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ORIGINAL ARTICLE

Effects of strength, explosive and plyometric training on energy cost of running in ultra-endurance athletes

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Abstract
The aim of the present study was to evaluate the effects of a 12-week home-based strength, explosive and plyometric (SEP) training on the cost of running (Cr) in well-trained ultra-marathoners and to assess the main mechanical parameters affecting changes in Cr. Twenty-five male runners (38.2 ± 7.1 years; body mass index: 23.0 ± 1.1 kg·m^{-2}; $\dot{V}O_2$max: 55.4 ± 4.0 mlO$_2$·kg^{-1}·min^{-1}) were divided into an exercise (EG = 13) and control group (CG = 12). Before and after a 12-week SEP training, Cr, spring-mass model parameters at four speeds (8, 10, 12, 14 km·h^{-1}) were calculated and maximal muscle power (MMP) of the lower limbs was measured. In EG, Cr decreased significantly ($p < .05$) at all tested running speeds (−6.4 ± 6.5% at 8 km·h^{-1}; −3.5 ± 5.3% at 10 km·h^{-1}; −4.0 ± 5.5% at 12 km·h^{-1}; −3.2 ± 4.5% at 14 km·h^{-1}), contact time (t_c) increased at 8, 10 and 12 km·h^{-1} by mean +4.4 ± 0.1% and t_a decreased by −25.6 ± 0.1% at 8 km·h^{-1} ($p < .05$). Further, inverse relationships between changes in Cr and MMP at 10 ($p = .013$; $r = -0.67$) and 12 km·h^{-1} ($p < .001$; $r = -0.86$) were shown. Conversely, no differences were detected in the CG in any of the studied parameters. Thus, 12-week SEP training programme lower the Cr in well-trained ultra-marathoners at submaximal speeds. Increased t_c and an inverse relationship between changes in Cr and changes in MMP could be in part explain the decreased Cr. Thus, adding at least three sessions per week of SEP exercises in the normal endurance-training programme may decrease the Cr.

Keywords: *Running mechanics, muscle power, running economy, ultra-marathon, strength training*

Highlights

- Strength, explosive and plyometric training positively affect the endurance performance.
- An home-based training programme leads to a better cost of running.
- Ultra-endurance athletes should improve their training programme by adding 2–3 sessions/week of strength, explosive and plyometric training.

Abbreviations

ΔCr	Cost of running change
ΔL	Leg-length change
Δz	Vertical displacement of the centre of mass
BM	Body mass
BMI	Body mass index
CG	Control group
Cr	Cost of running
EG	Experimental group
EXER	Explosive-ergometer
F	Fraction of $\dot{V}O_{2max}$ sustained during an endurance event
FFM	Free-fat mass
FM	Fat mass
F_{max}	Maximal vertical ground reaction force
HR	Heart rate
k_{leg}	Leg stiffness
k_{vert}	Vertical stiffness
L	Lower limb length
m	Meter
MMP	Maximal muscle power
RCP	Respiratory compensation point
RER	Respiratory exchange ratio
s	Seconds
SEP	Strength, explosive and plyometric
SF	Stride frequency
SL	Stride length
t_a	Aerial time
t_c	Contact time
v	Running velocity
$\dot{V}CO_2$	Carbon dioxide production
$\dot{V}O_2$	Oxygen consumption
$\dot{V}O_2$max	Maximal oxygen uptake

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Introduction

In ultra-marathons races maximal oxygen uptake ($\dot{V}O_2$max), its fraction sustained during the entire event (F) and the cost of running (Cr) are the most important physiological factors affecting the performance (di Prampero, Atchou, Bruckner, & Moia, 1986). $\dot{V}O_2$max and F can be enhanced by specific running or cycling training (Laursen, Shing, Peake, Coombes, & Jenkins, 2002; Midgley, McNaughton, & Wilkinson, 2006), while exercise economy can be improved by adding strength, explosive and plyometric (SEP) training to the normal training plan (Ronnestad, Kojedal, Losnegard, Kvamme, & Raastad, 2012; Spurrs, Murphy, & Watsford, 2003; Storen, Helgerud, Stoa, & Hoff, 2008). As previously reported (Lazzer et al., 2014), the importance of Cr is higher in determining the performance when athletes with similar $\dot{V}O_2$max are compared and its relevance increases in long races. Furthermore, lower Cr and lower ΔCr (i.e. the increase of Cr during the race) are associated with higher maximal muscle power (MMP) of the lower limbs (Lazzer et al., 2015).

Complementary strength and endurance training seems to be a good method to improve the Cr in different levels of runners (Balsalobre-Fernandez, Santos-Concejero, & Grivas, 2016; Denadai, de Aguiar, de Lima, Greco, & Caputo, 2016). Effects of SEP training on endurance performance have been extensively studied in different populations and sport situations (Hoff, Gran, & Helgerud, 2002; Osteras, Helgerud, & Hoff, 2002; Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 1999; Ronnestad et al., 2012; Ronnestad & Mujika, 2014; Turner, Owings, & Schwane, 2003). Adding SEP training to an endurance athlete's usual training schedule, may improve endurance performance by acting on exercise economy, anaerobic capacity, maximal speed and reducing the fatigue effects (Ronnestad & Mujika, 2014; Storen et al., 2008). Particularly, Storen et al. (2008) reported improvements in 1 repetition maximum (1RM), rate of force development, Cr and time to exhaustion at maximal aerobic speed among well-trained long-distance runners after 8 weeks of maximal strength training added to their usual running training. Other investigations (Spurrs et al., 2003; Turner et al., 2003) reported improvement in Cr at different speeds in distance runners after 6 weeks of plyometric training programme without changes in $\dot{V}O_2$max or anaerobic threshold. Conversely, Ferrauti, Bergermann, and Fernandez-Fernandez (2010) and Ronnestad et al. (2012) did not show any change in exercise economy during treadmill running and rollerskiing after 8 and 12 weeks of strength training performed twice a week in a group of recreational runners and well-trained Nordic Combined athletes. Nevertheless, they reported an increased 1RM in squat and seated pull-down, muscle thickness of vastus lateralis, squat jump performance and peak torque of leg extensors and trunk flexors.

Although different points of view are present between authors, it appears that the optimal training regime includes complementary SEP exercises added to endurance training. Indeed, complementary endurance and strength training performed for a period from 8-to-16 weeks may improve endurance performance more than endurance training alone (Aagaard et al., 2011; Hoff, Helgerud, & Wisloff, 1999; Spurrs et al., 2003) even if an interference phenomenon exists (Fyfe, Bishop, & Stepto, 2014). Cyclists, rowers, cross country skiers, triathletes and runners underwent different types of SEP training protocols to improve endurance performance (Aagaard et al., 2011; Hoff et al., 2002; Osteras et al., 2002; Ronnestad et al., 2012; Ronnestad & Mujika, 2014; Storen et al., 2008; Turner et al., 2003). However, to the best of our knowledge, in the literature there is a lack of information related to the effects of SEP training in well-trained ultra-marathoners, though the number of them have been increased exponentially in the latest years. Thus, the first objective of the present study was to evaluate the effects of a 12-week home-based SEP training protocol on the Cr in well-trained ultra-marathoners. We hypothesized (I) a decrease in Cr, and (II) an increase in MMP of the lower limbs. In addition, whether the training protocol led to a decrease in Cr, we aimed to define whether changes in running mechanics would affect the Cr.

Methods

Subjects

Twenty-five male runners (38.2 ± 7.1 years; body mass index (BMI): 23.0 ± 1.1 $kg \cdot m^{-2}$; $\dot{V}O_2$max: 55.4 ± 4.0 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$, Table I) participated in this study and provided written informed consent. The experimental protocol was approved by the local Ethics Committee. The participants were recruited among Italian well-trained ultra-endurance runners; some of them were in the national team (Italian Ultra-Marathon and Trail Association, IUTA). The inclusion criteria were: (1) the athletes had previously run at least one race longer than 50 km; (2) their training volume in the latest 3 months was greater than 60 $km \cdot week^{-1}$; (3) they did not perform strength training in the last six months; (4) none of the athletes had a history of neuromuscular or musculoskeletal impairments at the time of the study that could affect the results.

On average, athletes' training experience amounted to (mean ± SD) 11.7 ± 8.6 years, 4.7 ±

Table I. Physiological characteristics of the subjects.

	Control group (n: 12)	Exercise group (n: 13)	*p*
Age (years)	40.3 ± 6.5	36.3 ± 7.4	.170
BM (kg)	70.7 ± 7.9	71.9 ± 9.4	.721
Height (m)	1.75 ± 0.07	1.76 ± 0.08	.797
BMI (kg·m^{-2})	22.9 ± 1.3	23.1 ± 0.9	.735
FFM (kg)	55.7 ± 7.2	55.4 ± 5.4	.901
FM (kg)	14.9 ± 3.9	16.5 ± 5.2	.404
FM (%BM)	21.1 ± 4.8	22.6 ± 4.7	.440
$\dot{V}O_2$max (ml·kg^{-1}·min^{-1})	55.6 ± 4.1	55.2 ± 4.0	.831
RERmax	1.16 ± 0.04	1.14 ± 0.04	.187
HRmax (bpm)	175.6 ± 8.1	176.9 ± 10.2	.736
vmax (km·h^{-1})	17.7 ± 0.8	17.6 ± 0.9	.849
v$\dot{V}O_2$max (km·h^{-1})	17.2 ± 0.7	17.2 ± 0.7	.797
$\dot{V}O_2$ (ml·kg^{-1}·min^{-1})	46.7 ± 2.6	46.9 ± 3.6	0.790
$\dot{V}O_2$ (%$\dot{V}O_2$max)	84.1 ± 4.2	85.1 ± 3.5	.528
RER	0.97 ± 0.03	0.96 ± 0.04	.546
RER (%RERmax)	83.6 ± 3.0	84.5 ± 2.6	.433
HR (bpm)	165.1 ± 9.4	167.8 ± 9.17	.640
HR (%HRmax)	94.0 ± 1.7	94.4 ± 1.8	.597
v (km·h^{-1})	15.7 ± 0.6	15.7 ± 0.4	.716
v (%v$\dot{V}O_2$max)	91.9 ± 2.3	91.0 ± 2.1	.329

Note: All values are means ± SD P: unpaired *t*-test between Control and Exercise groups.
BM: body mass; BMI: body mass index; FFM: fat-free mass; FM: fat mass; $\dot{V}O_2$max: maximal oxygen uptake; RER: respiratory exchange ratio; HR: heart rate; v_{max}: maximal running speed; v$\dot{V}O_2$max: running speed at $\dot{V}O_2$max.

3.4 years of which were spent in ultra-endurance running. They reported to run on average 88.0 ± 33.1 km·week^{-1} and their personal best for the marathon race and 100-km race were (hours:minutes) 3:00 ± 0:17 and 9:00 ± 1:56, respectively.

Experimental design

Subjects came into the laboratory three times. During the first visit, they were fully informed regarding the experimental procedures, underwent medical examination and familiarized with all the experimental procedures.

During the second visit (PRE), body mass, height, body composition and MMP were determined. Then, Cr and spring-mass model parameters at four speeds (8, 10, 12, 14 km·h^{-1}) were calculated before performing a maximal test on a motorized treadmill. We used this test for determining respiratory compensation point (RCP), maximal oxygen uptake ($\dot{V}O_2$max) and the velocity associated with $\dot{V}O_2$max (v$\dot{V}O_2$max). After the second visit the subjects were divided into two homogenous groups (exercise group, EG, $n = 13$; control group, CG, $n = 12$) by using the block randomization. The EG added a 12-week of home-based SEP training protocol to its normal running training whilst the CG continued its usual running training. Immediately after the 12-week SEP training protocol, EG and CG came into the laboratory for the third visit (POST) and underwent the identical procedures performed during the second visit.

Anthropometric characteristics and body composition

Body mass (in kg) was measured with a manual weighing scale (Seca, Germany). Height was measured on a standardized wall-mounted height board and BMI was then calculated. Body composition was measured by bioelectrical impedance analysis (Akern, Italy) by using the software provided by the manufacturer (Bodygram, 1.31).

Energy cost of running and maximal oxygen uptake

Metabolic rate at 8, 10, 12 and 14 km·h^{-1} were measured during four steady state steps performed before a maximal test on a motorized treadmill (Saturn, HP Cosmos, Germany). We decided to use these speeds because they were the most used during the running training and race. Ventilation, oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were measured continuously with a metabolic unit (Quark-b^2, Cosmed, Italy). The volume and gas analysers were calibrated before every trial as described elsewhere (Lazzer et al., 2014). Heart rate was measured with a dedicated device (Polar, Finland). The test included a 5-minute rest period followed by four-running steps at 8, 10, 12, 14 km·h^{-1} for 5 minutes each; then, the speed was increased by 0.7 km·h^{-1} every minute until the volitional exhaustion.

After subtracting the standing metabolic rate to the gross metabolic rate, the Cr (in mlO$_2$·kg^{-1}·m^{-1}) at 8, 10, 12 and 14 km·h^{-1} was calculated as the ratio between the net $\dot{V}O_2$ (averaged in the last minute of every step (Lazzer et al., 2014)) and the corresponding running speed. Respiratory exchange ratio (RER = $\dot{V}CO_2/\dot{V}O_2$) was required to be lower than 1.0. During the incremental test, a levelling off of $\dot{V}O_2$ was observed in all subjects during the last 1 or 2 minutes indicating that $\dot{V}O_2$max was attained. $\dot{V}O_2$max and maximal heart rate were calculated as the average $\dot{V}O_2$ and HR of the last 30 s of the test. RCP was then determined by the V-slope method (Beaver, Wasserman, & Whipp, 1986).

Mechanical measurements

Running mechanics were studied at four different speeds (8, 10, 12, 14 km·h^{-1}) using a digital camera with a sample frequency of 400 Hz (Nikon J1, Japan). The camera was placed next to the treadmill and 10 subsequent steps between the 4th and the 5th min were analysed to measure contact (t_c, s) and aerial (t_a, s) time. Stride frequency (SF, step·s^{-1}) was then calculated as: $0.5/(t_a+t_c)$. Given t_c (s), t_a (s), v (m·s^{-1}), subject's BM (kg), and lower limb length (distance between great trochanter and ground during standing, L in m), spring-mass model parameters were calculated using the method proposed by Morin, Dalleau, Kyrolainen, Jeannin, and Belli (2005).

Maximal power of the lower limbs

The MMP during a squat jump was assessed by means of the Explosive-Ergometer previously described elsewhere (Lazzer et al., 2014). The MMP was obtained from the instantaneous product of the developed force (F, N) and the velocity (v, m·s^{-1}). The trial with the highest peak of power was analysed.

SEP training protocol

EG underwent a 12-week home-based training protocol adding three training sessions/week to its usual running training. These sessions included SEP exercises divided as described below.

Athletes performed the training protocol on alternate days avoiding the day after races or after high intensity or long (>2 h) training sessions. The training protocol was divided into three 4-week cycles. Since it was previously reported (Lazzer et al., 2015) that MMP is related to lower Cr the aim of the training protocol was to improve the MMP by performing explosive exercises. However, our priority was to avoid discomfort and/or injuries for the athletes who underwent the workout and we decided to gradually increase the volume and the intensity of the exercises suggesting the following progression: core training followed by strength training, then explosive and plyometric training. Indeed, the sessions in the first cycle included six sets of exercises for the core (plank, side plank, superman) three sets of exercises for the running technique (walk on toes, walk on heels and butt kicks) and two-to-six sets of exercises for the strength of the lower limbs (single leg half squat and step up). The first-four weeks of training period was devoted as "adaptation" period, to avoid discomfort or lower the injury risk. Indeed, it has been reported that the muscles of the core have a critical role for the transfer of energy from the larger torso to the terminal segments, which may be more involved in the ability to control the position and motion of the trunk over the pelvis during running and allows a better force transfer to the extremities (Kibler, Press, & Sciascia, 2006). Also, core training may improve endurance performance by reducing Cr (Tong et al., 2014). Further, some specific exercises (i.e. high knees, butt kicks …) could affect the running posture, which would lower Cr by moving the ground reaction force application point (Biewener, Farley, Roberts, & Temaner, 2004). The sessions in the second and third cycle included four-to-nine sets of strength exercises (single leg half squat, step up, lunges), two-to-five sets of plyometric exercises (jump rope, high knees) and two-to-six sets of explosive exercises for the lower limbs (counter movement jump, split squat). In addition, in these two cycles, three exercises were performed on unstable board (Disc'o'Sit, Ledraplastic, Italy). Exercises performed on a balance board may reduce the chances for lower back and extremity injuries and would allow exerting greater forces when there is an unstable situation (Behm & Colado, 2012), which is common in trail running.

Participants underwent 5–8 exercises three times per week. 1–3 sets for 6–15 repetitions were performed for each exercise. The sessions lasted about 25–30 min and athletes were free to undergo the workout without rest or with a short rest (<30 s) between each exercise to make more desirable the training programme. The workouts were performed without weight loading. During the first two weeks, athletes performed the exercises in the gym and they were supported by a research assistant, who verified the correct execution of the exercises. Then, all the subjects included in the EG reported to have completed more than 95% of the training programme.

Conversely, the CG continued to perform its normal endurance training, including 5–7 running sessions per week (70–140 km·week^{-1}).

Statistical analyses

Statistical analyses were performed using PASW Statistic 18 (SPSS Inc., USA) with significance set at $p < .05$. All results are expressed as means and standard deviation (SD). Normal distribution of the data was tested using the Shapiro–Wilk test. Sphericity (homogeneity of covariance) was verified by the Mauchly's test. Differences between groups (CG *vs* EG) on anthropometrics characteristics, body composition and physiological characteristics (reported in Table I) were analysed by unpaired two sample Student *t*-test. Changes of anthropometrics characteristics, body composition, MMP, RCP and $\dot{V}O_2$max were studied with a general linear model repeated measures considering two factors (time: PRE and POST; group: CG and EG) and interaction (Time × Group). Changes of Cr, biomechanical and spring-mass model parameters were studied with a general linear model repeated measures considering three factors (speed: 8, 10, 12, 14 $km \cdot h^{-1}$; time: PRE and POST; group: CG and EG). When significant differences were found, a Bonferroni post hoc test was used to determine the exact location of the difference. The magnitude of the changes was assessed using effect size (ES) statistic and percentage change. The interpretation of ES was as follows: <0.2 = trivial, 0.2–0.49 = small, 0.5–0.79 = medium, >0.80 = large (Cohen, 1992). In addition, the relationship between changes in mechanical parameters and MMP was investigated using Pearson's product–moment correlation coefficient.

Results

Physiological characteristics of the athletes

No significant differences were found between CG and EG on anthropometrics and body composition characteristics, in $\dot{V}O_2$max, $\dot{V}O_2$ at RCP and speed at RCP (Table I). Moreover, no significant differences were detected in any of the physiological characteristics of all athletes (CG and EG) between PRE and POST.

Energy cost of running

At PRE, no significant differences were shown in Cr between CG and EG. Further, Cr at 8 $km \cdot h^{-1}$ was significantly higher than Cr at other selected speeds in CG and in EG (+6.5 ± 2.0% on average, $p < .001$, ES:0.47, small). Conversely, Cr was not significantly different between 10, 12 and 14 $km \cdot h^{-1}$ ($p > .05$) in both groups.

At POST, Cr was not different between PRE and POST in CG. On the other hand, Cr decreased significantly in EG at all tested running speeds (−6.4 ± 6.5%, $p = .005$, ES:0.43, small at 8 $km \cdot h^{-1}$; −3.5 ± 5.3%, $p = .032$, ES:0.48, small at 10 $km \cdot h^{-1}$; −4.0 ± 5.5%, $p = .020$, ES:0.34, small at 12 $km \cdot h^{-1}$; −3.2 ± 4.5%, $p = .022$, ES:0.35, small at 14 $km \cdot h^{-1}$, Figure 1). Interestingly, at POST, Cr was significantly lower in EG than CG at every tested speed (−6.2 ± 1.7% on average, $p < .05$, ES:0.44, small).

Running mechanics and spring-mass model parameters

At PRE, no significant differences were shown in spring-mass model parameters between CG and EG.

As well, in the EG contact time (t_c, Figure 2(A)) significantly decreased by mean −8.9 ± 4.2% (ES:0.50, medium) as a function of speed. Further, in the EG the following mechanical parameters significantly increased as a function of the speed ($p < .05$): aerial time (t_a, mean +30.1 ± 33.4%, ES:0.30, small, Figure 2(B)), SF (mean +2.6 ± 0.1%, ES:0.32, small, Figure 2(C)), stride length (SL, mean +17.6 ± 4.0%, ES:0.85, large, Figure 2(D)), maximal ground reaction force (F_{max}, mean +7.1 ± 5.1%, ES:0.33, small), leg-length-changes (ΔL, mean +12.9 ± 1.6%, ES:0.51, medium) and vertical stiffness (k_{vert}, mean +7.2 ± 1.0%, ES:0.29, small). While leg stiffness (k_{leg}) decreased as a function of the speed by mean −4.6 ± 5.1% (ES:0.14, trivial) and Δz did not change significantly. At POST, similar changes in the above-mentioned parameters, as a function of speed, were observed in the EG.

After the training protocol, in the EG t_c increased at 8, 10 and 12 $km \cdot h^{-1}$ by mean 4.4 ± 0.1% (Figure 2(A), $p < .05$, ES:0.24, small) and t_a decreased by −25.6% ($p = .035$, ES:0.22, small) at 8 $km \cdot h^{-1}$,

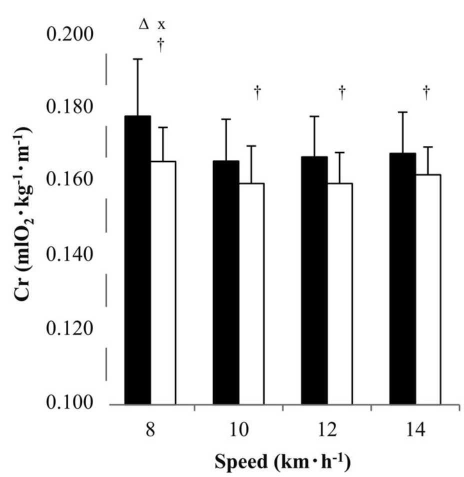

Figure 1. Cr ($mlO_2 \cdot kg^{-1} \cdot m^{-1}$) as a function of speed ($km \cdot h^{-1}$) in exercise group ($n = 13$), before (PRE, black bars) and after (POST, white bars) the training period. All values are means ± SD Δ, *x*: significantly higher compared with 10, 12, 14 $km \cdot h^{-1}$ before and after the training period, respectively; †: significantly different POST *vs*. PRE.

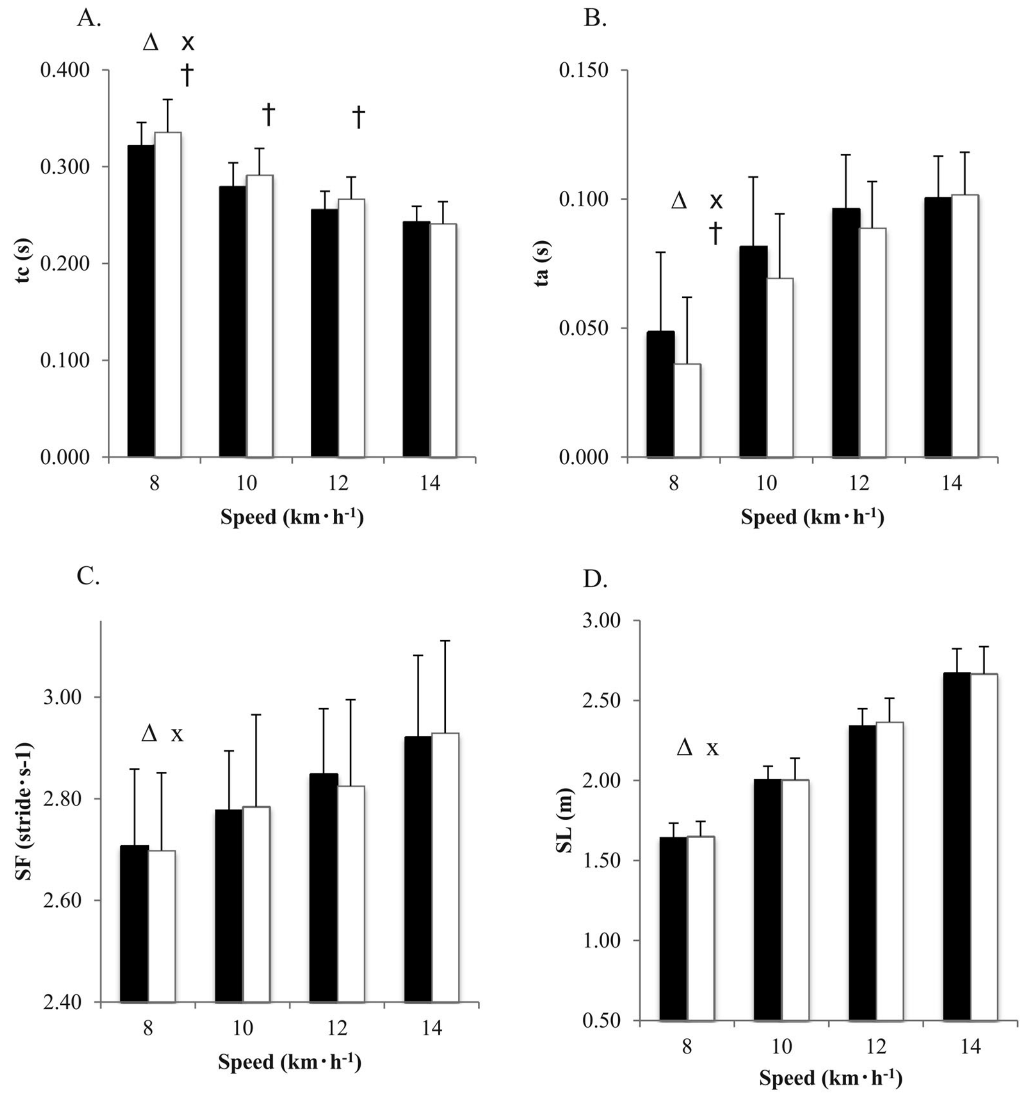

Figure 2. t_c (in s, Figure 2(A)), t_a (in s, Figure 2(B)), SF (in stride·s^{-1}, Figure 2(C)) and SL (in m, Figure 2(D)) in EG (n = 13), before (PRE, black bars) and after (POST, white bars) the training period. All values are means ± SD Δ, x: significantly different compared with 10, 12, 14 km·h^{-1} before and after the training period, respectively; †: significantly different POST *vs.* PRE.

while t_a decreased but not significantly at 10 and 12 km·h^{-1} (−15.2%, p = .093, ES:0.24, small and −8.0%, p = .117, ES:0.17, trivial, respectively) (Figure 2(B)). Then, F_{max} decreased by −3.7% (p = .032, ES: 0.20, small) at 8 km·h^{-1} and it slightly decreased at 10 and 12 km·h^{-1} (−4.4%, p = .077, ES:0.23, small, and −3.3%, p = .076, ES:0.22, small, respectively). Further, k_{leg} decreased at 10 and 12 km·h^{-1} (−9.5%, p = .034, ES:0.33, small., and −10.1%, p = .038, ES:0.33, small, respectively), while the decrease was not significant at 8 km·h^{-1} (−7.6%, p = .054, ES:0.28, small). No changes in SF, SL (Figure 2(C) and 2(D), ΔL, k_{vert} and vertical displacement of centre of mass (Δz) were detected in the EG after the training protocol. In addition, in the CG no differences in the above-mentioned parameters were detected between PRE and POST.

MMP of the lower limbs

At PRE, MMP was not significantly different between CG and EG in absolute (2961 ± 422 *vs.* 3257 ± 632 W, p =.186) and relative (42.3 ± 6.72 *vs.* 43.8 ± 7.4 W·kg^{-1}, p = .585) values. Similarly, at POST, MMP tended to increase in the EG (+5.1 ± 12.2%, p = .174) while it remained unchanged in the CG (+0.4 ± 8.5%, p = .874). In addition, EG showed inverse relationships between changes in Cr and MMP at 10 (p = .013, r = −0.67) and 12 km·h^{-1}- (p < .001, r = −0.86) (Figure 3).

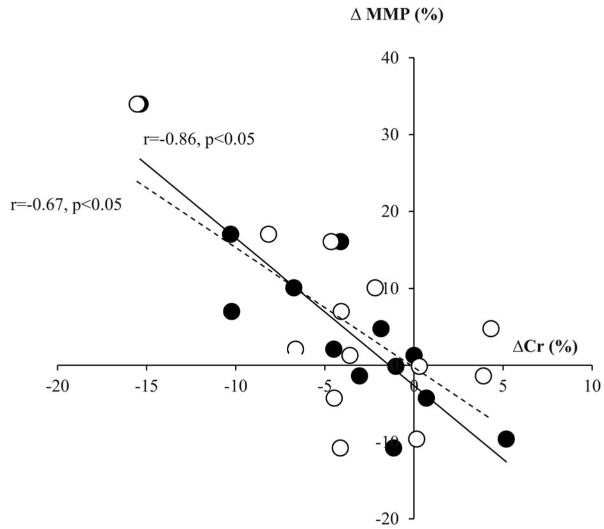

Figure 3. Relationships between changes in energy cost of running (ΔCr, %) and maximal muscle power (ΔMMP, %) in the exercise group (EG) at 10 km·h^{-1} (white dots, ——) and 12 km·h^{-1} (black dots).

Discussion

The main findings of the present study showed that in well-trained ultra-marathoners a 12-week SEP training protocol performed at home led to a lower Cr at submaximal speeds and t_c and MMP might have an important role in decreasing Cr.

We confirm our (I) hypothesis since in well-trained ultra-marathoners SEP training led to a lower Cr (−4.3 ± 1.5%), considering the four-selected running speeds altogether. We tested the range of speeds the athletes likely select during ultra-marathons (on average they ran a 100-km race in 9:00 ± 1:56 h, which means ∼11 km·h^{-1}) or during most of their training. The improvement in Cr (∼4%) might seem like a small progress; however, for these athletes a small performance enhancement can lead to an important step forward in the final rankings. According to the equation of di Prampero et al. (1986), where the endurance running speed is determined by the ratio between metabolic power and Cr, and assuming that athletes run a 100 km race at 70% of their $\dot{V}O_2$max (Davies & Thompson, 1979), decreasing Cr by 4% would improve their performance by ∼17 min (from 7h05' to 6h48'). Although this computation does not consider possible changes in Cr due to the distance covered (Lazzer et al., 2014; Vernillo et al., 2016) it highlights the relevance of Cr in ultra-endurance competitions.

Previous work (di Prampero et al., 1986) described that Cr is independent from the speed. However, at 8 km·h^{-1} we reported higher Cr compared to other speeds (+6.5 ± 2.0%). We suppose that this could be because these athletes never run slower than ∼10 km·h^{-1}, thus they are not adapted to this slow speed. They can carry out a 100-km running race in less than 10 h and some of them could run more than 240 km in 24 h running race. Farley, Blickhan, Saito, and Taylor (1991) predicted that metabolic rate increases at lower frequency during hopping because the body does not behave in an optimal spring-like manner and some elastic energy is dissipated. If we compare running to a series of subsequent hops, this may explain the higher Cr at 8 km·h^{-1} compared with other "optimal speeds".

In the present study SL and SF did not change after the training protocol, as previously shown by Ferrauti et al. (2010). These authors considered recreational marathon runners who underwent to 8-week intervention that consisted in two strength-training sessions per week. While they showed no significant changes in Cr, t_c increased at 8.6 and 10.1 km·h^{-1} by ∼3%. Regarding t_c, our results agree with this work, since it increased by mean +4.4 ± 0.1% at 8, 10 and 12 km·h^{-1} at POST. According to the cost of generating force hypothesis, running with a longer t_c should be more economical, since it requires slower and less expensive fibres and the force is applied in a longer period of time (Kram & Taylor, 1990). In agreement with this hypothesis the increased t_c could in part explain the lower Cr. It is necessary to point out that this study is cross-sectional and their theory derives from an inter-species comparison, so it is not known if it can be extended to humans. However, other authors (Di Michele & Merni, 2014) reported that longer t_c is related to lower Cr, and this may be particularly important when athletes compete in long-distance running. Conversely, Paavolainen et al. (1999) reported a decreased t_c along with a decrease in Cr and authors explained these results as a better adaptation of the neuromuscular characteristics. Nevertheless, we did not collect information about the neuromuscular characteristics, since we did not have electromyographic data during the running trials.

We reject our second hypothesis although MMP during the squat jump slightly increased (+5.1 ± 12.1%, p = .174) after the SEP training protocol. Anyway, this increase was not significant as opposed to previous studies' results (Hoff et al., 2002; Millet, Jaouen, Borrani, & Candau, 2002). We suppose that for these athletes the training protocol was too light and probably they need to train with maximal loads to improve the MMP. Since ultra-endurance athletes are rarely professionals (no one among the subjects we enrolled), we proposed a training protocol that athletes could easily perform at home three times per week without renouncing to their usual running training. However, an inverse relationship between changes in MMP and changes in Cr at 10 and 12 km·h^{-1} (Figure 3) suggests that athletes who slightly improved their MMP also decreased their Cr at submaximal speeds suggesting that MMP is an important parameter in determining Cr, as previously shown. In addition, since changes in Cr affect the final performance and higher MMP is related to lower increase in Cr, improving MMP with SEP training may help athletes to limit Cr changes during an ultra-endurance events, obtaining better results (Lazzer et al., 2015; Lazzer et al., 2014).

Several adaptive mechanisms may be involved in the decrease of the Cr after a concurrent strength-training protocol (Aagaard et al., 2011; Millet et al., 2002). We analysed some aspects of the mechanics of running (t_c, t_a, k_{leg}, k_{vert}, Δz and ΔL) but we reported no changes, except for the t_c. Previous studies supported the idea that power training leads to a higher muscle tendon complex stiffness (Millet et al., 2002; Spurrs et al., 2003) that affects positively the Cr (Arampatzis et al., 2006) but we do not have information about these aspects. We can assume that, well-trained athletes need longer and/or heavier training protocol to stimulate tissue changes, whereas in a group of both physically active and untrained subjects 4 weeks of training were enough to increase the synthesis of collagen type I in triceps surae tendon (Langberg, Rosendal, & Kjaer, 2001).

Critique of methods

The low magnitude of the results obtained in the present study is probably because athletes enrolled were well-trained and the training protocol they underwent was probably too light to induce significant muscular changes. Probably, some exercise performed with some weight would lead to more important changes. Nevertheless, we preferred to propose a training protocol that could be easily performed at home by not professional athletes and they could integrate this specific training in their habitual activities. Further, we could not measure the real improvement in real setting, and we can only suppose that the performance is improved because Cr decreased.

Practical applications

Results from the present study provide evidence that well-trained ultra-endurance runners may obtain advantages from an easy-to-perform home-based training protocol. Even if we did not report significant increase in the MMP we can assume that this training protocol leads to an improvement of the endurance performance. We proposed an alternative training method to the power training in the gym, which may be poorly accepted by many runners. However, since we did not register big improvements we suggest to perform some exercise with overload (i.e. lunges, squat …), to maximize the effects of this training protocol.

Conclusions

In summary, 12-week home-based SEP training programme led to a Cr improvement in well-trained ultra-endurance runners at different submaximal speeds. Increased t_c and an inverse relationship between changes in Cr and changes in MMP can partially explain the decreased Cr. Even if the mechanisms that led to a lower Cr are not clarified, we suggest adding at least three sessions per week of SEP exercises in the normal endurance-training programme.

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No competing interests, financial or otherwise, are declared by the author(s).

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