International Journal of Sports Physiology and Performance, 2015, 10, 238-247
http://dx.doi.org/10.1123/ijspp.2014-0057

INTERNATIONAL JOURNAL OF
SPORTS PHYSIOLOGY
AND PERFORMANCE
www.IJSPP-Journal.com
ORIGINAL INVESTIGATION

Effects of the Etna Uphill Ultramarathon on Energy Cost and Mechanics of Running

Stefano Lazzer, Desy Salvadego, Paolo Taboga, Enrico Rejc, Nicola Giovanelli, and Pietro E. di Prampero

Purpose: To investigate the effects of an extreme uphill marathon on the mechanical parameters that are likely to affect the energy cost of running (*C*r). ***Methods:*** Eleven runners (27–59 y) participated in the Etna SuperMarathon (43 km, 0–3063 m above sea level). Anthropometric characteristics, maximal explosive power of the lower limb (P_{max}), and maximal oxygen uptake were determined before the competition. In addition, before and immediately after the race, *C*r, contact (t_c) and aerial (t_a) times, step frequency (*f*), and running velocity were measured at constant self-selected speed. Then, peak vertical ground-reaction force (F_{max}), vertical downward displacement of the center of mass (Δz), leg-length change (ΔL), and vertical (k_{vert}) and leg (k_{leg}) stiffness were calculated. ***Results:*** A direct relationship between *C*r, measured before the race, and race time was shown ($r = .61$, $P < .001$). *C*r increased significantly at the end of the race by 8.7%. Immediately after the race, the subjects showed significantly lower t_a (–58.6%), *f* (–11.3%), F_{max} (–17.6%), k_{vert} (–45.6%), and k_{leg} (–42.3%) and higher t_c (+28.6%), Δz (+52.9%), and ΔL (+44.5%) than before the race. The increase of *C*r was associated with a decrement in F_{max} ($r = –.45$), k_{vert} ($r = –.44$), and k_{leg} ($r = –.51$). Finally, an inverse relationship between P_{max} measured before the race and ΔCr during race was found ($r = –.52$). ***Conclusions:*** Lower *C*r was related with better performance, and athletes characterized by the greater P_{max} showed lower increases in *C*r during the race. This suggests that specific power training of the lower limbs may lead to better performance in ultraendurance running competition.

Keywords: maximal oxygen uptake, cost of transport, trail, kinematics, stiffness

The energy cost of running (*C*r), together with maximal aerobic power (VO_{2max}), its fraction (*F*) sustained throughout the competition, and the maximal capacity of the anaerobic stores, represents the main factor determining running performances.[1] *C*r, defined as the amount of energy spent above resting to transport 1 kg body mass over 1 m distance (expressed in $J \cdot kg^{-1} \cdot m^{-1}$ or $mL\ O_2 \cdot kg^{-1} \cdot m^{-1}$), plays a relevant role in determining performance in middle- and long-distance runners with the same VO_{2max} and *F*.[2] Its average value is $0.182 \pm 0.014\ mL\ O_2 \cdot kg^{-1} \cdot m^{-1}$ ($3.75 \pm 0.29\ J \cdot kg^{-1} \cdot m^{-1}$),[1] with an interindividual variability of about 10%, and with lower values in endurance runners than in middle-distance runners.

*C*r is unaffected by speed from about 2.2 to 5 m/s,[1] where air resistance plays a minor role—less than 5% of the total energy cost.[3] In long-distance runners, *C*r increases with the distance covered because of fatigue effects. Brueckner et al[4] observed an increment of *C*r of about 0.142%/km of distance during a marathon, with a total increase greater than 5%. Indeed, Gimenez et al,[5] in subjects who ran 24 hours on a motorized treadmill, observed a substantial increase in *C*r after 8 hours; in addition, the subjects who maintained the highest speed (expressed in percentage of the velocity attained at VO_{2max}) were those having the smallest *C*r increase over the 24 hours. Furthermore, several authors[6,7] have shown that, in mountain ultramarathons, the changes in *C*r are brought about by changes in the mechanics of running, the principal aim of which is to minimize damage to lower-limb tissue, muscle fatigue, and symptoms associated with prolonged running over irregular terrain with a large positive/negative elevation variation along the race.[8,9]

The mechanics of running in different conditions have been frequently investigated using the spring-mass model,[10] that is, representing the leg in contact with the ground as a simple linear spring. In this model, the parameters most frequently studied are the leg (k_{leg}) and vertical (k_{vert}) stiffness coefficients associated with leg-spring deformation (ΔL) and with the vertical displacement (Δz) of the center of mass, respectively. Thus, whereas k_{vert} is a measure of the resistance of the body to vertical displacement after application of ground-reaction forces, k_{leg} is the resistance to change in leg length after application of internal or external forces.

The effects of long and ultralong races on running mechanics have recently been investigated. Morin et al,[11] considering a mountain ultramarathon race (166 km, total positive and negative elevation of 9500 m), showed that athletes significantly reduced ($P < .001$) aerial time (t_a), peak vertical ground-reaction force (F_{max}), and Δz with an increment in step frequency (*f*). On the other hand, the contact time (t_c) was not different from before the race. Furthermore, there was a nearly significant ($P = .053$) change in k_{vert}, which increased by 6% after the race. This study supports previous findings[12] where the same behavior of *f*, brought about by a shorter t_a with no changes in t_c, was reported. Conversely, after 24 hours of level treadmill running, Morin et al[13] observed a reduction in F_{max}, Δz, and ΔL and an increment in k_{vert} and *f*, but with lower t_c and constant t_a. This discrepancy in changes of t_c and t_a compared with previous studies could be due to the different mechanics of uphill and downhill mountain running compared with treadmill running. As evidenced by Fourchet et al,[14] a 5-hour hilly run induces different effects on ankle muscles than flat running; in particular, only plantar-flexor muscles are affected by neuromuscular alterations,

Lazzer, Salvadego, Taboga, Rejc, and Giovanelli are with the Dept of Medical and Biological Sciences, and di Prampero, the School of Sport Sciences, University of Udine, Udine, Italy. Address author correspondence to Stefano Lazzer at stefano.lazzer@uniud.it.

likely leading to different running mechanics between mountain and flat runs.

Indeed, interventions to reduce *C*r are constantly sought after by athletes, coaches, and sport scientists. Strength[15] and plyometric[16] training allow muscles and tendons to use more elastic energy and to reduce the amount of energy wasted in braking forces, thus reducing *C*r.

Therefore, the purpose of the current study was to investigate the effects of an extreme uphill marathon on several mechanical parameters that are likely to affect *C*r.

Research Design and Methods

Participants

Sixteen healthy Italian male runners (age range 27–59 y) were enrolled in this study as participants in the uphill marathon named the Etna SuperMarathon. The experimental protocol was approved by the ethics committee of the University of Udine. Before the study began, the purpose and objectives were carefully explained to each subject, and written informed consent was obtained from all of them. Subjects having overt metabolic and/or endocrine diseases and those taking medications regularly or using drugs known to influence energy metabolism were excluded. The participants were recruited from experienced ultraendurance runners who filled out questionnaires on physical exercise activity, demographics, medical history, and lifestyle.[17] All the participants of this study had run at least 1 ultraendurance race in their career. On average, subjects had 9.3 ± 5.4 and 5.8 ± 5.6 years of training history and of running ultraendurance races, respectively. They reported to run on average 69.2 ± 23.5 km every week. Sixteen athletes who were eligible for the study began the race, and the 11 who completed the entire competition were taken into account for data analysis.

Experimental Protocol

One week before the race, the subjects came to the exercise physiology laboratory, where anthropometric characteristics, mechanical power of the lower limbs, and a graded exercise test to exhaustion on a treadmill were assessed. The subjects were asked to refrain from any vigorous physical activity during the day preceding the test and during the preliminary testing session that they performed to familiarize themselves with all the different equipment.

The Etna SuperMarathon took place in June 2012. The race started at 8 AM from the beach of Marina di Cottone (Catania, Italy), at sea level, with temperature and relative humidity of 29°C and 42%, respectively. Athletes covered about 30 km on the road to the Etna volcano, while the last part of the race took place on a path of lava rock. After a total distance of about 43 km, athletes reached the finish line, covering an altitude difference of 3063 m with a mean slope of about 7% and with peak values reaching 14% (Garmin Forerunner 305 GPS, Kansas City, MO, USA). At the finish, temperature and relative humidity were 21°C and 52%, respectively.

The day before the race and immediately after the end of the race (4 ± 2 min), body mass (BM), *C*r, respiratory-exchange ratio (RER), and running mechanics were measured.

Physiological Measurements Before the Race

BM was measured to the nearest 0.1 kg with a manual weighing scale (Seca 709, Hamburg, Germany), and height was measured to the nearest 0.001 m on a standardized wall-mounted board. Body-mass index (BMI) was calculated as BM: kg/height^2 (m).

Maximal power of the lower limbs during a countermovement jump was assessed by means of the Bosco et al[18] test (Ergo Jump, Boscosystem, Italy). VO_{2max} and maximal heart rate (HR_{max}) were determined during a graded exercise test on a treadmill (Saturn, HP Cosmos, Germany) under medical supervision. During the experiment, ventilatory and gas-exchange responses were measured continuously with a metabolic unit (Quark-b^2, Cosmed, Italy). The volume and gas analyzers were calibrated using a 3-L calibration syringe and calibration gas (16.00% O_2, 4.00% CO_2), respectively. During the tests, electrocardiogram was continuously recorded and displayed online for visual monitoring, and HR was measured with a dedicated device (Polar, Finland). Before the start of the study, subjects were thoroughly familiarized with treadmill running.

The tests were performed 1 week before the race and consisted of a 5-minute rest period followed by running at 10 km/h for 5 minutes (treadmill slope: 1%); the speed was then increased by 0.7 km/h every minute until volitional exhaustion. A leveling off of VO_2 (defined as an increase of no more than 1 mL · kg^{-1} · min^{-1}) was observed in all subjects during the last 1 or 2 minutes of the exercise test, indicating that VO_{2max} had been attained. VO_{2max} and HR_{max} were calculated as the average VO_2 and HR of the last 20 seconds of the test.

*C*r and Mechanical Measurements During the Race

The day before and immediately after the race, the subjects ran for 6 minutes at a constant self-selected speed on 2 oval compact rock paths situated near the start line (at sea level) and near the finish line (at 3063 m above sea level), respectively. Both compact rock paths were flat and 50 m long.

*C*r and RER were measured continuously with a portable metabolic unit (k4, Cosmed, Italy). The analyzer, calibrated before each testing session, provided breath-by-breath data recording. The last minute of sampling was used for further analysis. For all subjects, real-time plots of VO_2 and RER indicated that metabolic steady state was achieved after 5 minutes. Net VO_2, obtained by subtracting preexercise standing VO_2 (measured for 6 min in resting condition before the race) from gross VO_2, was converted to joules using an energetic equivalent for O_2 based on the RER. This RER was always below 1.0, confirming that aerobic metabolism was the main metabolic pathway. *C*r was then obtained by dividing net energy expenditure (J · kg^{-1} · s^{-1}) by running speed (v, m/s); the latter was measured by means of 2 photocells placed immediately before and after the video-recording zone (see below), with a distance of 10 m between them. In addition, average lap speed was obtained by dividing the circuit length by the time needed to cover it. Average lap speed was not significantly different than running speed measured in the video-recording zone. All subjects were also asked to maintain the same self-selected speed during the tests before and after the race.

The running mechanics were studied using a digital camera with a sample frequency of 400 Hz (Nikon J1, Japan). The camera was placed perpendicular to the running direction of the athletes. For each subject, video was recorded between the fourth and the sixth minutes of running. Ten subsequent representative steps were analyzed, taking into account t_c (s) and t_a (s).

Step frequency (step/s) was calculated as $f = 1/(t_a + t_c)$. Given t_c (s), t_a (s), v (m/s), subject BM (kg), and lower-limb length (distance between great trochanter and ground during standing, L in m), spring-mass parameters were calculated using the computation method proposed by Morin et al.[19] This method, based on modeling of the ground-reaction-force signal during the contact phase by a sine function, allows the computation of k_{vert} (kN/m) as the ratio of the F_{max} (N) to the Δz (m). Then, k_{leg} (kN/m) was calculated as the ratio of F_{max} to ΔL (m) during contact of the foot on the ground.

Statistical Analyses

Statistical analyses were performed using PASW Statistics 18 (SPSS Inc, Chicago, IL, USA) with significance set at $P < .05$. All results are expressed as mean ± SD. Normal distribution of the data was tested using the Kolmogorov-Smirnov test. Changes of BM, *C*r, RER, and mechanical parameters during the competition were studied with the Student paired *t* test. The relationships between mechanical variables affecting *C*r were investigated using Pearson product–moment correlation coefficient.

Results

The physical characteristics before the race of the 11 subjects who completed the race are reported in Table 1, together with their performance time. Their average VO_{2max}, *C*r, and P_{max} were 49.2 ± 8.8 mL $O_2 \cdot m^{-1} \cdot$ kg BM^{-1}, 0.190 ± 0.023 mL $O_2 \cdot m^{-1} \cdot kg^{-1}$, and 1628 ± 212 W, respectively. As reported in Figure 1, a direct relationship between *C*r and race time was observed before ($r = .61$, $P < .001$), as well as after ($r = .48$, $P < .05$), the race. Immediately after the race, *C*r was 8.7% higher ($P < .001$) than before the race; on the contrary, BM and self-selected running speed were 5.7% and 7.3% lower ($P < .05$), respectively, than before the race (Table 2). In addition, subjects showed significantly lower t_a (–58.6%), f (–11.3%), F_{max} (–17.6%), k_{vert} (–45.6%), and k_{leg} (–42.3%) and higher t_c (+28.6%), Δz (+52.9%), and ΔL (+44.5%) than before the race (Table 2).

To identify the main factors affecting *C*r during the race, the mechanical parameters measured before and after the race were plotted for all subjects as a function of *C*r. Pearson correlation coefficients were then used to analyze the association between variables entering these equations. This analysis showed inverse relationships between *C*r and F_{max} ($r = –.45$; Figure 2[c]), *C*r and k_{vert} ($r = –.44$; Figure 2[e]), and *C*r and k_{leg} ($r = –.51$; Figure 2[f]). No significant relationships between *C*r and t_c, t_a, f, Δz, and ΔL were found. Finally, an inverse relationship between mechanical power of the lower limbs measured before the race and changes in *C*r during the race was found ($r = –.52$; Figure 3).

Table 1 Physical Characteristics of Subjects (N = 11) Before the Race

Characteristic	Mean ± SD	Range
Age (y)	43.2 ± 11.0	27.0–59.0
Body mass (kg)	72.9 ± 10.2	57.0–88.0
Stature (m)	1.77 ± 0.07	1.63–1.85
Body-mass index (kg/m^2)	23.1 ± 2.4	20.2–27.4
Lower-limb length (m)	0.89 ± 0.04	0.81–0.94
VO_{2max} (mL · min^{-1} · kg^{-1})	49.2 ± 8.8	37.9–61.5
HR_{max} (beats/min)	176.8 ± 11.0	161.0–193.0
*C*r (mL $O_2 \cdot m^{-1} \cdot kg^{-1}$)	0.190 ± 0.023	0.149–0.224
P_{max} (W)	1628 ± 212	1319–1971
Race time (h:min:s)	6:14:01 ± 1:04:29	4:24:12–7:09:36

Abbreviations: VO_{2max}, maximal oxygen uptake; HR_{max}, heart rate; *C*r, energy cost of running; P_{max}, maximal mechanical power of the lower limbs.

Note: 130 runners started the race, 109 completed it. Of the 11 runners of this study, 4 were classified within the 10th place, 2 between the 30th and 40th, 3 between the 50th and 60th, and 2 between the 70th and 80th.

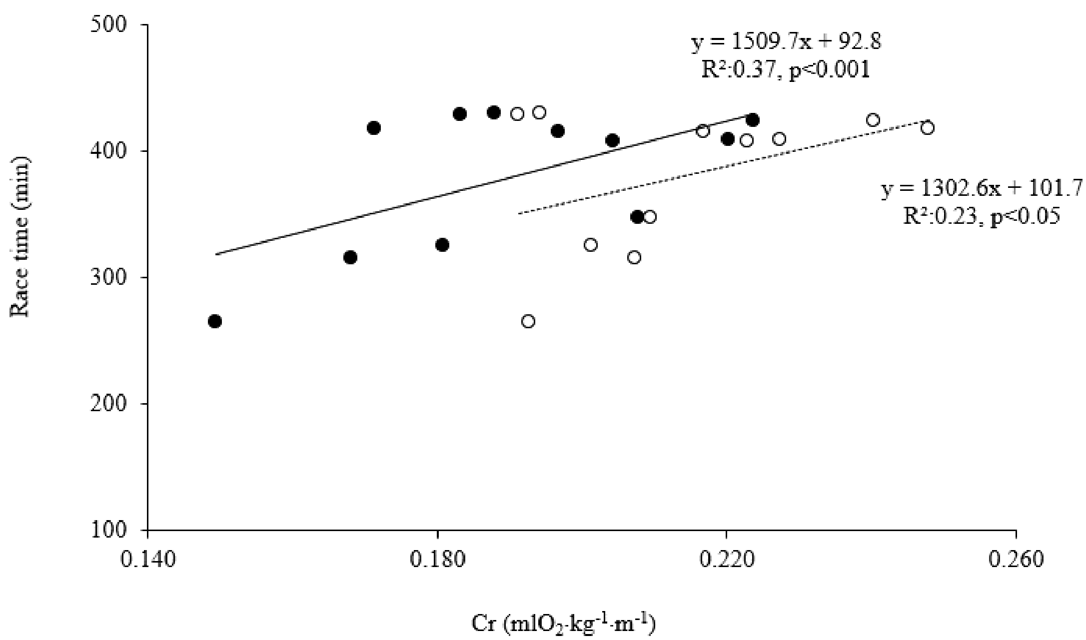

Figure 1 — Race time plotted for all subjects as a function of the energy cost of running (*C*r) measured before (closed circles) and immediately after (open circles) the race.

Discussion

The main results of the current study showed that *C*r is directly related with the race time; *C*r increased significantly at the end of this extreme uphill race (~9%); the increase in *C*r was associated with a decrease in F_{max}, k_{vert} and k_{leg}; and the greater the mechanical power of the lower limbs the lesser the changes in *C*r due to the race.

Several authors have shown that *C*r is an important part of success in athletes with comparable VO_{2max} and *F*, even if conflicting results have also been reported.[2] Millet et al[20] observed, during a 24-hour treadmill run, that *C*r was not directly related to performance but may nevertheless be important to be able to maintain a high $\%VO_{2max}$. In addition, Gimenez et al[5] have shown that *C*r measured before a 24-hour treadmill run was negatively correlated with the speed expressed in $\%VO_{2max}$. This finding suggests that a low *C*r could be important in determining performance during "low-intensity" ultraendurance events, and our results support this view, since *C*r was strongly related with race performance (Figure 1).

Table 2 Body Mass, Energy Cost of Running, Respiratory-Exchange Ratio, and Mechanical Parameters Determined Before and Immediately After the Race, Mean ± SD

	Before	After	Changes %	*P*[a]
Body mass (kg)	72.9 ± 10.2	68.7 ± 9.8	–5.7	.001
Energy cost of running (mL $O_2 \cdot m^{-1} \cdot kg^{-1}$)	0.190 ± 0.023	0.207 ± 0.019	+8.7	.001
Respiratory-exchange ratio	0.88 ± 0.06	0.82 ± 0.08	–6.6	.123
Self-selected running speed (m/s)	2.89 ± 0.17	2.68 ± 0.39	–7.3	.024
Contact time (s)	0.291 ± 0.021	0.375 ± 0.027	+28.6	.001
Aerial time (s)	0.066 ± 0.028	0.027 ± 0.014	–58.6	.001
Step frequency (steps/s)	2.81 ± 0.18	2.49 ± 0.11	–11.3	.001
Maximal vertical ground-reaction force (N)	1380.0 ± 213.1	1136.4 ± 152.9	–17.6	.001
Downward displacement of center of mass during contact (m)	0.067 ± 0.007	0.102 ± 0.013	+52.9	.001
Displacement of the leg spring (m)	0.175 ± 0.020	0.253 ± 0.034	+44.5	.001
Vertical stiffness (kN/m)	20.72 ± 2.81	11.26 ± 1.97	–45.6	.001
Leg stiffness (kN/m)	7.90 ± 0.96	4.56 ± 0.85	–42.3	.001

[a] Significance by Student paired *t* test.

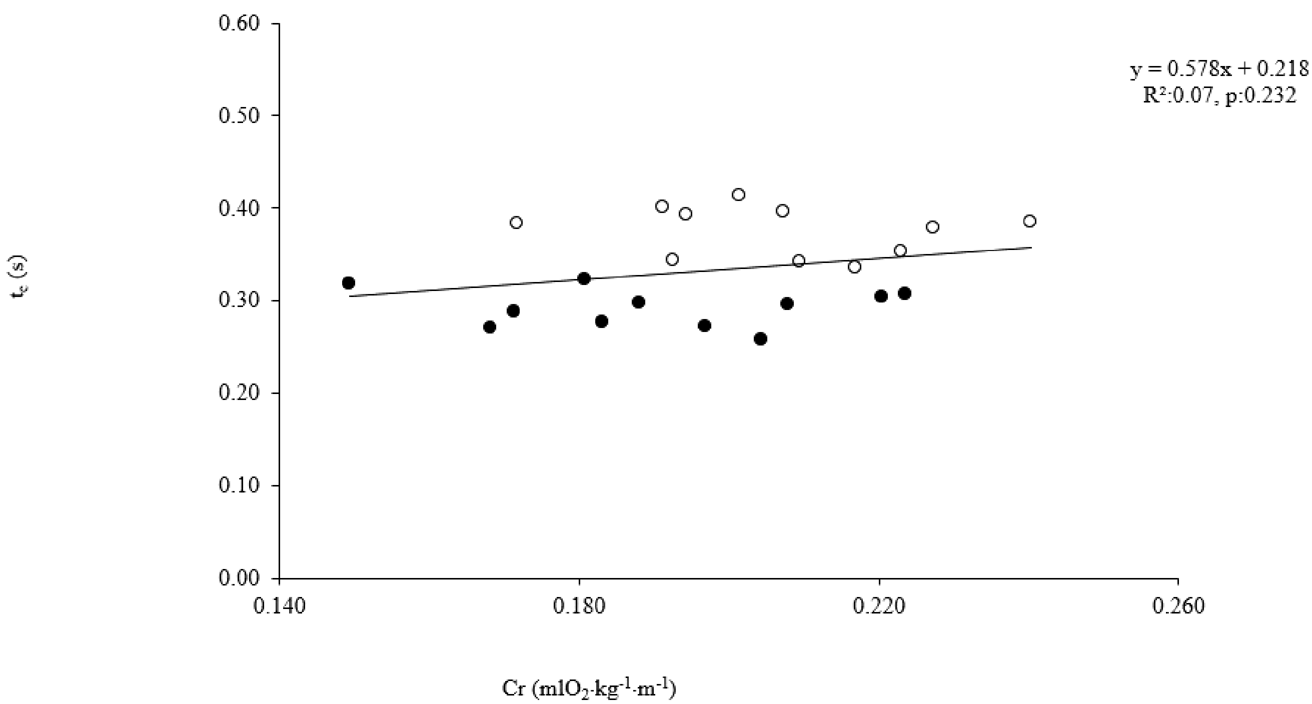

Figure 2(a) —Contact time (t_c) measured before (closed circles) and immediately after (open circles) the race plotted for all subjects as a function of the measured energy cost of running (C_r).

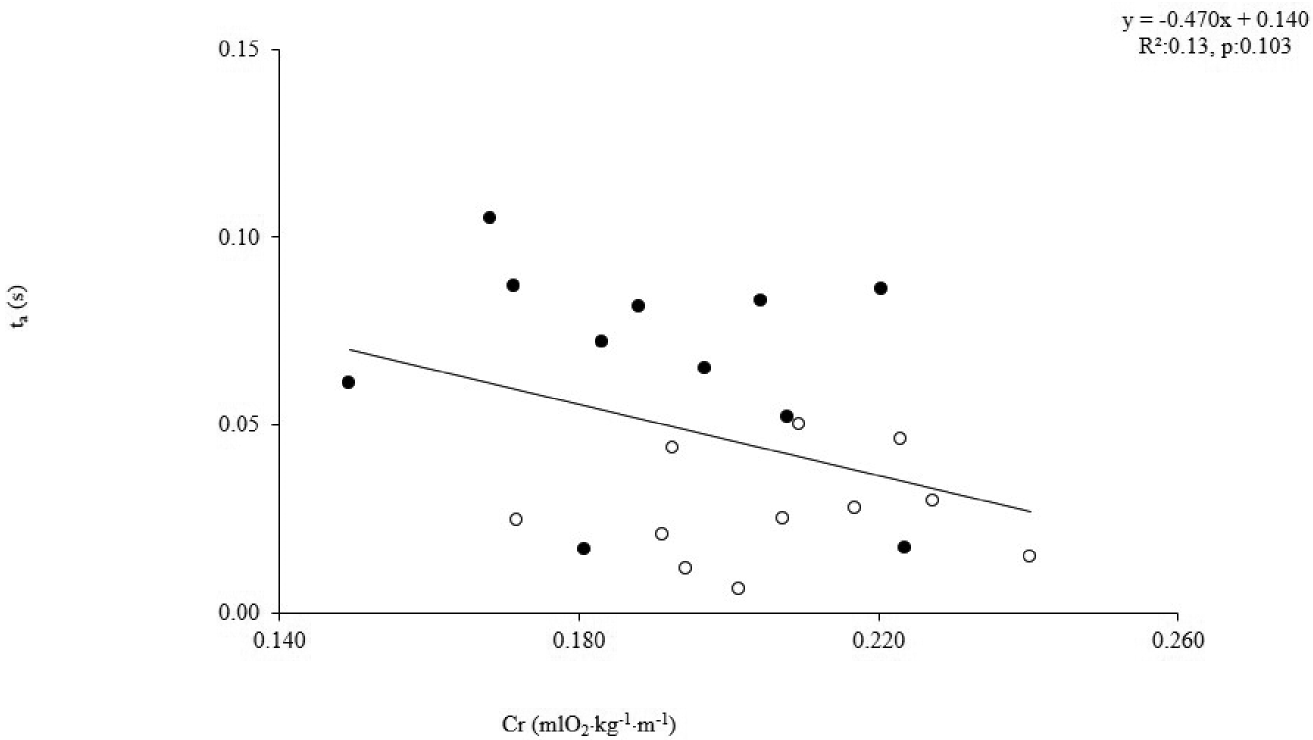

Figure 2(b) — Aerial time (t_a) measured before (closed circles) and immediately after (open circles) the race plotted for all subjects as a function of the measured energy cost of running (C_r).

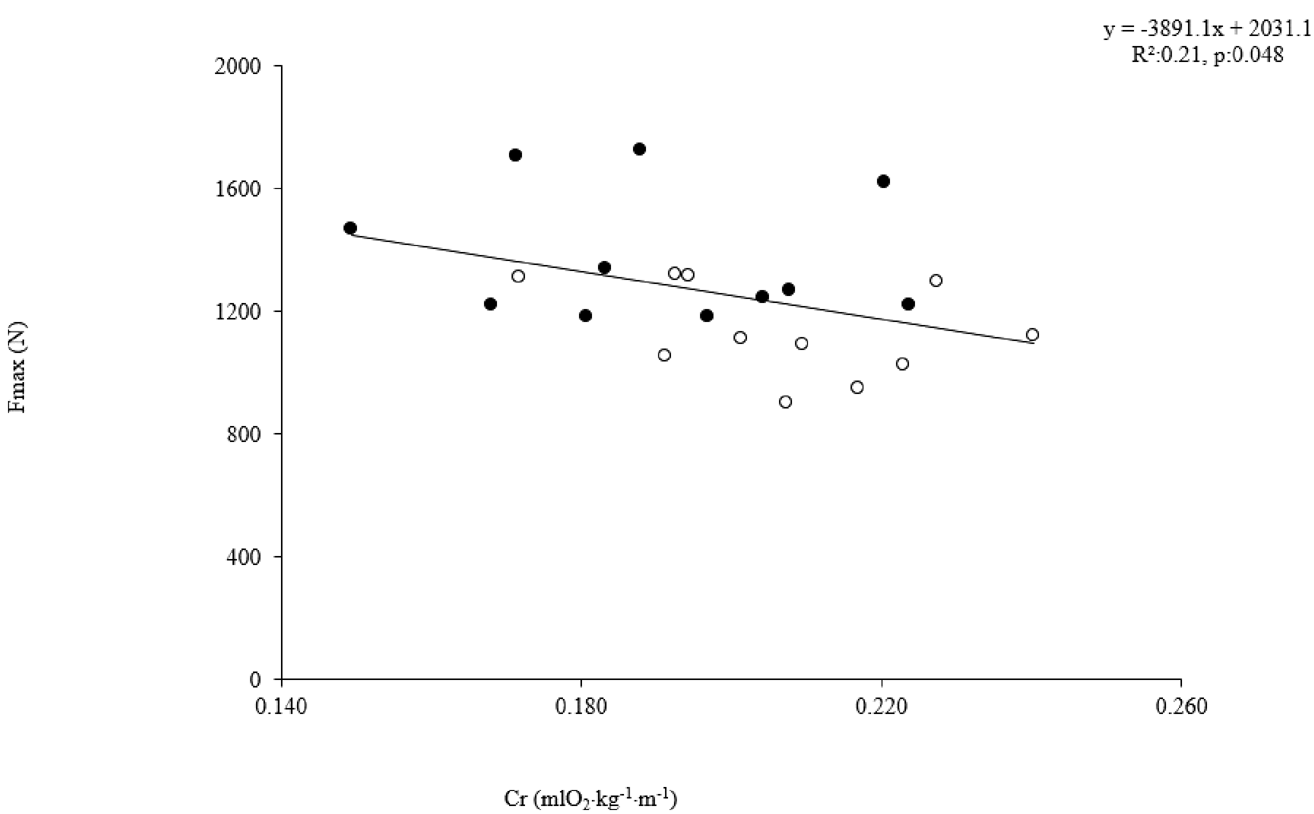

Figure 2(c) — Maximal vertical ground-reaction force (F_{max}) measured before (closed circles) and immediately after (open circles) the race plotted for all subjects as a function of the measured energy cost of running (C_r).

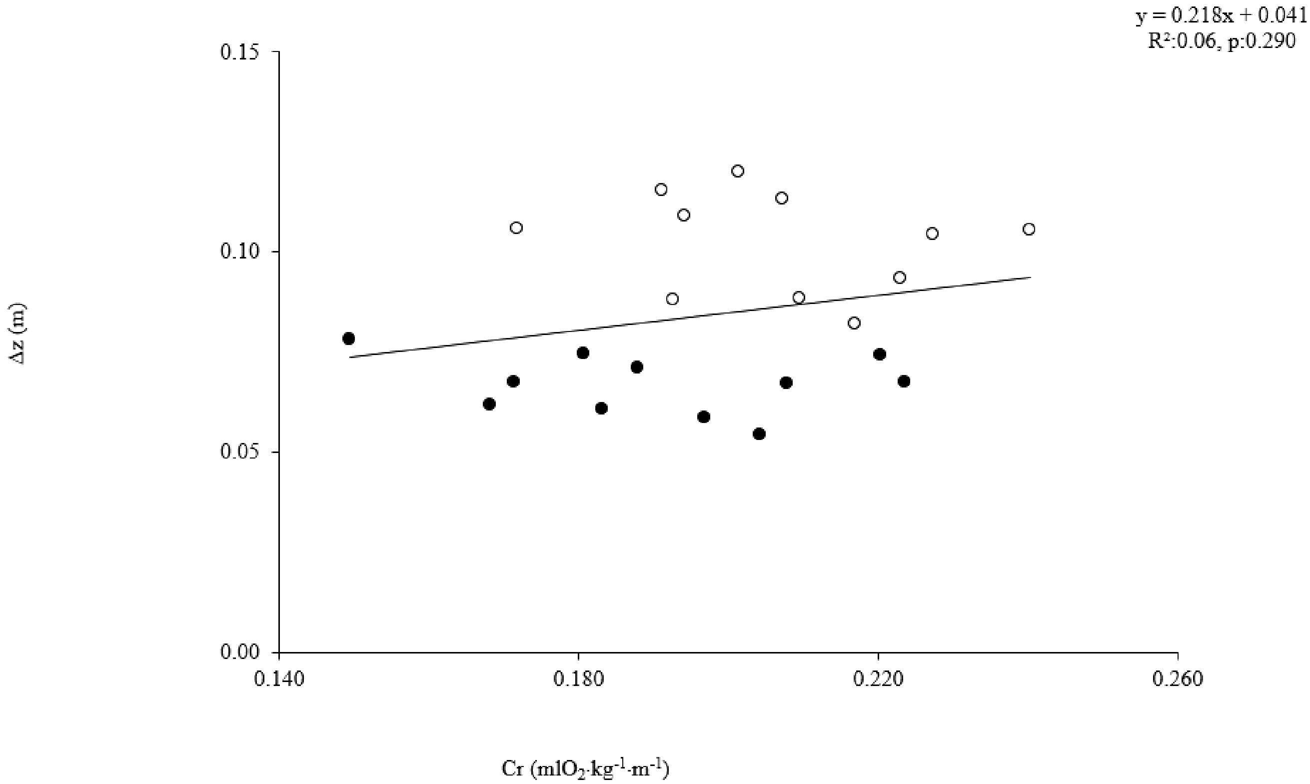

Figure 2(d) — Downward displacement of center of mass during contact (Δz) measured before (closed circles) and immediately after (open circles) the race plotted for all subjects as a function of the measured energy cost of running (C_r).

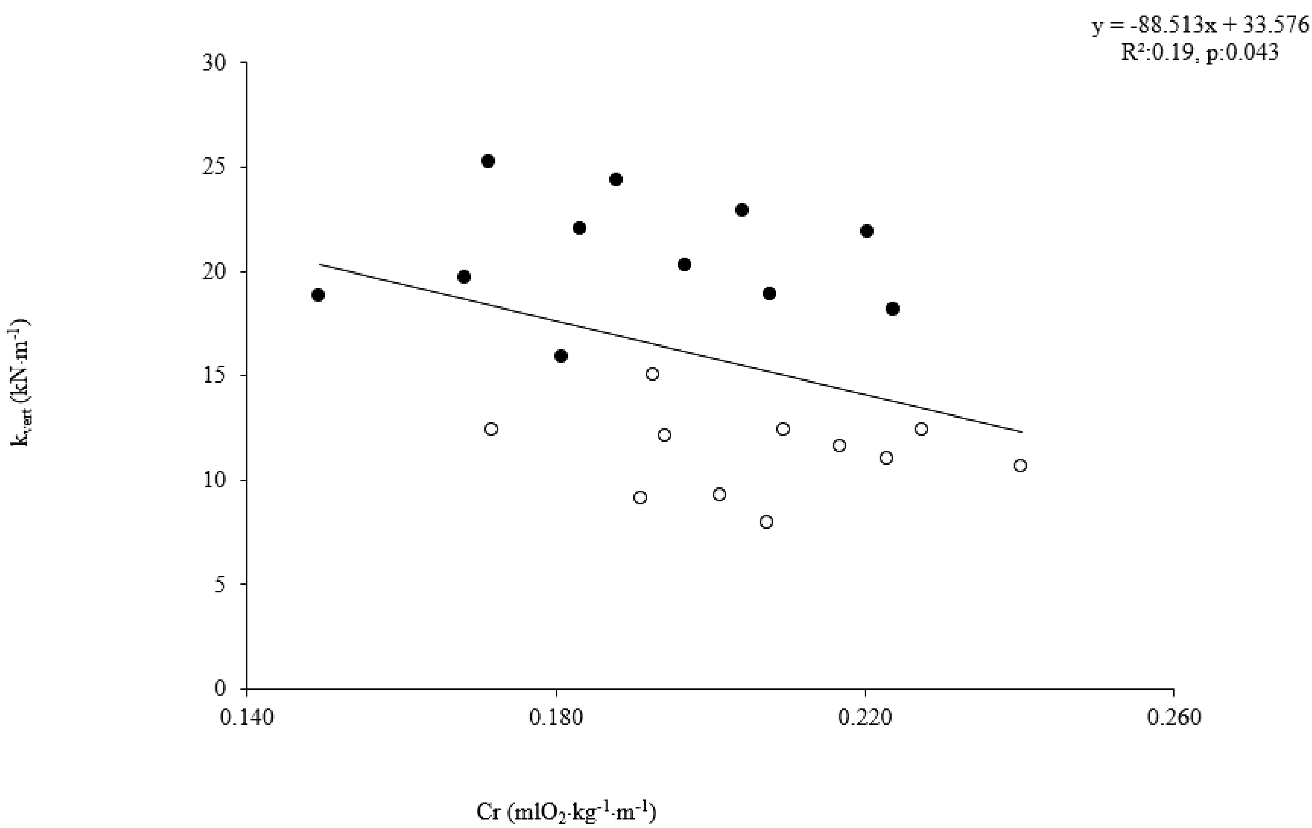

Figure 2(e) — Vertical stiffness (k_{vert}) measured before (closed circles) and immediately after (open circles) the race plotted for all subjects as a function of the measured energy cost of running (C_r).

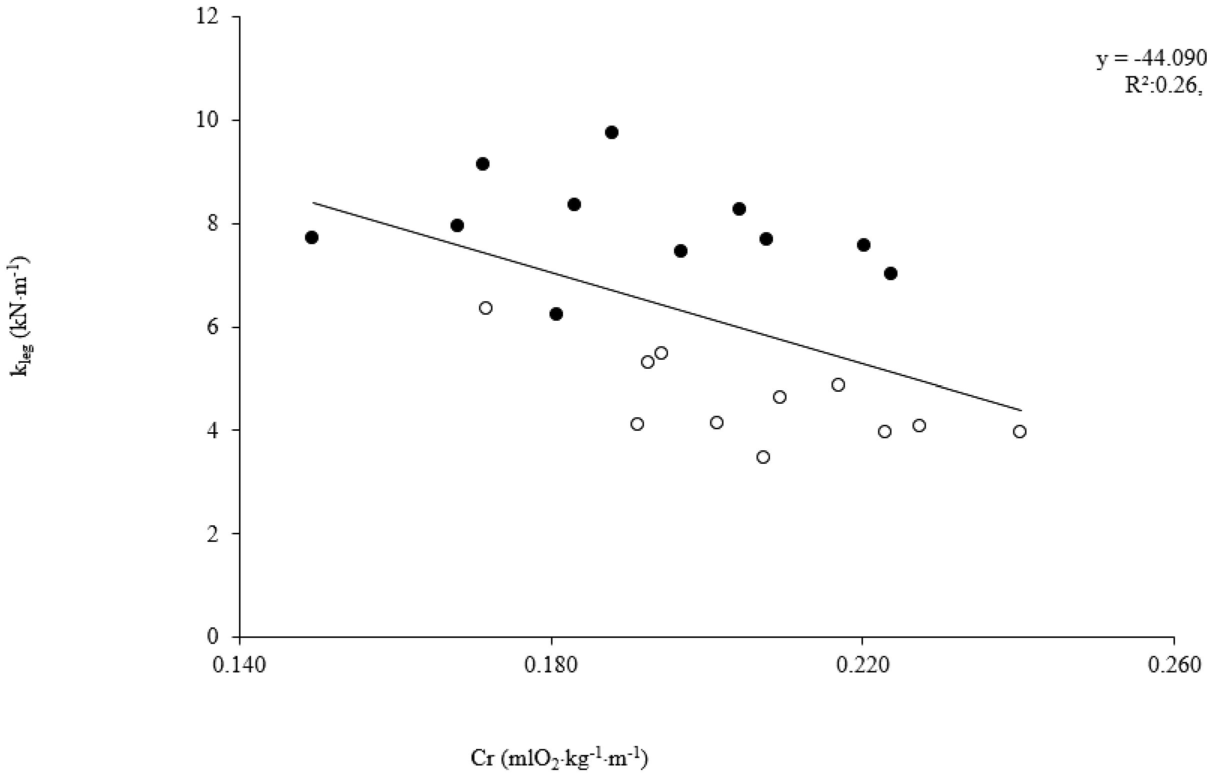

Figure 2(f) — Leg stiffness (k_{leg}) measured before (closed circles) and immediately after (open circles) the race plotted for all subjects as a function of the measured energy cost of running (C_r).

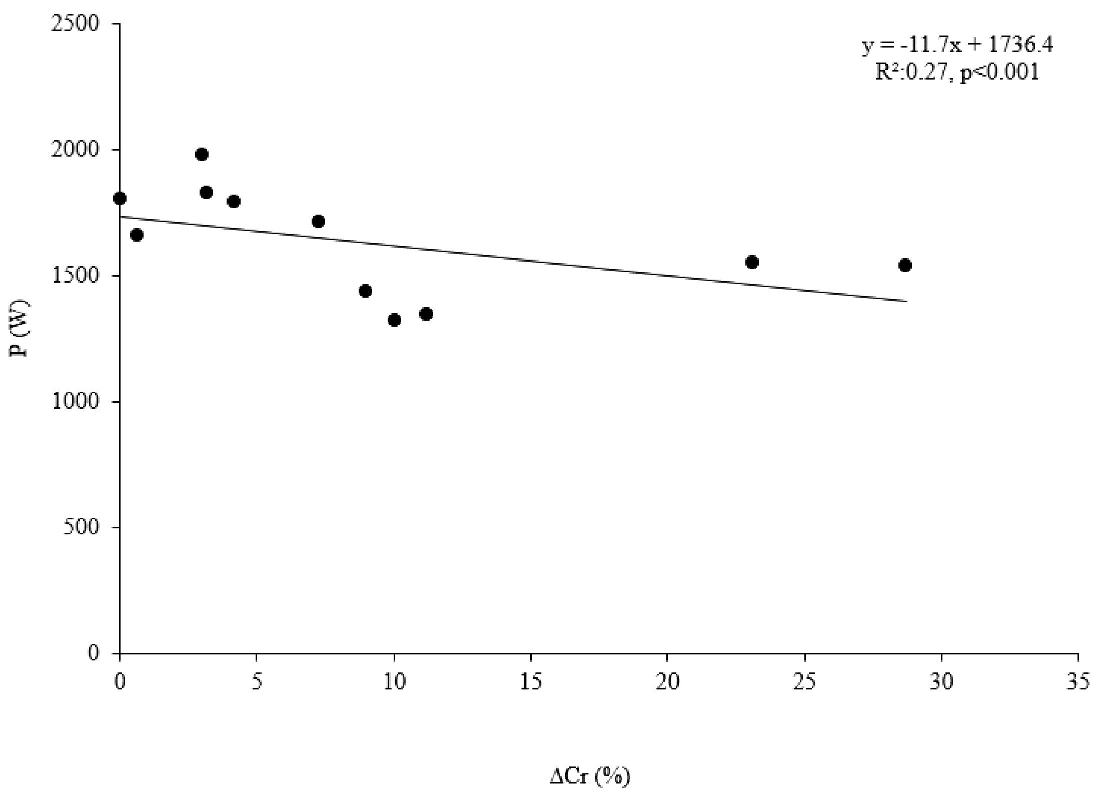

Figure 3 — Maximal mechanical power of the lower limbs (P) measured before the race plotted for all subjects as a function of changes in energy cost of running caused by the race (ΔCr).

At the end of this extreme uphill race, Cr was increased by about 9% compared with before the race, as observed in previous studies considering ultramarathon events.[5,6] This difference was greater than those observed during classic flat marathons,[4] probably because of the relevant slope and altitude difference covered by subjects and because of the type of road surface. As observed previously,[21] the increase in Cr with the slope is related with the increase in total work including internal work. Furthermore, in the last part of the race (~15 km), the subjects ran on a path of lava rock. This terrain can contribute to increasing Cr compared with compact terrain and could be attributed to a reduced recovery of potential and kinetic energy at each stride.[22] Indeed, as suggested by Millet et al,[6] during long-distance running events greatly exceeding the marathon, maintaining a high F may help reduce damage to lower-limb tissue, muscle fatigue, and symptoms associated with prolonged running, even if such a strategy may lead to increased Cr values, thus, in the end "sacrificing economy to improve running performance." On the other hand, in agreement with our results, some authors[23,24] are of the opinion that Cr in ultramarathon runners has an important role in setting performance, suggesting that the same phenotype and physiological factors, including Cr, that determine success in marathon running[25] are also likely to determine success in ultramarathons, and this should be even more evident when the level of ultraendurance athletes increases.[23]

Moreover, we do not think that the increasing altitude (from 0 to 3063 m above sea level) had any effect on Cr, although obviously leading to a fall of about 10% to 15% on VO_{2max}. We would like to point out that at sea level, before the race, VO_2 at the speed of 173 m/min was on the average 42.7 mL · kg^{-1} · min^{-1}—about 87% of the corresponding VO_{2max}. At altitude, immediately after the race, VO_2 was reduced to 36 mL · kg^{-1} · min^{-1} at the speed of 161 m/min—about 80% to 85% of the corresponding VO_{2max} estimated at altitude. The O_2 consumption of the respiratory muscles, as obtained from the expiration ventilation according to Coast et al,[26] amounted to 188 and 170 mL/min at sea level and at altitude, respectively. Thus, Cr, when subtracting the O_2 consumption of the respiratory muscles and the resting VO_2 (4.4 and 4.6 mL · kg^{-1} · min^{-1} at sea level and at altitude) amounted to 0.171 and 0.183 mL · kg^{-1} · min^{-1}, respectively. The resultant increase of Cr, about 7%, is therefore essentially equal to that reported above. Then, the observed increase of Cr is independent of the effects of altitude on VO_{2max} and on ventilation, which, as is well known, are widely different in different subjects and lead to larger decreases in individual VO_{2max}[27] the larger its sea level value.[28]

In addition, we would like to point out that the RER amounted to 0.88 and 0.82 at sea level and at altitude, respectively, and that these values are close to what can be expected for the metabolic respiratory quotient for these exercise intensities.

At the end of the race, the following changes in running mechanics were observed: lower t_a, f, F_{max}, k_{vert}, and k_{leg} and higher t_c, Δz, and ΔL (Table 2). Only the decreases of t_a and F_{max} were in line with previous studies on ultraendurance events.[11,13,29] These differences could be related to the fact that the subjects ran, before and after the race, at self-selected speed that represented their real optimal running speed. At the end of the race, subjects decreased their self-selected speed during the test by 7.3% on average; this reduction was related with their degree of fatigue and represents the real effort that they were able to sustain after the race. However, the changes in self-selected running speed observed during the test before and after the race had only a partial effect on changes in the mechanical parameters considered in the current study. In fact, as observed previously,[30] k_{leg} showed no statistical differences at speeds of 2.5 to 3.5 m/s; in addition, the speed has no effect on k_{leg}.[19] Indeed, if the speed was reduced from 2.9 to 2.7 m/s, k_{vert} decreased from 33 to 32 kN/m (–4%),[30] which was not statistically significant. Morin et al[19] did not measure k_{vert} at speeds as low as 2.9 and 2.7 m/s; even so, we fitted the data points reported in their study with a second-order polynomial, obtaining the equation $k_{vert} = 1.512s^2 - 6.906s + 34.022$, where k_{vert} is expressed in kN/m and the speed (s) in m/s (N = 5 data points, $r^2 = .997$). According to this equation, at 2.9 and 2.7 m/s, k_{vert} would be 27 and 26 kN/m[1], respectively (–1%). In the current study k_{leg} decreased by 42.3% and k_{vert} by 45.6%, thus suggesting that the changes in these mechanical parameters observed in the current study were largely affected by fatigue, and only marginally by speed.

In addition, at the end of the race t_c increased (by ~29%) and t_a decreased (by ~59%), leading to a significant decrease in f (by ~11%). In turn, the observed increase of t_c led to a significant increase in Δz (by ~53%) and ΔL (by ~45%). Furthermore, k_{vert} and k_{leg} decreases were strongly related to a reduction in F_{max} and to the increase in Δz, which can be interpreted as a safer running style, as discussed following.

The differences in the changes in the mechanical parameters between the current study and the previous ones on ultramarathon[11,13,29] can be explained as follows.

- We considered self-selected speed as representative of subjects' fatigue level, which induced different mechanical adaptations, particularly increasing t_c and consequently reducing t_a and f. Dutto and Smith[31] reported decreases in f accompanied by a decrease of k_{vert} in long running trials, suggesting that it is the inability of the system to maintain an optimal stiffness that leads to exhaustion. Furthermore, the decrease in f observed at the end of the race was probably related to the fact that this ultramarathon was characterized by continuous positive work. This condition implies mainly concentric muscle contractions, which induce less muscle damage in knee-extensor and plantarflexor muscles than the eccentric contractions characterizing downhill running generally included in ultramarathon.[8,9] This condition may lead to lesser changes in running mechanics (aiming at decreasing the load on the muscles) than observed in previous extreme ultramarathons.[11,13,29] In addition, the decrease in f observed in the current condition is likely associated with a decrease in internal work performance and thus in the corresponding cardiorespiratory responses, which in turn may be particularly relevant when running uphill at 3000 m above sea level.
- There was a greater continuous positive work performance than observed in previous studies,[11,29] which did not allow any recovery periods for the athletes during the race.
- The potential differences between ultra-long-distance running on a treadmill and over ground[13,20] may have induced different adaptations of t_c.
- The postrace tests were done immediately after the subjects crossed the finish line, which allowed us to examine the real effects of total fatigue on metabolic and mechanical parameters.

To identify the main factors affecting Cr during the ultraendurance running race, the effects of changes on mechanical parameters before and after the race were plotted for all subjects as a function of the corresponding changes on Cr (Figures 2[a–f]). In particular, the increases in t_c with decreases in t_a imply a decrease in F_{max}, which was related with the increase in Cr during the race (Figure 2[c]). These changes in running mechanics can be interpreted as a safer running style associated with an overall lower impact, especially during the eccentric phase of each step, to the detriment of an increase of *C*r.[6]

The decrease of k_{vert} and k_{leg}, brought about by fatigue, induced each runner to sink farther during contact, that is, increasing t_c and Δz. Furthermore, the decreased *f* likely led runners to a less efficient elastic energy utilization,[32] and therefore lower velocity, at the end of the stance phase, resulting in a decreased t_a. Finally, a shorter t_a implies that the runner landed with less downward momentum, thus requiring less upward impulse during the subsequent stance phase, so F_{max} was also lower. In addition, decreased F_{max} can also be due to reduced force capacity because of fatigue during the race. Our results are in accordance with those of Morin et al[13] and Degache et al,[29] who evidenced a decreased F_{max} at the end of long running trials; however, the question of whether this is a strategy intentionally adopted by runners or the result of fatigue remains unsolved.

Indeed, the most powerful athletes showed lower changes in *C*r (Figure 3). These results are in agreement with previous studies in athletes[15,16] that emphasize the importance of the muscle–tendon system and strength training to reduce *C*r. In addition, force reduction during the race can lead to ankle instability,[33] thus leading to a reduction of the foot's capacity to use all the mechanical energy transmitted by the muscle-tendon complex for forward displacement.

Practical Applications

*C*r represents one of the main factors determining performance in ultraendurance runners, and its increase during competition is related to mechanics of running deterioration and lower P_{max}. These data show the importance of the lower-limb muscle's characteristics, which maximize efficiency and reduce *C*r during running. This suggests that coaches and ultraendurance runners need to strengthen specific lower-limb power training in their preparation.

Conclusion

The increased *C*r during the Etna uphill marathon was related to changes in the mechanics of running, such as increases in t_c, Δz, and ΔL and decreases in t_a, *f*, F_{max}, k_{vert}, and k_{leg}. In addition, lower *C*r was related with better performance, and athletes characterized by the greater P_{max} showed lower increases in *C*r during the race. This suggests that specific power training of the lower limbs may lead to better performance in ultraendurance running.

Acknowledgments

We are grateful to the athletes for their kind collaboration and to Mr M. Malfitana, Mr E. Bertolissi, and the Unione Sportiva M. Tosi, Tarvisio (Italy), for their valuable contribution in carrying out measurement during the race. We are grateful to Prof G. Antonutto, Prof B. Grassi, and Dr A. Da Ponte for the assistance during the study. The financial support of the Unione Sportiva M. Tosi, Tarvisio (Italy), and Lions Club, Udine-Duomo (Italy), are gratefully acknowledged.

No conflicts of interest, financial or otherwise, are declared by the author(s).

References

1. di Prampero PE, Atchou G, Bruckner JC, Moia C. The energetics of endurance running. *Eur J Appl Physiol Occup Physiol*. 1986;55:259–266. PubMed doi:10.1007/BF02343797
2. Sjödin B, Svedenhag J. Applied physiology of marathon running. *Sports Med*. 1985;2:83–99. PubMed doi:10.2165/00007256-198502020-00002
3. Jones AM, Doust JH. A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *J Sports Sci*. 1996;14:321–327. PubMed doi:10.1080/02640419608727717
4. Brueckner JC, Atchou G, Capelli C, et al. The energy cost of running increases with the distance covered. *Eur J Appl Physiol Occup Physiol*. 1991;62:385–389. PubMed doi:10.1007/BF00626607
5. Gimenez P, Kerherve H, Messonnier LA, Feasson L, Millet GY. Changes in the energy cost of running during a 24-h treadmill exercise. *Med Sci Sports Exerc*. 2013;45:1807–1813. PubMed doi:10.1249/MSS.0b013e318292c0ec
6. Millet GY, Hoffman MD, Morin JB. Sacrificing economy to improve running performance—a reality in the ultramarathon? *J Appl Physiol*. 2012;113:507–509. PubMed doi:10.1152/japplphysiol.00016.2012
7. Vernillo G, Savoldelli A, Zignoli A, et al. Influence of the world's most challenging mountain ultra-marathon on energy cost and running mechanics. *Eur J Appl Physiol*. 2014;114:929–939. PubMed doi:10.1007/s00421-014-2824-y
8. Millet GY, Tomazin K, Verges S, et al. Neuromuscular consequences of an extreme mountain ultra-marathon. *PLoS ONE*. 2011;6:e17059. PubMed doi:10.1371/journal.pone.0017059
9. Saugy J, Place N, Millet GY, et al. Alterations of neuromuscular function after the world's most challenging mountain ultra-marathon. *PLoS ONE*. 2013;8:e65596. PubMed doi:10.1371/journal.pone.0065596
10. Blickhan R. The spring-mass model for running and hopping. *J Biomech*. 1989;22:1217–1227. PubMed doi:10.1016/0021-9290(89)90224-8
11. Morin JB, Tomazin K, Edouard P, Millet GY. Changes in running mechanics and spring-mass behavior induced by a mountain ultra-marathon race. *J Biomech*. 2011;44:1104–1107. PubMed doi:10.1016/j.jbiomech.2011.01.028
12. Morin JB, Samozino P, Peyrot N. Running pattern changes depending on the level of subjects' awareness of the measurements performed: a "sampling effect" in human locomotion experiments? *Gait Posture*. 2009;30:507–510. PubMed doi:10.1016/j.gaitpost.2009.07.123
13. Morin JB, Samozino P, Millet GY. Changes in running kinematics, kinetics, and spring-mass behavior over a 24-h run. *Med Sci Sports Exerc*. 2011;43:829–836. PubMed doi:10.1249/MSS.0b013e3181fec518
14. Fourchet F, Millet GP, Tomazin K, et al. Effects of a 5-h hilly running on ankle plantar and dorsal flexor force and fatigability. *Eur J Appl Physiol*. 2012;112:2645–2652. PubMed doi:10.1007/s00421-011-2220-9
15. Støren O, Helgerud J, Stoa EM, Hoff J. Maximal strength training improves running economy in distance runners. *Med Sci Sports Exerc*. 2008;40:1087–1092. PubMed doi:10.1249/MSS.0b013e318168da2f
16. Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol*. 2003;89:1–7. PubMed doi:10.1007/s00421-002-0741-y
17. Craig CL, Marshall AL, Sjostrom M, et al. International Physical Activity Questionnaire: 12-country reliability and validity. *Med Sci Sports Exerc*. 2003;35:1381–1395. PubMed doi:10.1249/01.MSS.0000078924.61453.FB
18. Bosco C, Luhtanen P, Komi PV. A simple method for measurement of mechanical power in jumping. *Eur J Appl Physiol Occup Physiol*. 1983;50:273–282. PubMed doi:10.1007/BF00422166

19. Morin JB, Dalleau G, Kyrolainen H, Jeannin T, Belli A. A simple method for measuring stiffness during running. *J Appl Biomech*. 2005;21:167–180. PubMed
20. Millet GY, Banfi JC, Kerherve H, et al. Physiological and biological factors associated with a 24 h treadmill ultra-marathon performance. *Scand J Med Sci Sports*. 2011;21:54–61. PubMed doi:10.1111/j.1600-0838.2009.01001.x
21. Minetti AE, Ardigo LP, Saibene F. Mechanical determinants of the minimum energy cost of gradient running in humans. *J Exp Biol*. 1994;195:211–225. PubMed
22. Zamparo P, Perini R, Orizio C, Sacher M, Ferretti G. The energy cost of walking or running on sand. *Eur J Appl Physiol Occup Physiol*. 1992;65:183–187. PubMed doi:10.1007/BF00705078
23. Millet GP. Economy is not sacrificed in ultramarathon runners. *J Appl Physiol*. 2012;113:686; author reply 687.
24. Perrey S, Joyner M, Ruiz JR, et al. Commentaries on viewpoint: sacrificing economy to improve running performance—a reality in the ultramarathon? *J Appl Physiol*. 2012;113(3):510–512. PubMed
25. Joyner MJ, Ruiz JR, Lucia A. The two-hour marathon: who and when? *J Appl Physiol*. 2011;110(1):275–277. PubMed
26. Coast JR, Rasmussen SA, Krause KM, et al. Ventilatory work and oxygen consumption during exercise and hyperventilation. *J Appl Physiol*. 1993;74:793–798. PubMed
27. Cerretelli P. Limiting factors to oxygen transport on Mount Everest. *J Appl Physiol*. 1976;40:658–667. PubMed
28. Ferretti G, Moia C, Thomet JM, Kayser B. The decrease of maximal oxygen consumption during hypoxia in man: a mirror image of the oxygen equilibrium curve. *J Physiol*. 1997;498:231–237. PubMed doi:10.1113/jphysiol.1997.sp021854
29. Degache F, Guex K, Fourchet F, et al. Changes in running mechanics and spring-mass behaviour induced by a 5-hour hilly running bout. *J Sports Sci*. 2013;31:299–304. PubMed doi:10.1080/02640414.2012.729136
30. Arampatzis A, Bruggemann GP, Metzler V. The effect of speed on leg stiffness and joint kinetics in human running. *J Biomech*. 1999;32:1349–1353. PubMed doi:10.1016/S0021-9290(99)00133-5
31. Dutto DJ, Smith GA. Changes in spring-mass characteristics during treadmill running to exhaustion. *Med Sci Sports Exerc*. 2002;34:1324–1331. PubMed doi:10.1097/00005768-200208000-00014
32. Snyder KL, Farley CT. Energetically optimal stride frequency in running: the effects of incline and decline. *J Exp Biol*. 2011;214:2089–2095. PubMed doi:10.1242/jeb.053157
33. Lazzer S, Taboga P, Salvadego D, et al. Factors affecting metabolic cost of transport during a multi-stage running race. *J Exp Biol*. 2014;217:787–795. PubMed doi:10.1242/jeb.091645