Effects of Strength Training on Running Economy

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Key words
- force
- power
- aerobic
- training methods
- athletes

Abstract

The objective of this study was to compare the effect of different strength training protocols added to endurance training on running economy (RE). Sixteen well-trained runners (27.4 ± 4.4 years; 62.7 ± 4.3 kg; 166.1 ± 5.0 cm), were randomized into two groups: explosive strength training (EST) (n = 9) and heavy weight strength training (HWT) (n = 7) group. They performed the following tests before and after 4 weeks of training: 1) incremental treadmill test to exhaustion to determine of peak oxygen uptake and the velocity corresponding to 3.5 mM of blood lactate concentration; 2) submaximal constant-intensity test to determine RE; 3) maximal countermovement jump test and; 4) one repetition maximal strength test in leg press. After the training period, there was an improvement in RE only in the HWT group (HWT = 47.3 ± 6.8 vs. 44.3 ± 4.9 ml · $kg^{-1} \cdot min^{-1}$; EST = 46.4 ± 4.1 vs. 45.5 ± 4.1 ml · $kg^{-1} \cdot min^{-1}$). In conclusion, a short period of traditional strength training can improve RE in well-trained runners, but this improvement can be dependent on the strength training characteristics. When comparing to explosive training performed in the same equipment, heavy weight training seems to be more efficient for the improvement of RE.

Introduction

Running economy (RE) has been defined as the oxygen uptake required at a given absolute exercise intensity [5]. The interindividual variability (> 15 %) observed even in highly trained runners with similar $\dot{V}O_{2max}$ values had been attributed to anthropometric (distribution of segments mass), physiologic (fiber type distribution, neural input, muscular strength and stiffness) and biomechanic aspects (stride length and frequency, mechanical and morphological properties of ankle and knee muscles) [1,25,31]. High economic runners present lower energetic costs at submaximal speeds and, consequently, tend to run faster at a given distance or to run longer at a constant speed.
Some studies have suggested that there is a relationship between neuromuscular characteristics and running economy. Noakes [24] proposed that runners with poor economy might have muscles that are less able to utilize the impact energy produced as they eccentrically absorb the force of landing, which depends on the relative stiffness of the musculotendinous system. Arampatzis et al. [1] analyzing endurance runners at submaximal speeds have confirmed that the most economical individuals presented higher levels of contractile strength and muscular stiffness.
Studies that have investigated the effect of endurance training on RE have produced equivocal results [8,18,29,30]. Interval training at 100% $\dot{V}O_{2max}$ [8] and continuous running at onset of blood lactate accumulation [29] have been shown to improve RE significantly. However, other studies using similar training intensities have reported no significant improvement in RE [18, 30]. Jones and Carter [16] have suggested that the total duration of the longitudinal studies (typically of 6 to 12 weeks duration) is too short to produce a measurable improvement on RE, among trained individuals. However, some studies using traditional strength training [15,21] and plyometric training [26,32] have verified significant improvements in RE and running performance after a few weeks of training (up to 14 weeks). Johnston et al. [15] studied the effects of a 10-week strength training program, consisting of 2 – 3 sets of 6 – 20 repetition maximum (RM) (i.e., each set is performed to a momentary con-

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centric failure), in female distance runners. This protocol, added to endurance training, promoted significant improvement in RE (4%). Paavolainen et al. [26] found that 9 weeks of explosive resistance training (plyometrics with and without additional weight, high-velocity leg press, knee extension, knee flexion with 0–40% 1RM) and endurance training improved RE by 8.1% in trained distance runners. Similarly, Millet et al. [21] have verified that the addition of heavy weight training (3–5 sets of 3–5 RM) to the endurance training of well-trained triathletes during 14 weeks was associated with a significant increase in RE (11%). Based on this data, it can be hypothesized that different types of resistance training (40–90% RM) may have a positive effect on RE. However, while Millet et al. [21] utilized heavy weight training, Johnston et al. [15] employed strength training program with moderate and high resistance. Moreover, Paavolainen et al. [26] combined explosive resistance training and plyometrics (with and without additional weight), which tends to increase the stiffness of the muscle-tendon system and, consequently, the capacity to store and utilize elastic energy from the eccentric contraction. This capacity has been considered an important key component to RE [4]. Thus, it is not possible to identify which traditional weight training is more efficient to improve RE of endurance runners. It is important to note that the number of repetitions allowed by the resistance will result in very specific training adaptations (i.e., "repetition maximum continuum") [9]. Taking into account all data cited above, it is possible to hypothesize that manipulation of the various acute resistance-training variables (e.g., number of maximum repetition and velocity) can stress the muscles in very different ways and promote different effects on RE. Thus, the main objective of this study was to compare the effect of two different strength training protocols in combination with an existing endurance-training program, on RE in well-trained runners.

Methods

Experimental approach to the problem

The hypothesis that explosive strength training (EST) or heavy weight strength training (HWT) added to regular endurance running training would lead to different neuromuscular adaptations, and consequently different effects on RE in well-trained runners was tested. To answer this question, a 4-week period of training was chosen because 4- to 8-week cycles of training targeted at specific training goals are common. Moreover, changes in RE have been demonstrated after as little as 3 weeks of explosive strength training [26].

Subjects

Seventeen endurance runners with an average training history of at least 5 years, volunteered to participate in this study. They were specialized in middle- and long-distance running events (3000 m to half-marathon), and were competing in regional and national level meets (5000-m performance equal to 71.1 ± 4.1% WR). They were randomized into two groups: explosive strength training (EST; n = 9; age 27.9 ± 8.2 years; body mass 62.3 ± 4.3 kg and; height 169.0 ± 5.6 cm) and heavy weight strength training (HWT; n = 8; age 31.0 ± 11.4 years; body mass 58.8 ± 6.6 kg and; height 171.3 ± 6.3 cm) group. The subjects had no previous experience with weight training. They were training a mean week volume of approximately 60–80 km in the last two months, and were at the beginning of the specific phase of the periodization. All subjects gave informed consent and the protocol was approved by the university's ethics committee.

Experimental design

Subjects were randomized into two groups: explosive strength training (EST) (n = 9) and heavy weight strength training (HWT) (n = 8) group. One subject of the HWT group withdrew from the study due to sporting commitments. Initially, in weeks 1–2 (pre-training), subjects performed the following tests: 1) incremental treadmill test to exhaustion for determination of peak oxygen uptake ($\dot{V}O_{2peak}$) and the velocity corresponding to 3.5 mM of blood lactate concentration (vOBLA); 2) submaximal constant-intensity test to determine running economy (RE); 3) maximal countermovement jump test on contact plate to determine rise of the center of gravity of the body (CMJ) and; 4) one repetition maximal strength test in leg press to determine maximum isoinertial strength (1RM). Subjects performed only one test per day, and tests were separated by ≥ 48 h but completed within the period of 2 wk, during which training was kept relatively constant. All tests were performed at the same time of day (± 2 hs) in a climate-controlled (21–22 °C) laboratory. Subjects were instructed to be fully rested when reporting to the laboratory and to refrain from using caffeine-containing food or beverages, drugs, alcohol, cigarette smoking, or any form of nicotine intake 24 h before testing. Subjects in the EST and HWT groups then undertook a 4-week training program consisting of two strength-training sessions and four submaximal run sessions per week. Final retesting of $\dot{V}O_{2peak}$, vOBLA, RE, CMJ and 1RM was completed on all subjects in the 2 weeks following the training program (post-training).

Tests and procedures

Anthropometry

The body fat content was estimated from the skin thickness, expressed in mm, representing the sum of three different skin areas (triceps, suprailiac and abdominal) measured on the right side of the body with Cescorf ® Calipers (Cescorf, Porto Alegre, Brazil) following the method described by Guedes [10].

Determination of $\dot{V}O_{2peak}$ and vOBLA

Peak oxygen uptake ($\dot{V}O_{2peak}$) was measured using an incremental protocol performed on a motorized treadmill (LIFE FITNESS 9800, Schiller Park, IL, USA) with the gradient set at 1%. The initial speed was set at 12 $km \cdot h^{-1}$ for 3 min and was then incremented 1 $km \cdot h^{-1}$ every 3 min, until voluntary exhaustion. All stages were followed by a 30-s period of rest. During this period, an earlobe capillary blood sample was collected. Throughout the tests, the respiratory and pulmonary gas-exchange variables were measured using a breath-by-breath portable gas analyzer (Cosmed K4b2, Rome, Italy). Before each test, the O_2 and CO_2 analysis systems were calibrated using ambient air and a gas of known O_2 and CO_2 concentration according to the manufacturer's instructions, while the K4b2 turbine flowmeter was calibrated using a 3-l syringe (Cosmed K4b2, Rome, Italy). Heart rate (HR) was also monitored throughout the tests (Polar, Kempele, Finland). Breath-by-breath data were smoothed using a five-step moving average filter, from which rolling 15-s averages were calculated. Earlobe capillary blood samples (25 µl) were collected into a glass tube and were analyzed for lactate concentration using an automated analyzer (YSI 2300, Yellow Springs, OH, USA). The $\dot{V}O_{2peak}$ was defined as the highest 15-s $\dot{V}O_2$ value reached during the incremental test. The velocity associated with $\dot{V}O_{2peak}$

Table 1 Example of the weekly program for explosive strength training (EST) and heavy weight training (HWT) groups

	Groups	
Days	**EST**	**HWT**
Mon	60 min at 60% $\dot{V}O_{2peak}$	60 min at 60% $\dot{V}O_{2peak}$
Tue	Warm-up: 4 km 3–4 × 12RM	Warm-up: 4 km 3–4 × 6RM
Wed	45 min at 70% $\dot{V}O_{2peak}$	45 min at 70% $\dot{V}O_{2peak}$
Thu	Warm-up: 4 km 3–4 × 12RM	Warm-up: 4 km 3–4 × 6RM
Fri	60 min at 60% $\dot{V}O_{2peak}$	60 min at 60% $\dot{V}O_{2peak}$
Sat	Warm-up: 3 km 2 × 20 min at vOBLA with 5 min of rest at 60% $\dot{V}O_{2peak}$ Cool-down: 2 km	Warm-up: 3 km 2 × 20 min at vOBLA with 5 min of rest at 60% $\dot{V}O_{2peak}$ Cool-down: 2 km
Sun	Rest	Rest

($v\dot{V}O_{2peak}$) was defined as the minimal velocity at which $\dot{V}O_{2peak}$ occurred [8]. vOBLA was determined by linear interpolation, using a fixed lactate concentration of 3.5 mM [7].

Determination of RE
For determination of running economy (RE), runners warmed up at 12 km·h^{-1} for 7 min, rested for 3 min, and then ran for 8 min at 14 km·h^{-1}. $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) was averaged between the 6th and 7th min at 14 km/h and taken as the reference for an athlete's RE.

Determination of CMJ
The maximal explosive strength (CMJ) of the leg muscles was measured on a contact platform (Ergojump, Belo Horizonte, Brazil) using a maximal countermovement jump with a preparatory movement from the extended leg position down to 90° of the knee flexion (controlled by an external goniometer – Carci, São Paulo, Brazil), followed by a subsequent concentric action. A digital timer was connected to the contact platform to measure the flight times of the jumps. The flight time measured was used to calculate the rise of the center of gravity of the body. The validity of the equipment was determined comparing to a force plate [20]. After a warm-up of 10–15 min consisting of stretches and jumps, each subject performed 5 maximal jumps with his hands on his waist, with 30 s of recovery between them. The mean of the 3 highest values obtained was used for data analysis.

Determination of 1RM
The maximum isoinertial strength (1RM) was determined for the leg extensor muscles using an inclined leg press machine at 45°. Athletes were required to perform a warm-up consisting of stretches and 3 sets with 15 repetitions (30% of body mass) and 60 s of rest between each set. The weight was then progressively increased until the athlete could not successively complete one repetition. A lift was deemed to be successful when subjects could lower the bar such that a knee angle of 90° was achieved and then raise the bar back to the upright starting position. A maximum of 5 attempts were performed on the same day, with 5 min of rest between each attempt [19].

Training program
In addition to the endurance training, the EST and HWT groups performed a strength training session of lower-limb muscles twice a week. Exercises (i.e., leg press 45°, parallel squat, leg extension, leg flexion, and 2 exercises of calf raise) were exclusively focused on quadriceps, hamstring, and calf muscles.

Table 2 Physical characteristics of the explosive strength training (EST) and heavy weight training (HWT) groups before (Pre) and after (Post) the training period

Group	HWT (n = 7)		EST (n = 9)	
	Pre	Post	Pre	Post
Body mass (kg)	58.8 ± 6.6	60.3 ± 6.8	62.3 ± 4.3	61.7 ± 4.3
Body fat (%)	6.8 ± 3.2	6.3 ± 3.0	8.0 ± 4.0	7.4 ± 3.5[a]

[a] $p < 0.05$ in relation to pre-training in the same group

The heavy weight training program consisted of three sets to failure of 6 reps (6RM), in the weeks 1 and 2. The resistance was progressively increased to maintain this number of repetitions per set. The rest interval was 3 min. In the weeks 3 and 4, training consisted of four and five sets, respectively. The explosive strength training program consisted of three sets to failure of 12 reps (12RM). The resistance was progressively increased to maintain this number of repetitions per set. The rest interval was 3 min. In the weeks 3 and 4, training consisted of four and five sets, respectively. Because of the reported increase in both 1RM tests and time to peak force [28], subjects were instructed to perform the concentric phase of movement as fast as possible. The training sessions were monitored throughout the experiment period by a fitness instructor.
In addition, the training week was composed of one running session at vOBLA (2 × 20 min with 5 min of active recovery between the two runs at 60% $\dot{V}O_{2peak}$) and three submaximal continuous sessions (45–60 min at 60–70% $\dot{V}O_{2peak}$). All running training sessions were performed on a 400-m track. Training logs for all subjects were monitored prior to and during the training period to ensure that running volumes and intensities were attained. ▶ **Table 1** presents an example of the weekly training program for EST and HWT groups.

Statistical analysis
Values are presented as mean ± SD. The data were analyzed using two-way ANOVA (group × time), with Scheffe's post hoc tests where appropriate. For all statistics, the significance level was set at $p \leq 0.05$ and effect sizes (ES) were calculated.

Results
▼
▶ **Table 2** shows the physical characteristics of the EST and HWT groups before and after 4 weeks of the experiment. After the training period, there was no significant difference in the body mass of both groups. However, there was a reduction in body fat in the EST group ($p < 0.05$).
The variables obtained during the incremental protocol are presented in ▶ **Table 3**. The $\dot{V}O_{2peak}$ (l/min), $v\dot{V}O_{2peak}$ and vOBLA did not differ significantly between the groups before the experiment. $\dot{V}O_{2peak}$ (ml·kg^{-1}·min^{-1}) was significantly higher in HWT than EST groups before the training period. There was no significant increase in $\dot{V}O_{2peak}$ ($p = 0.74$, ES = 0.20; $p = 0.93$, ES = 0.04) and $v\dot{V}O_{2peak}$ ($p = 0.65$, ES = 0.28; $p = 0.66$, ES = 0.20) for the HWT and EST groups, respectively. The vOBLA was significantly higher after the training period for both groups, compared to

Table 3 Mean ± SD values of peak oxygen uptake ($\dot{V}O_{2peak}$), the velocity associated with $\dot{V}O_{2peak}$ ($v\dot{V}O_{2peak}$), the velocity (vOBLA) and $\dot{V}O_2$ ($\dot{V}O_2OBLA$) at onset of blood lactate accumulation obtained during treadmill incremental test and running economy (RE) for heavy weight training (HWT) and explosive strength training groups (EST), before (Pre) and after (Post) the training period

	HWT (n = 7)		EST (n = 9)	
	Pre	**Post**	**Pre**	**Post**
$\dot{V}O_{2peak}$ ($l \cdot min^{-1}$)	3.78 ± 0.3	3.70 ± 0.4	3.69 ± 0.3	3.68 ± 0.3
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	64.1 ± 10.48^b	62.2 ± 10.6	59.6 ± 7.2	59.9 ± 7.0
$v\dot{V}O_{2peak}$ ($km \cdot h^{-1}$)	18.1 ± 1.2	18.4 ± 1.1	18.3 ± 1.0	18.5 ± 1.1
$\dot{V}O_2OBLA$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	53.0 ± 9.9	55.8 ± 6.9^a	51.4 ± 3.3	53.3 ± 3.3^a
vOBLA ($km \cdot h^{-1}$)	15.0 ± 1.4	16.0 ± 1.1^a	14.9 ± 0.7	15.5 ± 0.9^a
RE ($ml \cdot kg^{-1} \cdot min^{-1}$)	47.3 ± 6.8	44.3 ± 4.9^a	46.4 ± 4.1	45.5 ± 4.1

^{a} $p < 0.05$ in relation to pre-training in the same group; ^{b} $p < 0.05$ in relation to EST group pre-training

Table 4 Mean ± SD values of maximal isotonic strength (1RM) and maximal explosive strength (CMJ) for heavy weight training (HWT) and explosive strength training groups (EST), before (Pre) and after (Post) the training period

	HWT (n = 7)		EST (n = 9)	
	Pre	**Post**	**Pre**	**Post**
1RM (kg)	198.5 ± 38.4	275.7 ± 81.8^{ab}	226.6 ± 47.3	343.3 ± 139.0^a
CMJ (cm)	30.4 ± 3.5	32.4 ± 3.9^b	31.9 ± 3.7	36.0 ± 4.1^a

^{a} $p < 0.05$ in relation to pre-training in the same group; ^{b} $p < 0.05$ in relation to the EST group post-training

their baselines (HWT – $p < 0.05$, ES = 0.86; EST – $p < 0.05$, ES = 0.79). There was a significant improvement in RE for HWT (6.2%) ($p < 0.05$, ES = 0.55), but not for EST (1.9%) ($p = 0.67$, ES = 0.22). At the beginning of the study, the velocities corresponding to 60 (HWT = 10.8 ± 0.7; EST = 11.0 ± 0.6 $km \cdot h^{-1}$) and 70% $\dot{V}O_{2peak}$ (HWT = 12.7 ± 0.8; EST = 12.8 ± 0.7 $km \cdot h^{-1}$) were not different between groups.

Table 4 shows the effects of training on 1RM and CMJ. The CMJ and 1RM did not differ significantly between the groups before the experiment. There was a significant improvement in 1RM in the HWT (38%) ($p < 0.05$, ES = 1.30) and EST (51%) ($p < 0.05$, ES = 1.19) groups and in the CMJ in the EST group (HWT – $p = 0.32$, ES = 0.58; EST – $p < 0.05$, ES = 1.11). After the training period, 1RM was significantly higher in the EST group ($p < 0.05$, ES = 0.78).

Discussion

The objective of this study was to compare the effect of two different strength training protocols added to regular endurance running training on RE in well-trained runners. The results presented by the HWT group are in agreement with previous results reported in the literature [21], confirming that heavy strength training protocol performed during a short period (4 weeks) may promote significant improvement in RE. However, our main finding was that a protocol with intermediate resistance (3–5 series of 12RM) and high velocity of movement in the concentric phase may promote a significant improvement in maximal and explosive strength, with no modification in RE.

Maximum and explosive strength improvements

The improvements of maximum isoinertial strength (1RM) in the HWT (38%) and EST groups (51%) were higher than previously reported by other studies (~10 to 20%) in endurance athletes [21,26]. Our subjects did not present previous experience with a resistive training protocol, which could have contributed to these improvement levels. Recently, Campos et al. [3] have confirmed DeLorme's [6] theory of a strength–endurance continuum (i.e., the number of repetitions allowed by the resistance will result in very specific training adaptations). In this study [3], conducted in active subjects, those individuals who trained with heavier loads improved the most in maximum strength, whereas those who trained with the lighter loads improved the most using 60% of 1RM. It is important to note that the average volume of total work accomplished (resistance × repetitions × sets) was not different among low (4 sets of 3–5RM), intermediate (3 sets of 9–11RM) and high (2 sets of 20–28RM) repetition groups. Conversely, in our study the highest improvement occurred in the EST group, which used the higher repetition. However, the volume was also higher in the EST group, which may help to explain the highest strength improvement.

The improvement of CMJ height only in the EST group suggests that the increase in 1RM may not be sufficient to improve jump performance. Strength training protocol performed by the EST group had lower intensity but higher velocity of movement, especially in the concentric phase. Although movements were not the same, factors such as trainability level of subjects and characteristics of training protocol may have contributed to the improvement in jump performance. This suggests that the velocity of movement may be proportionally more important than strength level maintained during training.

Our results support and extend previous findings [26] that strength training resulted in significant improvements in strength performance (1RM and CMJ) in well-trained endurance runners, although a large volume of endurance training was performed simultaneously.

Running economy

Studies in the literature have emphasized that in addition to high-aerobic power, endurance athletes must be able to maintain high levels of velocity and strength during a race [23,26].

This suggests that specific neural, mechanical and muscular factors (i.e., motor units recruitment pattern, mechanical and morphological properties of muscle-tendon unit, muscle fiber distribution) may contribute to the performance. In running, some studies [1,23,25,26] have confirmed the importance of neuromuscular characteristics related to voluntary and reflex neural activation, muscle force and elasticity, and mechanics for endurance performance. In addition to this, the capacity to store and release elastic energy during stretch-shortening cycle is also important for the force production and mechanical efficiency in this modality [17].

In running, few studies have analyzed the RE responses after a traditional strength training protocol. Using a similar strength training protocol performed by our athletes (3 – 5 sets – 90% 1RM), Millet et al. [21] verified a significant improvement in RE after 14 weeks of training. In this study, the resistance was readjusted to maintain the number of repetitions between 3 and 5. The improvement in RE was 5.6% at the velocity associated to the second ventilatory threshold plus 25% of delta between the second ventilatory threshold and $\dot{V}O_{2max}$ velocities (25%Δ) and 6.9% at 75%Δ. This improvement was very similar to that found in our study (6.2%). Therefore, since strength training protocols were similar, we can suggest that most of the adaptations in RE may occur during the first 4 weeks of strength training, and using protocols longer than 4 weeks does not necessarily lead to a greater RE improvement.

In another study, Paavolainen et al. [26] used explosive strength training during 9 weeks and also verified a significant improvement in RE (8%). In this study, 32% of total week training volume was replaced by strength training. The explosive training was performed using sprints (20 – 100 m) and plyometric training. Traditional strength training was performed on leg press and leg extensor equipment, at a low resistance (0 – 40% 1RM) and high velocity of movement. In our study, the EST group also performed high-velocity movement during strength training, but there was no significant improvement in RE. However, our data cannot be compared directly with those obtained by Paavolainen et al. [26], because the authors also used sprints and plyometric training, which can modify some important characteristics of running, such as muscle and tendon stiffness [1]. Therefore, in the study conducted by Paavolainen et al. [26], the specific contribution of traditional strength training, if any, could not be determined. In this context, it is important to note that adding exclusively plyometric training to endurance training, Spurrs et al. [31] and Turner et al. [32] have shown that a 6-week plyometric training led to improvements in RE.

Although there is some evidence that plyometric training or HWT added to regular endurance training can improve RE in well-trained endurance athletes, there has been little research on the mechanisms of such improvement. Explosive-strength or plyometric training invokes specific neural adaptations such as an increased activation of the motor units, with less muscle hypertrophy than typical heavy-resistance strength training [11, 12]. Plyometric training also has the potential to increase the stiffness of the muscle-tendon system, which allows the body to store and utilize elastic energy more effectively. However, Turner et al. [32] have verified that the plyometric training improved RE, but did not result in changes in jump height or efficiency variables that would have indicated improved ability to store and return elastic energy. Apparently, the results obtained in our study are in accordance with Turner et al. [32], since the improvement of CMJ height occurred only in EST, which did not present a significant modification in RE. Thus, the neuromuscular mechanisms that determine increase of CMJ height can be different from those which improve RE.

Some studies, using heavy weight training during 2 – 8 weeks, have verified hypertrophy of type I, II a and II b muscle fibers, and fast-twitch fibers type conversion (from II b to II a). The decrease in the percentage of the type II b and the concomitant increase of the type II a fibers may lead to an increase of the oxidative capacity of the trained muscles [3]. These modifications might help to explain RE improvement observed in the HWT group. However, Campos et al. [3] verified that both hypertrophic response and alterations within the fast fiber-type population (II b to II a fiber conversions), were similar between low- (4 sets of 3 – 5RM) and intermediate- (3 sets of 9 – 11RM) repetition groups. Thus, these peripheral adaptations probably do not explain the different RE responses after strength training between HWT and EST groups. Alternatively, heavy weight training may have contributed to RE improvement mainly through neural factors (increased activation, more efficient recruitment, motor unit synchronization). Hoff et al. [14] suggested that the rate of force development may be more important to RE improvement than the increase in maximal muscle strength. In accordance to Hoff and Almåsbakk [13], to improve the rate of force development, a maximal strength training program should be used. These aspects may help to explain why only HWT improved RE, despite the bigger strength gains presented by the EST group.

Finally, some consideration about the typical intraindividual variation in RE is necessary when the effects of training on RE are analyzed. Well controlled reliability studies (diet, time of day and footwear) measuring RE show intraindividual variations between 1.5 – 5% [2,22]. Specifically in the well-trained male ($\dot{V}O_{2max}$ = 58.3 ml · kg^{-1} · min^{-1}), Pereira and Freedson [27] verified a mean coefficient of variation of 1.3% for RE at a similar exercise intensity performed by our athletes. As the improvement in RE presented by the HWT group (6.2%) exceeded the typical intraindividual variation cited above, changes in RE were probably determined by heavy weight training.

Conclusion

We can conclude that a short period of traditional strength training can improve RE in well-trained endurance runners, but this improvement can be dependent on the strength training characteristics. When compared to explosive training performed on the same equipment, heavy weight training seems to be more efficient for the improvement of RE. Future studies focusing on the effects of traditional weight training performed at different conditions (load, volume, velocity of movement and distribution of sessions over the week) are necessary to better understand the mechanisms involved in neuromuscular adaptations and RE improvement.

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