods at altitude to achieve similar changes in altitude natives. Sea-level natives had significantly poorer RE (mean +6.6 %), lower VO_{2max} (mean −5.9 %) and slower 1.5-mile run time (mean +5.4 %) compared with altitude natives following similar training at altitude. Similarly, Lundby et al. [146] reported that there were no significant changes in RE of sea-level natives after 8 weeks of exposure to 4,100 m compared with altitude natives who had a (mean) 15 % lower submaximal VO_2 than sea-level residents, consistent with the observations of others [132, 133, 147–149].

4.2 Adaptations to Different Hypoxic Environments

In sea-level natives, several studies [37–44, 150, 151] have demonstrated improvements (2–7 %) in RE following different types, ascents and durations of altitude exposure (Table 3). Conversely, an equivocal number of studies have demonstrated that submaximal VO_2 at sea level remains largely unchanged following exposure to different hypoxic environments (Table 3) [129, 131, 146, 152–155].

4.2.1 Blood Parameters

Mechanisms that have been suggested to explain the discrepancy in improvements in economy after altitude exposure have been related to differences in changes in hemoglobin mass and concentration, following hypoxic exposure. While the dosing of hypoxia for the enhancement of the total hemoglobin mass is currently well defined, this does not apply to RE. About 400 h of hypoxia corresponding to an altitude >2,100 m seems to be necessary to increase total hemoglobin mass [43]. In a study by Burtscher et al. [37], the duration of hypoxic exposure was only 30 h during one 5-week period, which unsurprisingly was insufficient to significantly increase total hemoglobin mass, but was adequate for the improvement of RE. The authors did report small increases in hemoglobin concentration and hematocrit, which were closely related to the improvement in RE. An increase in hematocrit results in a linear increase of the oxygen carrying capacity and an exponential increase in blood viscosity [37]. Because blood viscosity is not highly dependent on hematocrit at high cardiac outputs [37], the enhanced oxygen carrying capacity could contribute to the improved RE and performance after hypoxia by reducing the amount of oxygen required for higher heart rates (HRs) and ventilation. Levine and Stray-Gundersen [40] reported that moderately trained runners living at moderate altitude (2,500 m) and training at low altitude (1,250 m) increased red cell mass (9 %) as well as improved VO_{2max} (mean 5 %) and RE (2–5 %) after return to sea level.

4.2.2 Cardiorespiratory Adaptations

The findings from a number of studies suggests that enhancements in RE following hypoxic exposure may be the result of decreased cardiorespiratory costs [decreased minute ventilation (V_E), lower HR] [39, 43, 156], a shift toward a greater glycolytic involvement in ATP regeneration [156], greater carbohydrate utilization during oxidative phosphorylation [58, 157], increased ability of the excitation and contraction processes to perform work at lower energy costs [156, 158], and/or acclimatization-induced transformation of muscle fiber types [156]. One study examining the effects of ~46 nights at 2,860 m simulated altitude on RE and performance prior to the competitive track season found altitude improved RE by 1.0–5.2 %, increased hemoglobin mass by (mean) 4.9 %, and decreased submaximal HR by (mean) 3.1 % [43]. The authors suggest plausible mechanisms for improved RE include a decrease in the ATP cost of muscle contraction, or a decrease in the cardiorespiratory cost of O_2 transport. Another recent study demonstrated that 11–14 h a day for 17–24 days of normobaric hypoxia (2,500–3,500 m) improved RE by (mean) 7 % [44]. The authors suggested that changes in substrate utilization and lower cardiorespiratory costs contributed to the improved RE, which is supported by the increased submaximal respiratory exchange ratio (RER) and the decreased V_E and HR values within the experimental groups. More recently, it was demonstrated that 3 h per day for 2 weeks of intermittent exposure to normobaric hypoxia (equivalent of 4,500 m) improved RE by (mean) 2.6 % (14 km h^{-1}) and (mean) 2.9 % (16 km h^{-1}). The improved RE was accompanied by a decreased HR (mean 3.3 and 3.9 % at 14 and 16 km h^{-1}, respectively) and a trend towards improved 3,000-m run time (mean 1.3 %) [39].

The findings from other studies indicate that a small shift in substrate metabolism towards an increase in carbohydrate use and lower cardiorespiratory costs, such as decreased V_E and HR contributed to the improved RE after a period of altitude exposure [37, 44]. Both studies reported an improvement in RE (mean 2.3 % [37] and 7.7 % [44]) with an accompanying shift towards carbohydrate metabolism. The former study reported that two 5-week periods of intermittent hypoxia (3,200–5,500 m) 3 days per week for 2 h each day improved RE only during the first 5-week period of intermittent hypoxia when compared with training alone. Although RE continuously improved during the 13-week study period, no further changes occurred after the first 5-week period. These findings suggest that the first 5-week intermittent hypoxia exposure was responsible for the initial improvement in RE and the run training during the following 8 weeks was responsible for maintaining the enhancements in economy. These results emphasize the importance of the training phase on the effectiveness of altitude exposure on RE.

4.2.3 Metabolic Efficiency

Results from other studies [42, 158] suggest the physiological mechanisms eliciting an improved RE in highly trained runners after hypoxic exposure appear unrelated to decreased ventilation or a substantial shift in substrate use.

Table 3 Comparison of effects on running economy and performance following adaptation to hypoxia experienced in studies with various protocols of natural and artificial altitude

References	Subjects	Altitude type[a]	Intervention	Control	Results (%)	
					Running economy	Performance (distance)
Telford et al. [154]	18 highly trained male runners	Natural altitude, LHTH	4 weeks at 1,700–2,000 m, 24 h/day	LLTL	↔	↑ 2 (3.2-km)
Levine and Stray-Gundersen [40]	26 moderately trained male/female runners	Natural altitude, LHTL	4 weeks at 2,500 m, 16–20 h/day	LLTL	↑ 4.8	↑ 1.4 (5-km)
	26 moderately trained male/female runners	Natural altitude, LHTH	4 weeks at 2,500 m, 24 h/day	LLTL	↑ 2.8	↔ (5-km)
Bailey et al. [150]	23 moderately trained male/female runners	Natural altitude, LHTH	4 weeks at 1,500–2,000 m, 24 h/day	LLTL	↔	n/a
Stray-Gundersen et al. [131]	22 highly trained male/female runners	Natural altitude, LHTH	27 days at 2,500 m, 24 h/day	No control	↔	↑ 1.1 (3-km)
Katayama et al. [38]	12 highly trained male runners	Simulated altitude, LHTL	3 days/week for 3 weeks at 4,500 m, 90 min/day	LLTL	↑ 3.3	↑ 1 (3-km)
Julian et al. [152]	14 highly trained male/female runners	Simulated altitude, LHTL	5 days/week for 4 weeks at 3,600–5,000 m, 70 min/day	LLTL	↔	↔ (3-km)
Katayama et al. [39]	15 highly trained male runners	Simulated altitude, LHTL	14 days at 4,500 m, 3 h/day	LLTL	↑ 2.9	↑ 1.3 (3-km)
Saunders et al. [42]	10 highly trained male runners	Artificial altitude, LHTL	5 days/week for 4 weeks at 2,000–3,100 m, 9–12 h/day	LLTL	↑ 3.3	n/a
	10 highly trained male runners	Natural altitude, LHTL	5 days/week for 4 weeks at 2,000–3,100 m, 9–12 h/day	LLTL	↔	n/a
Schmitt et al. [44]	11 moderately trained male runners	Natural altitude, LHTL	17–24 days at 2,500–3,500 m, 11–14 h/day	LLTL	↑ 7.0	n/a
Lundby et al. [146]	24 highly trained male/female runners	Natural altitude, LHTH	4 week at 2,500–2,850 m, 24 h/day	No control	↔	n/a
Neya et al. [41]	16 highly trained male runners	Artificial altitude, LHTL	29 days at 3,000 m, 11 h/day	LLTL	↑ 5.5	n/a
	15 highly trained male runners	Artificial altitude, LHTH	29 days at 3,000 m, 11 h/day	LLTL	↔	n/a
Truijens et al. [155]	10 moderately trained male/female runners	Artificial altitude, LHTL	5 days/week for 4,000–5,500 m, 3 h/day	LLTL	↔	n/a
Saunders et al. [43]	18 highly trained runners	Artificial altitude, LHTL	46 days at 2,860 m, 9 h/day	LLTL	↑ 3.2	↑ 1.9 (1,500-m)
Burtscher et al. [37]	11 moderately trained male/female runners	Artificial altitude, LHTL	3 days/week for 2 × 5 weeks at 3,200–5,500 m, 2 h/day	LLTL	↑ 2.3	↑ 31 (time to exhaustion at MAS)

Table 3 continued

References	Subjects	Altitude type[a]	Intervention	Control	Results (%)	
					Running economy	Performance (distance)
Robertson et al. [153]	8 highly trained male/female runners	Artificial altitude, LHTL + TH	3 weeks at 3,000 m, 14 h/day + 4 days/week training at 2,200 m	No control	↔	↑ 1.1 (3-km)
	9 highly trained male/female runners	Artificial altitude, LLTH	4 days/week for 3 weeks training at 2,200 m	No control	↔	↔ (3-km)
	16 highly trained male/female runners	Artificial altitude, LHTL	3 weeks training at 3,000 m, 14 h/day	LLTL	↔	↑ 1.9 (3-km)

Highly trained national/international level and VO_{2max} >65 ml kg^{-1} min^{-1}, *moderately trained* weekly running volume >30 km $week^{-1}$, *LHTH* live high train low, *LHTL* live high train low, *LLTH* live low train high, *LLTL* live low train low, *MAS* maximal aerobic speed, *n/a* indicates not measured, *TH* train high, *VO_{2max}* maximal aerobic capacity, ↑ indicates increase, ↔ indicates no change

[a] See Bonetti and Hopkins [128] for definitions of natural and artificial altitude, sea-level, low, moderate and high altitude

Therefore, it is possible that the main mechanisms responsible for improved RE at sea level after a period of altitude exposure are either an increase in the ATP production per mole of oxygen used and/or a decrease in the ATP cost of muscle contraction; however, currently, there is no direct evidence to support these claims. Katayama et al. [38, 159] have demonstrated on two occasions that intermittent hypoxic exposure improves RE in highly trained runners without changes in ventilation, suggesting other mechanisms may be responsible for the changes in economy. The first study reported that simulated hypoxic exposure using intermittent hypobaria of 4,500 m 3 h per day for 14 consecutive days improved RE by (mean) 2.6 % (14 km h^{-1}) and (mean) 3.3 % (16 km h^{-1}), improved 3,000-m run time by 1 % and time to exhaustion on the treadmill by 2.7 % [38]. Another recent study demonstrated that 20 days of live high (simulated altitude 2,000–3,100 m) train low improved RE (mean 3.3 %) in the absence of any changes in V_E, RER, HR or hemoglobin mass [42]. There was also no evidence of an increase in lactate concentration after the live-high train-low intervention, suggesting that the lower aerobic demand of running was not attributable to an increased anaerobic energy contribution. Green et al. [156] suggested a reduced energy requirement of one or more processes involved in excitation and contraction of the working muscles could be a result of a reduction in by-product accumulation, such as adenosine diphosphate (ADP), inorganic phosphate or H^+ that occurs after altitude acclimatization. Such changes increase the amount of free energy released from ATP hydrolysis and depress the need to maintain hydrolysis rates at pre-acclimatized levels [60].

4.2.4 *Muscle Fiber Type*

It has been shown that the type I muscle fibers are considerably more efficient than type II muscle fibers. Acclimatization-induced transformation of fiber types could conceivably underlie changes in neuromuscular efficiency and subsequently RE; however, this is yet to be studied in runners.

4.3 Other Environmental Strategies

Several other environmental strategies have been previously identified as feasible strategies to improve RE, such as training in the heat [6, 10, 160] or cold and altering training surface [161], but have yet to be examined in the literature.

4.4 Summary

The literature indicates that altitude exposure for runners has no detrimental effects on RE and that there is good evidence to suggest that it may lead to worthwhile improvements in RE at sea level. Altitude acclimatization results in both central and peripheral adaptations that improve oxygen delivery and utilization and enhance metabolic efficiency; mechanisms that could potentially explain the changes in RE. Many of the studies that did not find an improvement in RE (Table 3) after altitude exposure were performed close to the competition season, which emphasizes the importance of timing and training phase on the effectiveness of altitude exposure on RE.

5 Flexibility and Stretching

5.1 Flexibility

There appears to be equivocal results in regard to the effects of stretching or flexibility on RE. Some researchers have identified an inverse relationship between flexibility and RE; that is, less flexibility is associated with better RE [45, 46, 48, 49, 162]. Gleim et al. [46] tested 100 male and female subjects over a range of speeds from 3 to 12 km h^{-1} and found that those who exhibited less flexibility in a battery of 11 trunk and lower limb flexibility tests were most economical. These results suggest that the inflexibility of the lower limbs and trunk musculature as well as limited range of motion around the joints of the lower body allow for greater elastic energy storage and use in the muscles and tendons during the running gait [46, 49]. Specifically, it was suggested that inflexibility in the transverse and frontal planes of the trunk and hip regions of the body may stabilize the pelvis at the time of foot impact with the ground, reducing excessive range of motion and metabolically expensive stabilizing muscular activity [46]. Furthermore, research has demonstrated that runners with tighter or stiffer musculotendonous structures store more elastic energy in their lower limbs, resulting in a lower VO_2 at submaximal running velocities [45, 46, 49, 163].

In contrast, other research fails to support the existence of an inverse relationship, countering that flexibility is an essential component of distance running performance [47, 164–166]. Godges et al. [47] found improved RE at 40, 60 and 80 % VO_{2max} in response to static stretching procedures in seven moderately trained athletic male college students when flexibility increased. They reported a reduced aerobic demand of running at all speeds when hip flexion and extension were increased [47]. Improved hip flexibility, myofascial balance, and pelvic symmetry due to stretching are thought to enhance neuromuscular balance and contraction, thus leading to a lower submaximal VO_2 and improved RE. These results corroborate general beliefs that improved flexibility is desirable for optimal running performance.

5.2 Stretching

Conflicting results among stretching studies may be associated with limitations in methodological design. Several studies [46, 47, 166] did not employ an adequate treadmill accommodation period; therefore, improvements in RE may have been associated with familiarization with treadmill running [45]. Furthermore, subjects were not described as runners of any caliber in several studies [46, 47, 164, 166]. Therefore, a lack of familiarity with treadmill running mechanics may have made economy measures invalid in these studies. Additionally, some studies [46, 162, 164] have combined male and female results in the analyses; because females are generally more flexible [162] and less economical than males [19], the true association between economy and flexibility may be difficult to discern if sexes are not studied separately. Finally, a recent systematic review concluded that an acute bout of stretching may improve RE, but regular stretching prior to running over time has no effect on economy [167].

5.3 Summary

Overall these findings suggest that an increase in the stiffness of lower body musculotendinous structures appears to improve RE. However, stretching should not be discounted as a training modality, because stretching exercises are commonly prescribed for runners to facilitate injury prevention and maximize stride length [10, 168].

6 Nutritional Interventions

Beyond the typical endurance athlete preparation, which features large amounts of aerobic training, HIT, resistance and/or plyometric training, and various environmental exposures during a periodized season [169], several nutritional interventions have received attention for their effects on reducing oxygen demand during exercise, most notably dietary nitrates.

6.1 Dietary Nitrates

Nitric oxide (NO) is an important physiological signaling molecule that can modulate skeletal muscle function through its role in the regulation of blood flow, muscle contractility, glucose and calcium homeostasis, and mitochondrial respiration and biogenesis [53]. It is now known that tissue concentrations of nitrate (NO_3^-) and nitrite (NO_2^-) can be increased by dietary means. Green leafy vegetables such as lettuce, spinach, rocket, celery and beetroot are particularly rich in nitrate. Therefore dietary nitrate supplementation represents a practical method to increase circulating plasma nitrite and thus nitric oxide to lower the oxygen demand of submaximal exercise (i.e., enhances metabolic efficiency and subsequently RE) and potentially enhance running performance [53, 170–176]. The physiological mechanisms responsible for the reduced oxygen demand following nitrate supplementation could result from two different mechanisms. First, a lower ATP cost of muscle contraction for the same force production (i.e., improved muscle contractile efficiency via sarcoplasmic reticulum calcium handling or actin-myosin interaction), or second, a lower oxygen consumption for the same rate of oxidative ATP resynthesis (i.e., enhanced mitochondrial efficiency via improved oxidative phosphorylation) [53, 170, 171].

While only one study to date has demonstrated an improved RE [54] following nitrate supplementation, a reduced oxygen demand and improved work efficiency has been reported for several other types of exercise, including cycling [175–178], walking [54], and knee extension exercise [174, 179]. Larsen et al. [176] reported that 3 days of sodium nitrate supplementation increased plasma nitrite and reduced the oxygen demand of submaximal cycling exercise. These findings were corroborated in a study by Bailey et al. [175] in which nitrate was administered in the form of beetroot juice. The reduction in VO_2 after nitrate supplementation was of the order of 5 % in the studies of Larsen et al. [176] and Bailey et al. [175], in which supplementation was continued for 3–6 days. A similar reduction in steady-state VO_2 has been reported following acute nitrate supplementation. Vanhatalo et al. [178] reported a significant reduction in steady-state VO_2 just 2.5 h following beetroot juice ingestion.

6.2 Other Nutritional Interventions

There is a paucity of data examining the effects of other dietary interventions on RE. One investigation found 4 weeks of oral *Echinacea* supplementation had a trivial enhancement (mean 1.7 %) on RE [55]. However, the margin of improvement was well within the normal variation in RE (typical error of 2.4 % [180]) and could have occurred by chance. Results from a study examining caffeine ingestion in cross-country runners suggest that the ingestion of caffeine at 7 mg kg^{-1} of body weight prior to submaximal running might provide a modest ergogenic effect via improved respiratory efficiency and a psychological lift [52]. Combined creatine and glycerol ingestion has been shown to be an effective means in reducing thermal and cardiovascular strain during exercise in the heat, without negatively impacting on RE [51].

6.3 Summary

Although dietary nitrate appears to be a promising ergogenic aid, additional research is required to determine the scope of its effects on well-trained distance runners and across different competition events. Future research should also examine the efficacy of using other nutritional interventions to enhance RE.

7 Conclusions and Future Directions

A variety of training strategies have been adopted in an attempt to improve RE by modifying one or more factors that influence metabolic, biomechanical and/or neuromuscular efficiency. The most common strategies used are resistance training, plyometric training and explosive resistance training. Each of these modes of ancillary training have been reported to improve RE in recreational, moderately trained, and highly trained runners through primarily neuromuscular mechanisms. Results from HIT studies are unclear, but the best results to improve RE appear to occur when training at near maximal or supramaximal intensities on flat or uphill terrain. Adaptations to living and training at natural and artificial altitude have been primarily attributed to increased hematological parameters that improve RE. There appears to be equivocal results regarding the effects of stretching or flexibility on RE. Ingestion of dietary nitrate, especially in the form of beetroot juice, also appears to hold promise as a natural means to improve RE. From a practical standpoint, it is clear that training and passive interventions affect RE, and researchers should concentrate their investigative efforts on more fully understanding the types and mechanisms which affect RE and the practicality and extent to which RE can be improved outside the laboratory.

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