Running economy and performance. High and low intensity efforts during training and warm-up. A bibliographic review

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Summary

Interest in relation to running economy has increased such as determinant of running performance in scientific literature in trained long and middle distance runners and recreational runners. Trained runners are more efficient than untrained runners, meaning it is a "trainable" parameter. A key factor during endurance training is the intensity of corresponding effort, characterized by two endurance training methods such as interval and continuous training. In recreational runners, there is some controversy about which intensities are optimal in order to improve running economy, thus, periodized endurance training with a logical relationship between high and low-intensity training is recommended. We recommend the inclusion of 2-3 session per week of interval training, compensated with continuous training. Regarding to trained runners, interval training (at intensities close to VO_2max) will be more important because of the need to be more economical at competitive intensities. Very high training intensities would not lead improvements in running economy due to it is not posible to accumulate enough training volumen during the training period. Conversely, the high-intensity efforts prior to competition (intensities above anaerobic threshold), during a warm-up protocol, increase the energy cost (reduce the running economy) and therefore, it is recommended a long transient phase (9-20 min) before to competition so as not to disturb the subsequent performance. An increase of scientific studies regarding the effects of high-intensity efforts during a warm-up protocol is needed in order to know the optimal intensities, flat or uphill ground, or the adequate recovery to improve the subsequent performance.

Key words:
Endurance training. Energy cost. Runner. High intensity.

Economía de carrera y rendimiento. Esfuerzos de alta y baja intensidad en el entrenamiento y calentamiento. Revisión bibliográfica

Resumen

La economía de carrera ha crecido en importancia en la literatura científica como factor de rendimiento en corredores de fondo y medio fondo tanto de alto nivel como recreacional. Los atletas entrenados son más económicos que aquellos no entrenados, mostrando que es una variable que se mejora con el entrenamiento. Un factor clave en la selección del entrenamiento de resistencia es la intensidad del esfuerzo a realizar, principalmente caracterizado por dos métodos de entrenamientos como son el interválico y el continuo. En corredores de nivel recreacional, existe cierta controversia en relación a qué intensidades son las óptimas para mejorar la economía de carrera, recomendándose la realización de entrenamiento periodizado y exista una lógica relación entre entrenamiento de alta y baja intensidad. Recomendamos la inclusión de 2-3 sesiones semanales de entrenamiento interválico, compensado con entrenamiento continuo. En cuanto a los corredores entrenados de más nivel, el entrenamiento interválico cobra mayor importancia (intensidades cercanas al VO_2max) dado que la realización de esfuerzos de mayor intensidad provocará que sean más económicos a intensidades de competición. Intensidades de entrenamiento muy altas no conllevarán mejoras en la economía de carrera debido a que no es posible acumular suficiente volumen de entrenamiento. Por otro lado, los esfuerzos de alta intensidad previos a la competición (intensidades superiores al umbral anaeróbico), es decir, durante el calentamiento, aumentan el coste de energía (reducción de la economía de carrera) y, por lo tanto, se recomienda una amplia fase de transición entre tales esfuerzos y la competición (entre 9-20 min), para que el rendimiento no se vea perturbado. Se recomienda un aumento en el aporte científico en relación a los efectos de esfuerzos de alta intensidad durante el calentamiento, con el fin de conocer qué intensidades son más óptimas, el terreno a utilizar (llano o pendiente), o la recuperación necesaria para mejorar el rendimiento.

Palabras clave:
Entrenamiento de resistencia. Coste de energía. Corredor. Alta intensidad.

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Introduction

Endurance sports call for a certain amount of exertion over a long period of time. Hill and Lupton[1] were already discussing Maximal Oxygen Uptake (VO_2max) and its importance to sports performance in scientific publications back in the 1920s. Their view has come to be accepted over the years and in more recent times further physiological factors which may affect performance in endurance sports have been advanced. In addition to VO_2max, both the anaerobic threshold (AT)[2,3] and running economy (RE)[4,5] have been documented and incorporated as determinants of performance in endurance sports, especially long- and middle-distance running[6]. Although differences in VO_2max can be observed between distinct populations and sports, such differences cannot be identified so well when focusing on elite runners. Daniels[7] was puzzled to find athletes with comparatively low VO_2max values achieving better times and performing better in competitions than others with higher VO_2max values. This could be explained by RE. Athletes with poor RE values tend to have higher VO_2max values (inverse relationship), it being possible to improve RE and see VO_2max negatively impacted[8,9]. In highly trained athletes, a weak-to-moderate relationship was found between RE and VO_2max[10]. While such variables as VO_2max have been widely studied as a determining factor in runners, RE was ignored until a few decades ago, but has gradually grown in importance in the scientific literature since the 1970s[11].

RE is the result of the complex interplay of multiple factors. Of these, we could single out biomechanical variables[12], neuromuscular variables such as leg stiffness, exposure to periods of training at altitude and anthropometric variables[6]. In this review, we will explain what running economy is and the ways in which it is measured, and will centre on endurance training through the use of two training methods, continuous and interval training, and consequently high- and low-intensity exercise, and their relationship with RE. High-intensity work (interval method) shall be understood as intensities over the anaerobic threshold, i.e. over 85-90% of vVO_2max and maximum HR. Low-intensity work, consequently, shall be understood as intensities below these limits. Finally, we will discuss the impact of high- and low-intensity exercise in warm-ups prior to competitions or performance testing, and the relationship with RE.

Running economy. Definition and evaluation methods

Running economy (RE) is generally used to refer to the steady-state consumption of oxygen at a certain running speed[4,13,14] and expresses the energy expenditure required to perform at this intensity. The economy of effort is a variable which has been used to evaluate endurance sports in the scientific literature[15]. There are currently several ways to measure RE. The main, most commonly used method in articles is oxygen cost. Given that it is necessary to ascertain the subject's oxygen consumption (VO_2) during the exercise in order to measure RE, oxygen cost is the easiest way to find out his/her RE. Since steady-state VO_2 is needed to quantify RE, the intensities selected should be below the lactate threshold[4,16] and the blood lactate concentration should be similar to basal levels[17]. A respiratory exchange ratio of less than 1 at the selected running speeds is another easy way to know that the subject has attained steady state[4]. This respiratory exchange ratio is the relationship between the consumption of CO_2 and O_2, and can be used to determine energy use, energy production and the energy cost of an activity. Measuring RE as oxygen cost, however, does not take into account changes in the energy substrate used at the running speed. For this reason, Fletcher *et al.*[18] compared two ways of measuring RE, as oxygen cost and as energy cost, and concluded that the latter was more sensitive to changes in intensity and, therefore, more correct. The running speed most used to measure RE in the literature is 16 km h^{-1}, although a range between 12 and 21 km h^{-1} has been used in different studies depending on the level of the sample used[4,6,19]. In a recent review, Barnes and Kilding[20] established a range of speeds at which to measure RE depending on the level of the sample based on VO_2max values: for recreational athletes (54.2-62.2 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$), the speed would be 10-14 $km{\cdot}h^{-1}$; for moderately trained runners (62.2-70.8 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$), 12-16 $km{\cdot}h^{-1}$; for highly trained runners (70.8-75.4 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$), 12-20 $km{\cdot}h^{-1}$ and for elite runners (> 75.4 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$), 14-20 $km{\cdot}h^{-1}$.

Running economy and its relationship with performance

The scientific literature has documented the relationship between RE and performance in long- and middle-distance runners quite well. Recently, Hoogkamer *et al.*[21] reached the conclusion that changes in RE led directly to changes in performance. These authors registered changes in RE and performance with increasingly heavy sports footwear. They concluded that increments of 100 g. in footwear weight worsened RE by 1.1% and this reduced performance by 0.78% in a 3,000 m. run. This means that any change which affects RE may also affect the end result of a competition. For example, Kenyan runners have small gastrocnemius muscles compared to European athletes and have less weight away from the axis of movement of their legs. As a result, they have a lower moment of inertia and require less muscular effort to move their legs[22], as could happen with the heavier footwear. Previously, Pollock[19] observed differences in RE between elite runners (runners with times of less than 30 minutes in a 6-mile test, according to the author's definition) and good runners, establishing the categories by performance level, proving more economical those who performed the best. Subsequently, Conley and Kranhenbuhl[4] established RE as a good predictor of performance over 10 km., those athletes with better performance proving to be the most economical (r = 0.83). Later, di Prampero *et al.*[23] found that an improvement of 5% in RE meant an improvement of 3.8% in performance. Meanwhile, focusing on the changes produced over a prolonged period of training, Svedenhag and Sjodin[24] observed improvements in RE (-1.0 ± 0.3 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ per year) after a long period of training (approximately 22 months) and, at the same time, improvements in performance over 5,000 m. without observing changes in VO_2max. This tells us that, in trained runners, a situation can arise in which no changes in VO_2max are observed, but changes in performance are. One of the causes of this could be the improvements in RE and the speed at which VO_2max (vVO_2max) is achieved, as Morgan *et al.*[16] observed, RE and vVO_2max serving as reliable predictors of performance over 10 km.

A clear example of the relationship between RE and performance is the progression of the athlete Paula Radcliffe, the holder of the marathon world record (2h15:25). Jones[25] studied her physiological changes over more than 10 years. He saw that her RE improved by 15% (from 205 $ml \cdot kg^{1} \cdot km^{-1}$ in 1992 to 175 $ml \cdot kg^{-1} \cdot km^{-1}$ in 2003) during this time, improving all her times from 5,000 m to marathon. Similarly, the American athlete Steve Scott, who held the world record for the mile, improved his RE by 5% over a period of training[26]. There exists consensus in the scientific literature regarding the importance of RE as a performance factor and that improving it is key to improving the performance of runners. As we can see, RE is a variable which changes according to a runner's training, but it is essential to know what type of training is the most suitable for improvement and why. Tables 1 and 2 describe several studies which have observed improvements in RE accompanied by improvements in the performance tests used in each case, showing a relationship between RE and improvement in performance.

Endurance training and running economy

We know how endurance training affects the body. Improvements have been noted in the cardiorespiratory system and skeletal muscle oxidative capacity[27,28]. At the same time, the improvement in oxidative capacity is associated with an improved mitochondrial function[6,29] and this entails a reduction in the oxygen use needed to work at submaximal intensity[30], thus improving RE. There are also changes in the skeletal muscle buffering capacity[31] and at blood level[32]. Although the mechanisms involved in the relationship between buffering capacity and improvements in mechanical efficiency are not clear, these processes have been observed following training at altitude. It may be due to a more marked use of carbohydrate oxidation compared to fat oxidation[31]. Haematologically, increases in the mass of red blood cells and a relationship with improvements in RE have been observed[32]. Regarding endurance training and its effects on RE, it has been well established in the scientific literature that trained athletes are more economical than those less trained[33].

Two endurance training methods are commonly used today by coaches and athletes all over the world: interval training and continuous training. Interval training (INT) was first used in the 1920s by the Finnish athlete Paavo Nurmi[34]. He won numerous long- and middle-distance medals at the 1920, 1924 and 1928 Olympic Games. But it was not until a few years later, in the 1930s, that a coach and a doctor (Gerschler and Reindell), both German, introduced the term "interval training" and it started to become better known in other parts of the world[34]. This method can be defined as a series of repeated bouts of exercise lasting a short to moderate period of time (between 10 seconds and 5 minutes) completed at an intensity higher than the anaerobic threshold[35,36]. The peculiarity of this method is that there exist a multitude of variants depending on the length of the stimulus, the length of recovery following the stimulus and the number of repetitions and series of the stimulus carried out. A total of nine variables can be altered in this method to change its effects[37]. The intensity and duration of the intervals are key factors, while the number of intervals and the number of series they comprise, the recovery between intervals and series, and the type of exercise all influence the final outcome. Hetlelid and Seiler[38] studied 6x4 min. at the maximum intensity possible for the session and task in which the only difference was the length of recovery between repetitions (1, 2 and 4 min), which modified the running intensity. Switching from a recovery time of 1 min. to one of 2 min. led to an increase in intensity, but changing from 2 to 4 min. did not. VO_2 worked more with 2 min. of recovery, but the blood lactate concentration did not change. Surprisingly, when they let the subjects choose the recovery time between repetitions, they chose something close to 2 min. (118 ± 23s). This is a clear indication of how complex manipulating the variables which affect the INT training method is.

The continuous training method (CON), on the other hand, is characterised by lower-intensity work without pause, i.e. continuous work at an intensity beneath the anaerobic threshold. The main difference, therefore, between the two methods is the intensity of effort during training and this may be the key to the modifications and improvements which take place in the body.

Regarding altering the volume and intensity of training, there is no evidence yet of a relationship between more training (chiefly using the CON method as a large percentage of training) and better RE. What intensities, therefore, are optimal for improvement and what combination of intensities and, consequently, training methods is the most suitable?

The scientific literature tells us that intensities near the speed at which maximal oxygen uptake is achieved have commonly been employed in endurance training using the INT method. INT training with recreational athletes (Table 1) at intensities between 93% and 106% of VO_2max[39], and between 90% and 95% of maximum heart rate[40,41] (HRmax) has registered RE improvements of 1 to 9%. Other authors, however, have not found improvements in RE after INT training. Gliemann *et al.*[42] found no changes in RE after 8 weeks with two sessions/week of INT training (alternating 10-20-30s at intensities of 30%, 60% and 90-100% of maximum running speed). González-Mohíno *et al.*[9] did not observe RE improvements after INT training at 95-110% of vVO_2max.

Turning to CON training, a single low-intensity training session produces no change in RE[43,44], meaning that a long training period is needed to produce changes. Zaton and Michalik[45] noted significant improvements in RE (17%) following 3-4 sessions of CON a week (voluntary

Table 1. Effects of interval and continuous training on the running economy and performance of recreational athletes. Participants, design and results.

Study	Participants	Research design			Results	
	Description	Interval training (n)	Continuous training (n)	Duration (sessions/week)	RE	Performance
Franch *et al.*(1988)	n = 36 M; 30,4 y.o.; 54,8 ml·kg^{-1}·min^{-1}; Recreational athletes	Long (12) 4x4 min. with 2 min. recovery, Short (12) 30-40x 15 sec. with 15 sec. recovery	20-30 min. at 15km/h	2-3 days/week for 6 weeks	↑ 3.1% CON;↑ 3.0% LONG; ↑ 0.9% SHORT	T-Lim at 87% vVO_2max: ↑ 94% CON; ↑ 67% LONG; ↑ 65% SHORT
Sproule (1998)	n= 15 M; 23 y.o.; 56 ml·kg^{-1}·min^{-1}; PE students		Acute effect of 40-60 min. sessions at 70% VO_2max. G1 40 min. at 80%; G2 60 min. at 70%; G3 60 min. at 80%	3x40-60 min. at 80% VO_2max.	↓4.4% (G1); 6.6% (G2); 9.5% (G3)	
Beneke y Hutler (2005)	n=16 M; 24.8 y.o.; n/a ml·kg^{-1}·min^{-1}; Recreational athletes		CON training for 20-30 min. for first 4 weeks (intensity 50% HR reserve) increased to 45-60 min. in weeks 5-8 (60-75% reserve HR).	8 weeks: 3 sessions in week 1, 4 in weeks 2-6 and 5 in weeks 7 & 8.	↑ 10% CON	↑ 56% CON
Helgerud *et al.* (2007)	n = 40 M; 24.6 y.o.; 57.8 ml·kg^{-1}·min^{-1}; Students	Long (10) 4x4 min. at 90-95% HRmax with 3min. rec. at 70% HRmax, Short (10) 47x15s at 95% HRmax with 15 sec. rec. at 70% HRmax	Slow pace (10) 45 min. at 70% HRmax, anaerobic threshold pace (10) 25 min. at 85% HRmax	3 days/week for 8 weeks	No diff. between groups: ↑7,5-11,7%	
Quinn y Manley (2012)	n = 15 M 35.3 y.o.; 63.6 ml·kg^{-1}·min^{-1}; Healthy participants		Effect of long continuous training (26 km.).	Acute effect 1 session	No changes in subsequent days.	
Zaton y Michalik (2015)	n = 17 (11M, 6W); 34 y.o.; 50.7 ml·kg^{-1}·min^{-1}; Recreational athletes	G1 did 2 sessions of 4x20-30 sec. at max. intensity to complete 90-200 m. with active recovery (ratio 2:1) plus one continuous training session per week	G2: 3-4 sessions of continuous training per week without specifying intensity.	8 weeks	↑17% significant in relative VO_2max% in G2	↑2,5% in G1 ↑1,3% in G2 in Cooper Test
Gliemann *et al.* (2015)	n = 160 (73M, 84W); 47y.o.; 52,3 ml·kg^{-1}·min^{-1}; Recreational athletes	2 sessions of 3-4 x 5 min. alternating 10-20-30 sec. with 2 min. rec. Intensity of 30%, 60%, 90-100% maximal speed + 1 CON session (75-85% HRmax).	3 sessions per week at intensity 75-85% HRmax	8 weeks	↓2,85% INT, ↓ 1,95% CON	~
González-Mohíno *et al.* (2016)	n = 11 H; 33,1 y.o.; 56,7 ml·kg^{-1}·min^{-1}; Recreational athletes	3 sessions/week of repetitions of 1, 2 and 3 min. at 110%, 100% and 95% vVO_2max	3 sessions/week at 70% and 75% vVO_2max	6 weeks	↑ 17.8 and 8.5% CON sig. at 60% and 90% vVO_2max	vVO_2max ↑ 7,9% INT
Hoydal y Hareide (2016)	n = 22 (8M, 14W); 27,7 y.o.; 51,7 ml·kg^{-1}·min^{-1}; Healthy participants	4x4 min. (11) at 90-95% HRmax, 3 min. active recovery at 70%	75 min. (11) at 75% HRmax	3 days/week for 8 weeks	↑ 6% INT; 9% CON	3000 m: ↑ 3,06 min and 1,59 min (INT, CON)

Symbols: ↑ increase or improvement; ↓ decrease or deterioration; ~ no change.
Abbreviations: M: Men; W: Women; y.o.: Years old; n: Number of participants; PE: Physical Education; G: Group; HRmax: Maximum heart rate; CON: Continuous method; INT: Interval method; VO_2max: Maximal oxygen uptake; vVO_2max: Speed at maximal oxygen uptake intensity; T-Lim: Time to exhaustion; n/a: Not available.

intensity dictated by the subject). Intensities of 50% to 75% HR reserve[46], 70-85% maximum HR[40,41] and 70-75% of vVO_2max[9] have also produced RE improvements, although some authors have failed to observe changes at intensities of 75% to 80% maximum HR[42]. However, sessions of 40 to 60 min. at intensities between 70% and 80% of VO_2max evaluated as acute effect led to a reduction in RE in Physical Education students[44], showing that it is not advisable to evaluate RE after training sessions.

RE improvements in recreational runners could be due to biomechanical changes which make them more economical at the same running speed[47]. Hence the need to include biomechanical variables in the evaluations of recreational athletes when studying changes in RE.

Table 1 shows the studies of recreational athletes analysed in this section. Note the wide range of protocols used and results obtained in the different studies.

In trained athletes, INT training intensities of 100% vVO_2max[48,49] have obtained improvements of between 1 and 6.7%. Other high-intensity exercises, such as maximum sprints lasting 30 seconds[50], have revealed improvements of 6-7.2% and intensities of vΔ50[51-53] (intensity corresponding to 50% between speed at lactate threshold (vLT) and vVO_2max) have shown RE improvements of 3.6 to 5.4%. High-intensity training can also be carried out on terrain with different gradients. Intensities of 80% to 120% VO_2max[54] (4-18% gradient) have shown improvements in RE.

Billat *et al*[55], on the other hand, investigated the effect of increasing the number of INT training sessions at 100% vVO_2max from 1 to 3, combined with 5 and 3 CON sessions, respectively, and its influence on RE. These authors noted an increase of 6% in RE with a single session of INT training, compared to a 2.7% increase when the sessions were raised to 3 per week and the CON training was reduced. This means that the relationship between high-intensity (INT) and low-intensity (CON) sessions is essential when it comes to improving the RE of trained runners. Enoksen *et al.*[56] conducted a study in which an INT training group did 33% of all its training using the INT method (3 sessions/week) at 82-92% HRmax and used the CON method at 65-82% HRmax for the rest. The CON training group did 13% of all its training with the INT method (1 session/week) and used the CON method at 65-82% HRmax for the rest. Both groups' RE improved: between 2.5% and 5% in the INT group, and between 1.5% and 4.8% in the CON group. Finally, it is important to note that very high training intensities (132% vVO_2max) do not lead to improvements in RE[39], possibly because they seriously limit the volume of training achievable. INT training and its acute effect on RE has also been studied. Collins *et al*.[57] evaluated the effect of three sessions of 10x400 with different recovery times (1, 2 and 3 min.). In all the sessions, RE suffered from 2 to 5%, indicating that RE should not be evaluated after training sessions, because high-intensity sessions increase the subsequent energy cost in the runner.

With the CON training method, training at vOBLA intensity[58,59] (intensity at which 4 mmol/L is produced in the body) has registered RE improvements of 2.8%. Table 2 shows the studies of trained athletes analysed in this section, describing the protocols used and results obtained in each study.

As can be seen, the RE improvements are proportionally higher in recreational athletes compared to trained athletes, reflecting the complexity of improving athletic performance through training at high levels. We can also see that, at high levels of performance, small improvements in any performance factor can be decisive to the final outcome.

Finally, it is important to note that athletes are normally more economical at the intensities at which they train[60], so it would be interesting to include intensities similar to competition intensities. Changes in RE depend on the intensity of training. In a comparative study of middle-distance and marathon runners by Daniels and Daniels[61], the results showed that the athletes were more economical at the intensities at which they compete (1,500 m or marathon). Therefore, these competition intensities, which will be high intensity, would lean us towards INT training to work at those paces and be more efficient.

While it is very important to know the effects of the two training methods on RE, discerning the best combination of the two will be key to future research and this calls for longitudinal studies capable of addressing the issue[62].

Warm-up intensity, running economy and performance

The effort involved in the warm-up prior to competition and its influence on RE can determine final performance, but this has not been studied very much to date. Warming up, of course, is an accepted practice in all sports prior to high-intensity exertion, be it later on in training or in a competition[63]. Given its specificity, the active warm-up is the method most widely used by runners[63]. High-intensity exercise (80% of the lactate threshold or vΔ50) prior to a performance test can alter the VO_2 response in the test, increase the magnitude of the main component of VO_2 and reduce the slow component[64,65]. Any intervention resulting in a rapid VO_2 dynamic (acceleration of VO_2 with respect to the baseline by increasing the absolute magnitude of VO_2) tends to result in an improvement in performance[66].

In the little research linking high-intensity exertion, RE and performance, some authors have found increases in energy cost (reduction of running economy) of 3% to7% after intense exercise[57,67-71] above the anaerobic threshold. A recent study by Barnes and Kilding[72], however, observed an improvement in performance after a warm-up with a series of 10-second sprints with a weighted vest at an intensity similar to competition intensity in the 1,500 metres. In this case, RE improved by 6% after the warm-up and the authors associated the improvement in performance with the improvement in RE and leg stiffness (neuromuscular variable). To date, studies suggest that high-intensity work prior to a performance test or competition increases energy cost (worsening RE), so it is essential that we investigate how long the recovery time between the high-intensity work and the competition should be for the physiological variables involved to return to basal levels so as not to hinder later performance.

Table 2. Effects of interval and continuous training on the running economy and performance of trained athletes. Participants, design and results.

Study	Participants	Research design		Results		
	Description	Interval training (n)	Continuous training (n)	Duration (sessions/week)	RE	Performance
Sjödin y Svedenhag (1982)	n = 8 M; 19.8 y.o.; 68.7 ml·kg^{-1}·min^{-1}; Middle- and long-distance runners		20 min. at vOBLA	1 day/week for 14	↑ 2.8%	
Yoshida *et al*. (1990)	n = 6 W; 19 y.o.; 51.8 ml·kg^{-1}·min^{-1}; Trained athletes		6x vOBLA (20 min.) + normal training (120 min. at threshold speed)	6 days/week for 8 weeks	↑2.8%	↑3,000 m test
Billat *et al.* (1999)	n = 8 M; 24 y.o.; 71.2 ml·kg^{-1}·min^{-1}; Well-trained athletes	Comparative study of 1 and 3 sessions/week of INT training at vVO-2max intensity, with 5 and 3 sessions CON training, resp.		4 weeks: 1 session/ week and another 4 weeks: 3 sessions/week	↑ 6.1% with 1 session/week and 2.7% switching from 1 to 3 sessions/week	↑ 2.9% in vVO$_2$max with 1 session/week, and 1.9% with 3 sessions/week
Collins *et al.* (2000)	n = 7 M; 25.4 y.o.; 72 ml·kg^{-1}·min^{-1}; Highly trained athletes	Three sessions of 10x400 with variation in recovery (1, 2, 3 min.)		Acute effect (3 random sessions)	↓ 4.6% y ↓1.8% at 3.33 and 4.47 m.·s^{-1}	
Demarle *et al.* (2001)	n = 6 M; 27 y.o.; 61.2 ml·kg^{-1}·min^{-1}; Trained athletes	2 INT sessions (50% at intensity vΔ50) in usual training. The number of repetitions was increased over the week.		2x interval + 3x continuous training sessions for 8 weeks	↑3.6%	↑10.24 and 10.1% in vVO2max in only 3 subjects
Slawinski *et al.* (2001)	n = 6 M; 27 y.o.; 61.2 ml·kg^{-1}·min^{-1}; Trained athletes	2 sessions of severe (vΔ50) and moderate (50%vVO-2max) INT training per week + 3 CON training sessions at 60%vVO$_2$max.		2xINT+ 3xCON, 8 weeks	↑3.6%	T-Lim at 17km/h. ↑17% not sig T-Lim at 17km/h. ↑17% not sig
Smith *et al*. (2001)	n = 27 M; 25.2 y.o.; 61.4 ml·kg^{-1}·min^{-1}; Well-trained athletes	6x2 min. vVO$_2$max + 1 x continuous at 60% and 5x 2.5 min. at vVO$_2$max + 1 x continuous at 70% vVO$_2$max			↑3.3% in 60% group and 0.8% in 70% group. Not sig.	↑ 6% T-Lim vVO$_2$max in 60% group.
Laffite *et al.* (2003)	n = 7 M; 24 y.o.; 61.1 ml·kg^{-1}·min^{-1}; Trained athletes	2x Δ50 INT; 3xCON		3xINT, 2xCON, 8 weeks	↑5.4%	Incremental test without changes
Denadai *et al.* (2006)	n = 17 M; 27.4 y.o.; 59.5 ml·kg^{-1}·min^{-1}; Trained athletes	2 x INT at 95 and 100% vVO$_2$max + 1 CON session vOBLA + 3 CON training sessions at 60-70%VO$_2$max		2 days/week INT + 4 days CON for 4 weeks	↑2.6 in 95% group; ↑6.7% in 100% vVO$_2$max group	↑2% in 1,500 m. and 1.4% in 5,000 in 100% vVO$_2$max group
Iaia *et al.* (2009)	n = 17 M; 33.9 y.o.; 55.5 ml·kg^{-1}·min^{-1}; Trained athletes	(9) Replaced training with 8-12x30" with 3' rec. Intensity of 93% per 30" maximum sprint	(8) Usual training + moderate-intensity training	3-5 days/week for 4 weeks	↑ 6-7.2% INT	~ 10k test
Enoksen *et al*. (2011)	n = 26 M; 19.9 y.o.; 70.3 ml·kg^{-1}·min^{-1}; Well-trained athletes	33% of training at 82-92% HRmax; the rest at 65-82% HRmax (G1). 3 INT sessions/week	13% of training at 82-92% HRmax, and the rest at 65-82% (G2). 1 INT session/week		↑2.5-5% in G1; ↑1.5-4.8% in G2	~ T-Lim at vVO$_2$max
Barnes *et al.* (2013)	n = 20 M; 21 y.o.; 63.9 ml·kg^{-1}·min^{-1}; Trained long-distance runners	At gradient: (G1) 12-24 x 8-12 sec. at 120%vVO$_2$max; (G2) 8-16 x 30-45 sec. at 110%vVO$_2$max; (G3) 5-9 x 2-2.5 min. at 100%vVO$_2$max; (G4) 4-7 x 4-5 min. at 90%vVO2max; (G5) 1-3 x 10-25 min. at 80% vVO$_2$max. *In addition to usual training		2 days/week for 6 weeks	↑ 2.4% (G1); ↑ 0.6 (G2); ↓ 1.2 (G3); ↓ 2.4 (G4); ↓ 3.2 (G5)	↑ 2.15% T-Lim without differences between groups

Symbols: ↑ increase or improvement; ↓ decrease or deterioration; ~ no change.
Abbreviations: M: Men; W: Women; y.o.: Years old; n: Number of participants: PE Physical Education; G: Group; HRmax: Maximum heart rate; CON: Continuous method; INT: Interval method; VO$_2$max: Maximal oxygen uptake; vVO$_2$max: Speed at maximal oxygen uptake intensity; T-Lim: Time to exhaustion; vOBLA: speed as of 4mmol/L; vΔ50: 50% intensity between lactate threshold speed (vLT) and vVO$_2$max; n/a: Not available.

Regarding the effect of the intensity of the warm-up on subsequent performance, Zourdos *et al*[73] recently came to the conclusion that a warm-up at submaximal intensity (45-65% VO_2max) had little effect on performance compared to no warm-up at all. Van den Tillar *et al.*[74] compared two warm-up protocols and assessed their effects on subsequent performance. The first protocol was longer (general part plus specific high-intensity part) and the shorter one only consisted of the specific part (8x60 m. sprint). They found no differences in performance between the warm-up protocols and came to the conclusion that, because it represents a more efficient use of time, the shorter option may be a good alternative. Ingham *et al.*[75] used competition intensity (800 m.) to quantify the impact of the prior warm-up on their performance test. They came to the conclusion that sustained high-intensity exertion (2x50 m. + 200 m. at competition intensity) improved performance compared to less sustained effort (6x50 m.) at the same intensity. As can be seen, recent research[74,75] shows that the inclusion of high-intensity exercise in warm-up sessions improves later performance more than low-intensity exercise[71], although high-intensity exercise may worsen RE[57,67-71] and this should be taken into account, especially regarding the amount of time between the high-intensity work and the competition or performance test.

Conclusions

As we have seen, RE is a basic variable which, due to its direct relationship with performance, needs to be evaluated to establish how much runners improve. Endurance training modifies this variable and the intensity of training is crucial when it comes to achieving this.

With recreational runners, disparate results are obtained when INT and CON training are compared. For this group of athletes, controlled training organised into periods should lead to improvements in RE over time. INT training (2-3 sessions per week) should be included gradually and always in combination with a lot of CON training[42], because a greater proportion of INT compared to low-intensity training (CON) does not lead to any improvement in RE[45]. Besides biomechanical changes[47], the increase in the volume of training could be the chief reason for improvements in RE. With trained athletes, the relationship between high-intensity (INT) and low-intensity (CON) sessions is essential when it comes to improving RE[55]. Intensities near vVO_2max are recommended to improve RE and the speed associated with VO_2max[51], but when these are too high (132% VO_2max), they do not lead to improvements in RE, possibly because it is not possible to do enough high-intensity training[39]. With long-distance runners, CON training at vOBLA[58] produces RE improvements approaching 3%. Given the great variety of methodologies used in the studies reviewed, it is difficult to pinpoint an optimal intensity for RE improvement. We recommend that trained runners train at intensities near 100% vVO_2max to improve RE and intensities close to competition intensity to enhance the efficiency of this work.

Finally, regarding the effect of race intensity during the warm-up on RE, high-intensity exercise[57,67-71] reduces RE by 3-7%. This means that there should be a generous transition and recovery stage between such exercise and a competition. This transitional period could be between 9 min.[67] and 20 min.[2]. The incorporation of high intensity exercise[74,75] improves final performance when compared with low-intensity exercise[73].

In conclusion, and on a practical note, we recommend that coaches and athletes include high-intensity training (INT) in their programmes, bearing in mind that it should be accompanied by low-intensity training (CON) so that the training loads can be assumed. For trained athletes, a ratio of 80:20 is usually recommended, giving priority to low-intensity training and only working at high intensity, above the anaerobic threshold, in the remaining 20%[76]. The inclusion of intensities similar to competition intensity could also be recommendable for both recreational and trained athletes.

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