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Human Kinetics
ORIGINAL INVESTIGATION

Effects of an Uphill Marathon on Running Mechanics and Lower-Limb Muscle Fatigue

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Purpose: To investigate the effects of an uphill marathon (43 km, 3063-m elevation gain) on running mechanics and neuromuscular fatigue in lower-limb muscles. ***Methods:*** Maximal mechanical power of lower limbs (MMP), temporal tensiomyographic (TMG) parameters, and muscle-belly displacement (D_m) were determined in the vastus lateralis muscle before and after the competition in 18 runners (age 42.8 ± 9.9 y, body mass 70.1 ± 7.3 kg, maximal oxygen uptake 55.5 ± 7.5 mL · kg^{-1} · min^{-1}). Contact (t_c) and aerial (t_a) times, step frequency (f), and running velocity (v) were measured at 3, 14, and 30 km and after the finish line (POST). Peak vertical ground-reaction force (F_{max}), vertical displacement of the center of mass (Δz), leg-length change (ΔL), and vertical (k_{vert}) and leg (k_{leg}) stiffness were calculated. ***Results:*** MMP was inversely related with race time ($r = -.56$, $P = .016$), t_c ($r = -.61$, $P = .008$), and Δz ($r = -.57$, $P = .012$) and directly related with F_{max} ($r = .59$, $P = .010$), t_a ($r = .48$, $P = .040$), and k_{vert} ($r = .51$, $P = .027$). In the fastest subgroup (n = 9) the following parameters were lower in POST ($P < .05$) than at km 3: t_a (–14.1% ± 17.8%), F_{max} (–6.2% ± 6.4%), k_{vert} (–17.5% ± 17.2%), and k_{leg} (–11.4% ± 10.9%). The slowest subgroup (n = 9) showed changes ($P < .05$) at km 30 and POST in F_{max} (–5.5% ± 4.9% and –5.3% ± 4.1%), t_a (–20.5% ± 16.2% and –21.5% ± 14.4%), t_c (5.5% ± 7.5% and 3.2% ± 5.2%), k_{vert} (–14.0% ± 12.8% and –11.8% ± 10.0%), and k_{leg} (–8.9% ± 11.5% and –11.9% ± 12%). TMG temporal parameters decreased in all runners (–27.35% ± 18.0%, $P < .001$), while D_m increased (24.0% ± 35.0%, $P = .005$), showing lower-limb stiffness and higher muscle sensibility to the electrical stimulus. ***Conclusions:*** Greater MMP was related with smaller changes in running mechanics induced by fatigue. Thus, lower-limb power training could improve running performance in uphill marathons.

Keywords: kinematics, stiffness, tensiomyography, postactivation potentiation

The mechanics of running in different conditions[1–3] have been frequently investigated using the spring-mass model.[4] This model consists of a point of mass supported by a single massless linear spring, which allows one to investigate the leg- (k_{leg}) and vertical- (k_{vert}) stiffness coefficients associated with leg-spring compression (ΔL) and with the vertical displacement (Δz) of the center of mass at the middle of the stance phase.[3] In this model, k_{leg} is defined as the ratio between peak vertical ground-reaction force (F_{max}) and ΔL, while k_{vert} is the ratio of F_{max} to Δz.[5]

Previous studies[2,5,6] showed a reduction in F_{max}, Δz, and ΔL and an increment in k_{vert} and step frequency (f) after many hours of prolonged running (mountain ultramarathon, 24-h treadmill run, 5-h hilly running) with different behavior of contact (t_c) and aerial (t_a) time. Morin et al[5] hypothesized that these changes in the running pattern could lead to a smoother and safer running style, likely preserving the body structures, especially during the braking phase of each step. Moreover, the different changes in t_c and t_a among these studies could be due to the different running conditions (treadmill vs overground running, level vs uphill/downhill running). Some authors suggested that treadmill and overground running can be considered similar only when the sample size is sufficiently wide, because large individual differences between the 2 running conditions were found.[7] In addition, the inclination of the running surface influences running mechanics.[8] Indeed, in uphill running, the peak forces recorded are smaller, f is greater, and stride length is shorter than in level and downhill running[8]; similarly, the eccentric step phase is reduced. In addition, the muscle volume activated in the lower limbs is larger in uphill than in horizontal running. Besides, uphill running requires considerably greater activation of the vastus and soleus and lesser activation of the rectus femoris, gracilis, and semitendinosus than horizontal running.[9] It follows that, as shown by Lazzer et al,[3] uphill running may lead to different changes in running mechanics than those observed in previous mountain ultramarathons.[2,5,6]

Furthermore, neuromuscular fatigue (ie, an exercise-related decrease in the maximal voluntary force or power of a muscle group[10]) has been shown to significantly impair the performance of ultraendurance athletes.[10,11] This potentially involves processes at all levels of the motor pathway from the brain to skeletal muscle.

Muscle fatigue was previously investigated by analyzing electromyography together with muscle mechanical output during dynamic and static muscle contractions.[11,12] Recently, the noninvasive technique of tensiomyography (TMG) has been used to examine the contractile properties of skeletal muscle. Simunic et al[13] also suggested that this methodology could be used to evaluate peripheral fatigue; however, few authors have used TMG to study this phenomenon.[14–16]

To the best of our knowledge, no study has already analyzed running mechanics and muscle fatigue during and after an uphill race. This type of event is peculiar because it is characterized by lower impact and lower eccentric phase than a classic "flat" marathon or mountain ultramarathon.

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Therefore, the primary purpose of the current study was to investigate the effects of an extreme uphill-running marathon on running mechanics and on spring-mass model. The secondary purpose was to evaluate the effect of race-induced fatigue on muscle contractile properties by TMG. The third aim was to examine whether the changes in running mechanics and TMG parameters due to the race-induced fatigue were different between faster and slower runners.

We hypothesized that the changes in spring-mass model induced by the investigated uphill running would be different than those brought about by level running or classical mountain ultramarathon; in particular, we expected a decrease in k_{vert} and k_{leg}. In addition, we hypothesized that the fastest runners would show smaller changes in running mechanics than the slowest athletes. Finally, we expected different muscle stiffness and sensibility to the electrical stimulus between the 2 groups.

Methods

Subjects

Twenty-five healthy Italian male runners were enrolled in this study as participants in the "Supermaratona dell'Etna," and the 18 athletes who completed the race were considered for data analysis (mean ± SD age = 42.8 ± 9.9 y, body mass = 70.1 ± 7.3 kg, height = 1.71 ± 0.05 m, maximal oxygen uptake [$\dot{V}O_{2\text{max}}$] = 55.5 ± 7.5 mL · kg^{-1} · min^{-1}, maximal mechanical power [MMP] of the lower limbs = 27.6 ± 7.7 W/kg) (Table 1).

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. The participants were recruited among experienced ultraendurance runners (12.4 ± 8.5 y of training history in running, 6.5 ± 3.5 y of ultraendurance-running race experience, and 88.4 ± 39.5 km/wk of running training) and were asked to fill out a questionnaire on physical exercise activity, demographics, medical history, and lifestyle. Subjects who reported any muscular or metabolic diseases or recent physical injury were excluded from the study.

Experimental Protocol

The race took place in June 2013. The starting time was set at 8:00 AM in Marina di Cottone (Catania, Italy), at sea level, and the temperature and relative humidity were 27°C and 22%, respectively. The first 30 km of the race to Etna North (1810 m above mean sea level) were on paved road, whereas its final part led to the finish line at 3000 m above mean sea level over an all-trail course. The overall distance was 43 km, with 3063 m of elevation gain and a mean slope of about 7% with peak values reaching 14% (Figure 1). At the finish line, temperature and relative humidity were 16°C and 45%, respectively.

During the week before the race, participants were asked to come to the laboratory to perform a graded exercise test on a treadmill to evaluate their $\dot{V}O_{2\text{max}}$. They were also 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 them with all the equipment. Moreover, the day before the race and immediately after the end of the race, the jumping test[17] and TMG assessment were performed, and anthropometric measurements were carried out. Furthermore, running mechanics were evaluated during the race at km 3, 14, and 30 and immediately after the athletes reached the finish line (POST). In addition, GPS coordinates were continuously recorded throughout the competition (Garmin Forerunner 305 GPS, Kansas City, MO, USA).

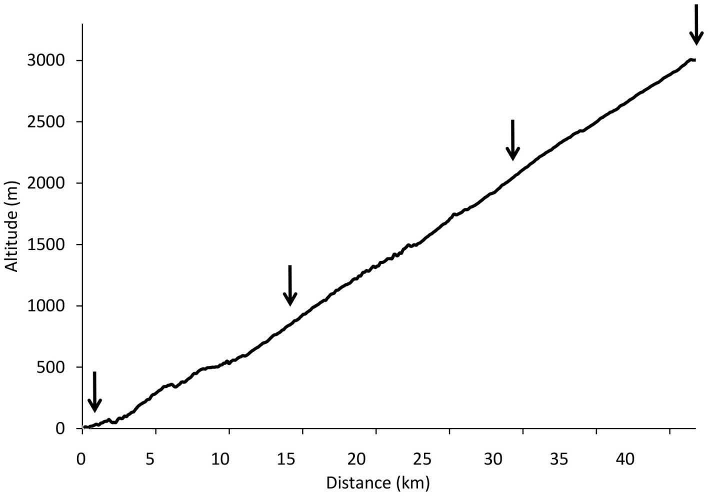

Figure 1 — Race profile of Supermaratona dell'Etna obtained from the GPS device. Black arrows indicate where the videos were taken (km 3 to 14 to 30 and postrace).

Table 1 Physical Characteristics of Subjects Measured Before the Race in All Athletes and in the 9 Fastest and 9 Slowest Runners of the Group

	All runners, mean ± SD (range)	9 fastest runners, mean ± SD	9 slowest runners, mean ± SD	P[a]
Age (y)	42.8 ± 9.9 (24.0–60.0)	37.7 ± 8.4	48.0 ± 8.8	.024
Body mass (kg)	70.1 ± 7.3 (60.0–83.0)	65.5 ± 5.7	74.6 ± 5.8	.004
Stature (m)	1.72 ± 0.05 (1.65–1.84)	1.72 ± 0.05	1.73 ± 0.04	.720
Body-mass index (kg/m^2)	23.5 ± 2.2 (20.1–28.3)	22.0 ± 1.2	24.9 ± 2.1	.002
Lower-limb length (m)	0.91 ± 0.05 (0.82–1.00)	0.89 ± 0.04	0.93 ± 0.05	.064
Maximum oxygen uptake (mL · kg^{-1} · min^{-1})	55.5 ± 7.5 (40.4–71.8)	59.9 ± 7.3	51.0 ± 4.6	.007
Maximal mechanical power of the lower limbs (W/kg)	27.6 ± 7.7 (15.8–45.8)	31.2 ± 8.2	24.1 ± 5.5	.047
Race time (h:min:s)	05:29:10 ± 01:01:12 (03:50:38–07:16:28)	04:38:13 ± 00:35:21	06:20:07 ± 00:29:30	.001

[a] Significance by ANOVA test (fastest 9 vs slowest 9 runners).

Physiological Measurements Before and After the Race

Body mass (BM) and $\dot{V}O_{2max}$ were assessed the week before the race as described by Lazzer et al.[18] The day before and immediately after the race, MMP was assessed during a countermovement jump by means of the Bosco test[17] (Ergo Jump, Boscosystem, Italy).

In addition, the subjects underwent TMG before the race and immediately after (2–4 min) crossing the finish line, using a protocol previously described by Simunic et al.[13] From every twitch response, the displacement of muscle belly (D_m), delay time (T_d), contraction time ($T_{contraction}$), sustained contraction time (T_s), and relaxation time (T_r) were calculated. D_m was defined as the peak amplitude in the displacement–time curve of the TMG twitch response, T_d was defined as the time between the electrical stimulus and displacement of the sensor to 10% of D_m, $T_{contraction}$ was the time from 10% to 90% of D_m reached, T_s was the time period in which muscle response remained greater than 50%, and T_r was the time from 90% D_m to decline to one-half of the D_m in the relaxation phase.[13,15]

Mechanical Measurements During the Race

Running mechanics were studied using 4 digital cameras with a sample frequency of 400 Hz (Nikon J1, Japan). The cameras were placed perpendicular to the athletes' running direction at km 3, 14, and 30 and POST. The recording zone during the race (km 3, 14, and 30) was selected to include at least 15 m of flat road (inclination <1%, as measured by means of GPS devices the day before the race). Then, immediately after the race, the athletes were asked to run at a constant self-selected speed, as close as possible to the race speed, for 50 m on a flat compact rock path situated near the finish line. Three attempts were performed, and the 1 with the running speed closest to that recorded during the race (at the 3 checkpoints) was used for video analysis. Running speed was measured by means of 2 photocells placed immediately before and after each video-recording zone. Because of the limited space available for placing the camera, only 5 subsequent steps were analyzed to measure t_c (s) and t_a (s). Step frequency (f, step/s) was calculated as $1/(t_a + t_c)$.

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.[1] This method, based on modeling of the ground-reaction force during the contact phase by a sine function, allows the computation of k_{vert} (kN/m) as the ratio of F_{max} (N) to Δz (m) and of k_{leg} (kN/m) as the ratio of F_{max} to ΔL (m). Moreover, to identify the effect of MMP on biomechanical parameters during the race, MMP measured before and after the race was plotted as a function of the biomechanical parameters for all athletes.

Statistical Analyses

Statistical analyses were performed using PASW Statistic 18 (SPSS Inc, Chicago, IL, USA) with significance set at $P < .05$. All results are expressed as mean ± SD. Normal distribution of the data were tested using the Kolmogorov-Smirnov test.

The median value of the subjects' final ranking was considered to split all subjects into 2 subgroups of 9 subjects (the 9 fastest and the 9 slowest runners). Changes of speed and mechanical parameters during the race were studied with general-linear-model repeated measures, with the 2 factors of group (G: the 9 fastest vs the 9 slowest runners) and distance (D: 3 km vs 14 km vs 30 km vs POST). As well, changes of BM, MMP of the lower limbs, and TMG parameters before and after the race were studied with general-linear-model repeated measures with the 2 factors of group and time (T: pre vs post). When significant differences were found, a Bonferroni post hoc test was run to determine the exact location of the difference.

The relationships of $\dot{V}O_{2max}$ with performance time, MMP, and mechanical variables were investigated using Pearson product–moment correlation coefficient.

Results

Race time and physical characteristics of the athletes measured before the race (PRE) are reported in Table 1. Race time of the winner of the Supermaratona dell'Etna was 3:50:38, while the average time of the subjects was 5:29:10 ± 1:01:12 (ranking 1–101).

An inverse relationship between $\dot{V}O_{2max}$ and race time ($r = -.85$, $P < .001$), as well as between MMP-PRE and race time ($r = -.56$, $P = .016$), was observed.

When MMP measured before and after the race was plotted as a function of mechanical parameters, inverse relationships between MMP and t_c (Figure 2[a]), as well as Δz (Figure 2[d]), were observed. However, direct relationships between MMP and t_a (Figure 2[b]), F_{max} (Figure 2[c]), and k_{vert} (Figure 2[e]) were observed. No significant relationships of MMP with f, ΔL, and k_{leg} were found.

A further analysis was focused on the comparison between 2 subgroups of athletes (n = 9) who were divided according to the final ranking. The 9 fastest runners were younger (–21.5% in age, $P = .024$), with lower BM (–12.2%, $P = .004$) and body-mass index (–11.7%, $P = .002$) and higher $\dot{V}O_{2max}$ (+17.5%, $P = .007$) and MMP (+29.5%, $P = .047$) than the 9 slowest runners (Table 1).

Mechanical Parameters

When the results recorded from all 18 athletes were averaged (Table 2), there was a decrement at km 14 and 30 in speed (–2.4% ± 3.4% and –4.8% ± 7.2%, $P < .01$) and at km 30 and POST in t_a (–14.6% ± 18.2% and –18.0% ± 16.4%, respectively, $P < .01$), F_{max} (–4.2% ± 6.4% and –5.6% ± 5.2%, respectively, $P < .001$), and k_{vert} (–12.1% ± 15.0% and –15.0% ± 14.0%, respectively, $P < .01$). Moreover, k_{leg} decreased only POST (–11.7% ± 11.2%, $P < .001$). Conversely, at km 30 and POST, an increment in Δz (7.5% ± 11.8% and 7.5% ± 17.6%, respectively, $P < .05$) and in t_c (4.8% ± 7.8% and 5.2% ± 9.6%, respectively, $P < .05$) was observed.

When the 2 subgroups were analyzed separately, the fastest runners did not show any significant change in v and mechanical parameters throughout the race (Table 3). On the contrary, at POST they showed lower t_a (–14.1% ± 17.8%, $P < .05$), F_{max} (–6.2% ± 6.4%, $P < .05$), k_{vert} (–17.5% ± 17.2%, $P < .05$), k_{leg} (–11.4% ± 10.9%, $P < .05$), and MMP (–23.6% ± 26.2%, $P < .05$, Table 4). The slowest runners showed a decrease in F_{max} at km 30 and POST (–5.5% ± 4.9% and –5.3% ± 4.1%; $P < .05$), a t_a decrease at km 30 and POST (–20.5% ± 16.2% and –21.5% ± 14.4%, respectively, $P < .005$), and t_c increase at km 30 and POST (5.5% ± 7.5% and 3.2% ± 5.2%, respectively, $P < .05$). Consequently, k_{vert} and k_{leg} decreased at km 30 and POST (–14.0% ± 12.8% and –11.8% ± 10.0%; –8.9% ± 11.5% and –11.9% ± 12%, respectively; $P < .05$) (Table 3). In this group, MMP decreased by –23.2% ± 15.3% after the race ($P < .005$, Table 4). Moreover, MMP was higher in the fastest runners before and after the race than in the slowest ones (28.9% ± 0.4%, $P < .05$, Table 4). The gait parameters were not compared between

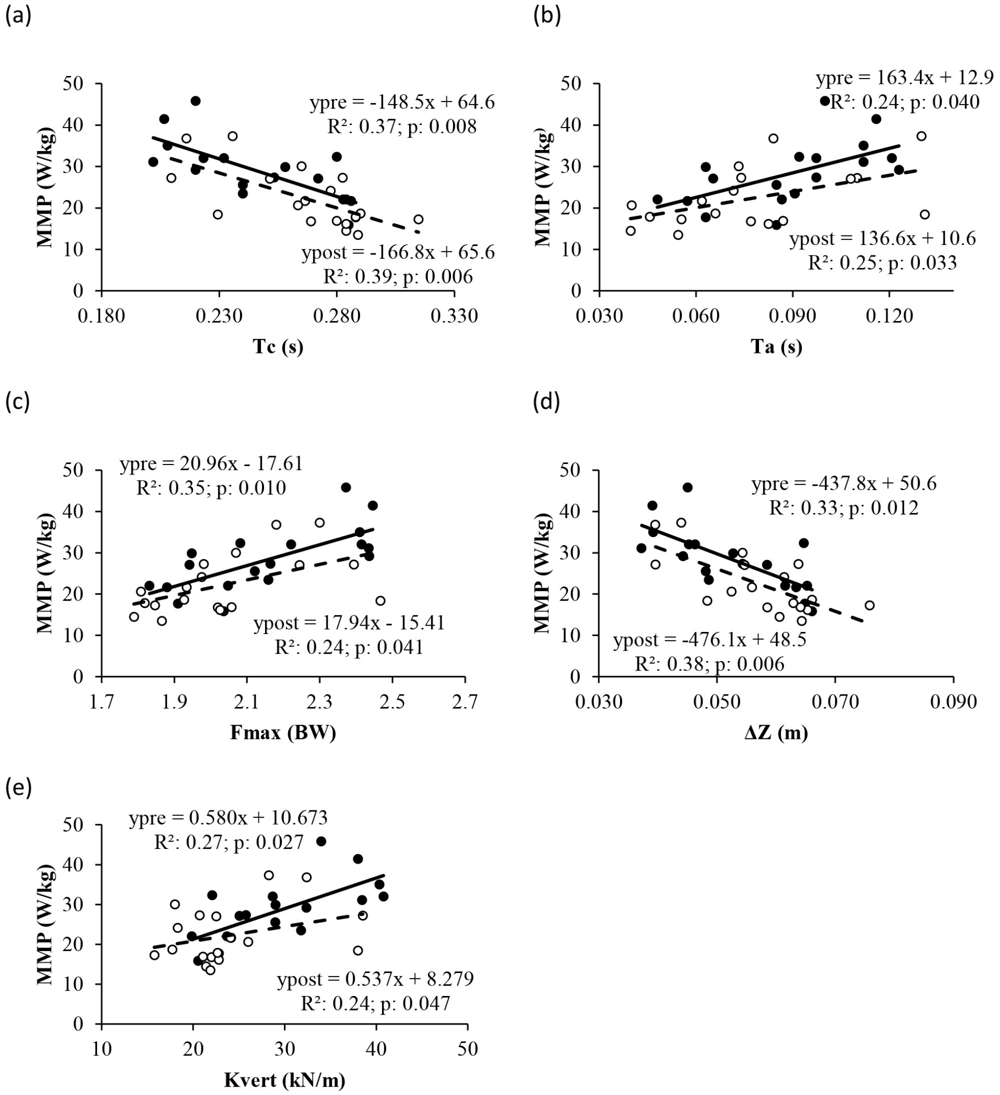

Figure 2 — Maximal mechanical power (MMP) plotted for all subjects as a function of (a) contact time (t_c), (b) aerial time (t_a), (c) maximal vertical ground-reaction force (F_{max}), (d) downward displacement of center of mass during contact (Δz) and (e) vertical stiffness (k_{vert}) measured before (closed circles) and immediately after (open circles) the race.

Table 2 Mechanical Parameters Determined at km 3, 14, and 30 and Immediately After the Race in All Subjects (N = 18), Mean ± SD

	3 km	14 km	30 km	Postrace
v (m/s)	3.69 ± 0.62	3.60* ± 0.61	3.51* ± 0.68	3.54 ± 0.72
t_c (s)	0.251 ± 0.030	0.252 ± 0.031	0.263* ± 0.034	0.265* ± 0.030
t_a (s)	0.089 ± 0.023	0.086 ± 0.021	0.076* ± 0.027	0.073* ± 0.025
f (Hz)	2.96 ± 0.15	2.96 ± 0.16	2.96 ± 0.16	2.97 ± 0.24
F_{max} (body mass)	2.14 ± 0.21	2.13 ± 0.20	2.05* ± 0.22	2.02* ± 0.19
Δz (m)	0.053 ± 0.010	0.053 ± 0.010	0.057* ± 0.011	0.057* ± 0.010
ΔL (m)	0.178 ± 0.029	0.173 ± 0.027	0.181 ± 0.033	0.187 ± 0.037
k_{vert} (kN/m)	28.85 ± 6.77	28.13 ± 6.87	25.37* ± 6.85	24.45* ± 6.34
k_{leg} (kN/m)	8.48 ± 1.73	8.53 ± 1.55	7.86 ± 1.93	7.46* ± 1.87

Abbreviations: v, speed; t_c, contact time; t_a, aerial time; f, step frequency; F_{max}, maximal vertical ground-reaction force; Δz, downward displacement of center of mass during contact; ΔL, displacement of the leg spring; k_{vert}, vertical stiffness; k_{leg}, leg stiffness.

*$P < .05$ compared with the first checkpoint.

Table 3 Mechanical Parameters Determined at km 3, 14, and 30 and Immediately After the Race in the 9 Fastest and 9 Slowest Runners, Mean ± SD

	9 Fastest Runners				9 Slowest Runners				P^a		
	3 km	14 km	30 km	Postrace	3 km	14 km	30 km	Postrace	Group	Distance	G × D
v (m/s)	4.19 ± 0.40	4.08 ± 0.43	4.01 ± 0.56	3.90 ± 0.77	3.20 ± 0.32	3.11 ± 0.29	2.99 ± 0.25	3.18 ± 0.48	.001	.121	.844
t_c (s)	0.229 ± 0.026	0.230 ± 0.028	0.240 ± 0.031	0.248 ± 0.034	0.272 ± 0.017	0.275 ± 0.012	0.287 ± 0.015	0.281 ± 0.010	.001	.001	.653
t_a (s)	0.099 ± 0.025	0.100 ± 0.019	0.091 ± 0.026	0.085 ± 0.026	0.078 ± 0.015	0.073 ± 0.014	0.062 ± 0.018	0.061 ± 0.018	.011	.005	.596
f (Hz)	3.04 ± 0.09	3.03 ± 0.12	3.03 ± 0.08	3.02 ± 0.27	2.87 ± 0.15	2.89 ± 0.18	2.88 ± 0.18	2.93 ± 0.19	.098	.970	.782
F_{max} (BM)	2.27 ± 0.22	2.27 ± 0.19	2.19 ± 0.23	2.13 ± 0.21	2.02 ± 0.10	1.99 ± 0.07	1.91 ± 0.10	1.91 ± 0.10	.003	.048	.369
Δz (m)	0.046 ± 0.007	0.046 ± 0.009	0.049 ± 0.009	0.052 ± 0.012	0.060 ± 0.006	0.060 ± 0.005	0.064 ± 0.006	0.062 ± 0.005	.002	.004	.405
ΔL (m)	0.186 ± 0.022	0.179 ± 0.017	0.192 ± 0.037	0.190 ± 0.020	0.170 ± 0.034	0.167 ± 0.035	0.171 ± 0.027	0.182 ± 0.049	.271	.323	.441
k_{vert} (kN/m)	32.71 ± 7.19	32.27 ± 7.37	29.25 ± 7.56	26.98 ± 8.15	24.99 ± 3.50	23.99 ± 2.72	21.48 ± 2.92	22.05 ± 2.31	.007	.003	.740
k_{leg} (kN/m)	7.97 ± 1.65	8.16 ± 1.38	7.53 ± 2.37	7.05 ± 1.52	8.98 ± 1.74	8.89 ± 1.70	8.19 ± 1.42	7.92 ± 2.17	.182	.008	.916

Abbreviations: v, speed; t_c, contact time; t_a, aerial time; f, step frequency; F_{max}, maximal vertical ground-reaction force; BM, body mass; Δz, downward displacement of center of mass during contact; ΔL, displacement of the leg spring; k_{vert}, vertical stiffness; k_{leg}, leg stiffness.

[a] Significance by repeated-measures generalized linear model with 2 factors of the main effects of group (G), distance (D), and interaction (G × D).

Table 4 Body Mass, Maximal Mechanical Power of the Lower Limbs, and Tensiomyographic Parameters in the Vastus Lateralis Muscle Measured Before and Immediately After the Race in the 9 Fastest and 9 Slowest Runners of the Group, Mean ± SD

	9 Fastest Runners		9 Slowest Runners		P^a		
	Before	After	Before	After	Group	Time	G × T
Body mass (kg)	65.6 ± 5.7	63.2 ± 6.1	74.8 ± 5.8	72.3 ± 5.8	.004	.001	.001
Maximal mechanical power (W/kg)	31.2 ± 8.2	23.8 ± 9.3	24.1 ± 5.5	18.5 ± 4.2	.048	.008	.379
$T_{contraction}$ (ms)	25.8 ± 5.4	22.0 ± 3.5	25.3 ± 4.1	22.6 ± 2.4	.972	.004	.382
T_s (ms)	139.8 ± 60.0	93.8 ± 69.1	134.2 ± 63.2	72.6 ± 47.9	.611	.012	.447
T_r (ms)	92.3 ± 45.4	50.2 ± 45.8	89.6 ± 45.6	47.6 ± 46.5	.883	.007	.995
T_d (ms)	23.9 ± 1.9	21.4 ± 2.1	25.3 ± 3.9	22.3 ± 1.9	.172	.003	.697
D_m (mm)	6.6 ± 1.7	8.1 ± 3.0	6.2 ± 2.3	7.9 ± 2.8	.785	.010	.874

Abbreviations: $T_{contraction}$, contraction time; T_s, sustain time; T_r, relaxation time; T_d, delay time; D_m, maximal radial displacement.

[a] Significance by repeated-measures generalized linear model with 2 factors of the main effects of group (G), time (T), and interaction (G × T).

fastest and slowest athletes because of the significant difference in speed at every checkpoint (29.9% ± 5.3%, $P < .001$).

TMG Parameters

Figure 3 shows the TMG responses averaged among all runners that were carried out before and immediately after the race. After the race, a significant decrease ($P < .001$) in $T_{\text{contraction}}$ (–12.8% ± 9.7%), T_s (–39.3% ± 31.6%), T_r (–46.2% ± 33.5%) and T_d (–11.1% ± 9.5%) was observed, together with an increase of D_m (24.0% ± 35.0%, $P = .005$). When these parameters were compared between the fastest and slowest group, no significant differences were found (Table 4).

Discussion

The main results of the current study showed that (1) race time was inversely related with $\dot{V}O_{2max}$ and MMP; (2) running mechanics did not change throughout the race in the fastest runners, while it changed from km 30 onward in the slowest runners—however, in both groups, running mechanics before the race (PRE) were significantly different than POST; and (3) TMG time parameters ($T_{\text{contraction}}$, T_s, T_r, and T_d) decreased and D_m increased after the race in both groups.

As previously observed by several authors, strong correlations have been shown between $\dot{V}O_{2max}$ and running performance in subjects with different running levels.[18] However, when groups of athletes with a relatively narrow range of $\dot{V}O_{2max}$ are studied, $\dot{V}O_{2max}$ becomes a less sensitive predictor of performance, while its fraction that can be sustained throughout the race and the energy cost of running becomes more and more important for predicting performance in distance running.[18] Particularly, some authors,[18] showed that lower energy costs of running in trained runners were related with higher values of MMP and k_{vert} and low footprint index (ie, the mediolateral displacement of the foot during the whole stance phase), supporting previous studies that underlined the role of muscle–tendon-complex stiffness in storing and releasing elastic energy.[19]

Indeed, in the current study, the athletes with higher values of MMP presented lower t_c and Δz and higher t_a, F_{max}, and k_{vert}; these are all factors that could promote higher running velocity[20] and lower energy expenditure because of the lower oscillation of the center of mass.[18,19]

In contrast to previous studies,[2,6] no changes in f and an increase in Δz were observed. This suggests that the lower eccentric phase that is involved in uphill races like Supermaratona dell'Etna promoted peculiar adaptations so that the characteristics of the spring-mass system rather than the running speed were modulated throughout the race. Indeed, during an uphill-running race it may not be necessary to adopt a safer running style because of the peculiarity of the course profile. Furthermore, the increase in Δz observed in the current study could be a consequence of the decrease in k_{vert} and F_{max}, as observed previously in exhaustive but much shorter running efforts,[20–23] in which spring-mass characteristics changed toward a longer contact time,[22–24] higher Δz, and lower k_{vert}.[21]

Furthermore, the fastest runners changed their running pattern only at the last checkpoint, immediately after they crossed the finish line. We can speculate that these athletes changed their running pattern between km 30 and km 43, in the nonpaved leg of the race. This part of the race, where the surface stiffness was different than in the first part, could affect the running mechanics even in the fastest and most trained runners, although previous studies have shown that runners adjust their stiffness to maintain consistent support mechanics across different surfaces.[25] Conversely, the slowest runners changed their spring-mass parameters between km 14 and km 30. Note that the transit at km 30 for the slowest athletes occurred about 4 hours from the race start, while the fastest athletes reached this checkpoint in about 3 hours. Our hypothesis, in accordance with the study of Morin et al,[2] is that the spring-mass parameters change after a certain time of exercise performed rather than after a certain amount of distance covered.

Neuromuscular alterations due to fatigue[2] and muscle damage that occur during an ultraendurance event could affect running mechanics.[5] Millet et al.[12] demonstrated that central fatigue plays the main role in decreasing force after an ultramarathon. As well, alterations of neuromuscular propagation, excitation–contraction-coupling failure, and modifications of the contractile apparatus may be involved in decreasing force.[26] Hunter et al[16] used TMG to assess peripheral fatigue 24 hours after exercise-induced muscle damage and observed a decrease in D_m and an increase in $T_{\text{contraction}}$, by –31% and +21%, respectively. However, a different behavior of TMG parameters during various fatigue protocols has been shown by other authors,[14,15] even if, to our knowledge, TMG has been used only once to evaluate muscle fatigue during an ultraendurance event. After an Ironman triathlon, authors found that muscle

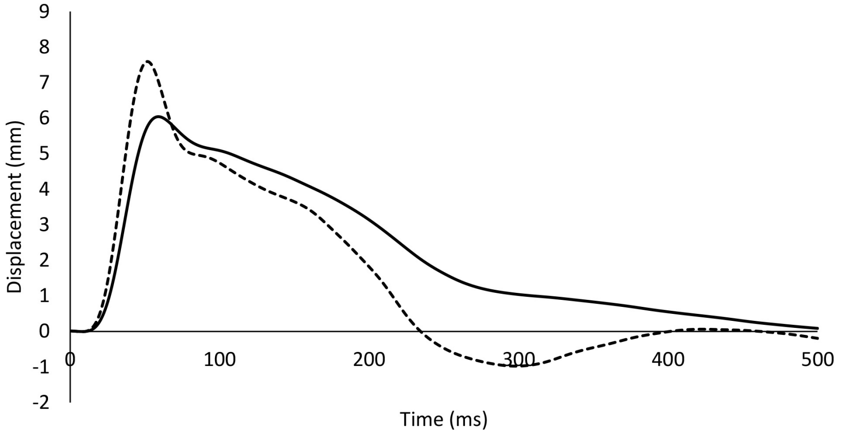

Figure 3 — Muscle response averaged among all runners to an electric stimulus obtained using tensiomyography on the vastus lateralis muscle, measured before (solid line) and immediately after (dashed line) the race.

specific decreased T_d in rectus femoris and increased $T_{contraction}$, T_r, and D_m in biceps femoris.[14] In contrast with our hypothesis, in the current study no differences in TMG parameters between the 2 subgroups of athletes before and after the race were found. When all 18 athletes were analyzed together, D_m increased by 24% while the other investigated parameters decreased, suggesting that the vastus lateralis muscle was less stiff and reacted faster to the electrical stimulus. Our results are in agreement with Millet et al,[12] who electrically stimulated the femoral nerve before and after a 65-km ultramarathon race, showing greater peak twitch tension and shorter contraction time after the race. The authors hypothesized that these changes could be due to the potentiation of the twitch force after fatigue.[12] In fact, a shift to the left of both torque[27] curve and TMG curve, similar to that observed in the current study after the race (Figure 3), is analogous to the shift usually observed in postactivation potentiation. Postactivation potentiation is commonly detected after short burst of strength or power exercise,[28] and it was also seen in endurance athletes after maximal isometric contractions.[27] Therefore, we suggest that enhanced postactivation potentiation may counteract fatigue during endurance exercise, which affects the behavior of the muscle fibers.

Limits of the Study

In this study, 1 issue was related to the running speed, which was self-selected both throughout the race and after its conclusion. However, the difference in speed was –2.4% between the second and the first checkpoint, –4.9% between the third and the first checkpoint, and –4.1% between the last and the first checkpoint. As previously observed,[5] these differences can be considered acceptable when comparing gait parameters by video analysis. To minimize this issue for the POST time point, athletes performed 3 running attempts, and the 1 with the speed closest to the average speed value recorded during the race (at km 3, 14, and 30) was taken into account for further analysis. Also in this case, the speed difference was negligible (–4.1%).

A second limit of this study was related to the number of subsequent steps that were analyzed to calculate the spring-mass-model parameters. We considered 5 subsequent steps, the maximum allowed by the camera placement with respect to the environment characteristics. However, other studies have analyzed running mechanics taking into consideration a similar number of consecutive steps (5 to either 8 steps[5] or 10 steps[3,18]), thus supporting our approach.

Finally, muscle contractile properties can be affected by muscle temperature.[29] To minimize this issue in the current study, prior the beginning of the race athletes underwent TMG measurements after a 10-minute warm-up. This countermeasure conceivably increased intramuscular temperature to values similar to those present after the end of the race, as this physiological variable shows steep increments in the first 10 minutes, reaching its plateau or values comparable to those recorded after prolonged exercise.[30]

Practical Applications

The current study shows that greater values of MMP are related to smaller changes in running mechanics induced by fatigue. Thus, lower-limb power training could be important for long-distance uphill-running performance. This suggests that coaches and athletes should consider the integration of specific lower-limb power training in their training programs to enhance long-distance uphill-running performance.

Conclusions

An inverse relationship between race time and $\dot{V}O_{2max}$, as well as MMP, was found. Higher MMP was related with higher F_{max}, t_a, and k_{vert}, as well as lower t_c and Δz; all these factors could conceivably promote higher running velocity. These findings suggest that lower-limb muscle power plays an important role in determining the performance of uphill long-distance runners. Future interventional studies are required to investigate whether lower-limb power training can improve running performance in long-distance uphill competitions. TMG analysis showed a decrement in muscle stiffness and higher sensibility of the muscle to the electrical stimulus, suggesting that the potentiation of fast-twitch fibers and the fatigue of slow-twitch fibers are 2 parallel mechanisms involved in this type of race.

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