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Running Mechanics During the World's Most Challenging Mountain Ultramarathon

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The aim of study was to examine the effects of the world's most challenging mountain ultramarathon (Tor des Géants [TdG]) on running mechanics. Mechanical measurements were undertaken in male runners (n = 16) and a control group (n = 8) before (PRE), during (MID), and after (POST) the TdG. Contact (t_c) and aerial (t_a) times, step frequency (f), and running velocity (v) were sampled. Spring-mass parameters of 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 computed. Significant decreases were observed in runners between PRE and MID for t_a ($P < .001$), F_{max} ($P < .001$), Δz ($P < .05$), and k_{leg} ($P < .01$). In contrast, f significantly increased ($P < .05$) between PRE and MID-TdG. No further changes were observed at POST for any of those variables, with the exception of k_{leg}, which went back to PRE. During the TdG, experienced runners modified their running pattern and spring-mass behavior mainly during the first half. The current results suggest that these mechanical changes aim at minimizing the pain occurring in lower limbs mainly during the eccentric phases. One cannot rule out that this switch to a "safer" technique may also aim to anticipate further damages.

Keywords*:* spring-mass behavior, anticipatory adaptations, sleep deprivation, safer technique

Running mechanics and spring-mass behavior are important factors to understand and improve the running efficiency and therefore overall performance in marathon[1–3] and ultramarathon.[4–7] During human constant submaximal running, the mechanical behavior of the musculoskeletal structures of the lower limbs is often described as that of a spring-mass system bouncing onto the ground.[8,9] This model has been used to describe and study the mechanics and energetics of bouncing and running gaits[10–13] and consists of a point mass supported by a single massless linear "leg spring." The main mechanical variables describing the spring-mass behavior of the runner are vertical stiffness (k_{vert}) and leg stiffness (k_{leg}). One important mechanical parameter studied when using this model is the stiffness of the leg spring, defined as the ratio of the maximal force to the vertical displacement (ie, k_{vert}) or maximum leg compression (ie, k_{leg}).[14] These variables are integrative, macroscopic mechanical parameters that encompass numerous complex neuromuscular and mechanical phenomena simultaneously characterizing the running motion.[14–16] Although it is inevitably based on some mechanical simplifying assumptions,[17] this model provides comprehensive information as to the overall adaptations induced by specific conditions such as fatigue. This advantage of seeing the "big picture" through this simple model has been used in several recent protocols about running-induced fatigue.[3,5,7]

Neuromuscular fatigue, usually defined as an exercise-related decrease in the maximal voluntary force or power of a muscle or muscle group associated with an increase in the perceived effort necessary to exert the desired force,[18] has recently been characterized during extreme running exercise.[4,19] It potentially involves processes at all levels of the motor pathway from the brain to the skeletal muscles. Fatigue was also found to alter running mechanics and spring-mass behavior after ultramarathon running.[3,5–7,20] Recently, Morin et al[5] showed that spring-mass behavior significantly changed after a 24-hour run on a treadmill, with ~5% higher step frequency (f) and 4.4% lower peak ground-reaction forces. Furthermore, the vertical displacement of the center of mass (Δz) and the leg-length change (ΔL) during contact were lower, which resulted in ~10% higher k_{vert} and k_{leg} values. Degache et al[3] recently showed that "only" 5 hours of hilly running induced modifications of the running step mechanics and spring-mass behavior of runners toward a lower vertical ground-reaction force and center-of-mass oscillating amplitude and higher f, k_{vert}, and k_{leg}. Despite the shorter time (5 h), which was similar in duration (while hillier) to that of a standard marathon run, the changes in running mechanics appeared to be in the same direction (ie, increased f and k_{vert}, decrease in displacement of the leg spring [ΔL] and maximal force [F_{max}]) but of lower amplitude than those obtained after an ultratrail.[7] In this latter study, a 166-km mountain-ultramarathon (MUM) run resulted in modified running step mechanics and spring-mass behavior of experienced runners toward a higher f (5.9%) and k_{vert} (5.6%) and a reduced aerial time (–18.5%), vertical ground-reaction forces (–6.3%), and center of mass oscillating amplitude (–11.6%).

Overall, it results in participants running with a "safer" running pattern that is thought to help reduce the deleterious effects of ultradistance running and minimize muscle and/or joint damage and/or pain.[7,20] Indeed, all the changes in running mechanics

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observed consistently concur to a "smoother" running style, that is, with less vertical oscillation of the center of mass and a higher *f*. Whether these changes directly result from increased nociceptive afferent feedbacks and joint/muscle pain or from (conscious or unconscious) anticipatory mechanisms used by participants to anticipate and generate less pain at each step is still unclear. In this MUM, the maximum time allowed for completing the race was 150 hours, including sleep duration. Overall, the runners spend 3 to 6 nights walking/running outdoors with a very limited amount of sleep (see Table 1).

However, we have shown that it was not related to strength loss in the lower limbs.[21] There is a debate regarding the change in energy cost during MUMs.[22,23] Indeed, this smoother running style is associated with an increase of *f*, which in turn might lead to a worsened running economy. However, a study reported an unchanged or improved economy after MUM.[6] So the relationships between the mechanical adaptations and the metabolic changes are still unclear for this type of ultraendurance event.

Ultramarathon is an interesting model for investigating the effects of extreme fatigue in healthy athletes.[24] Previous studies have assessed the acute consequences of an MUM >300 km, the Tor des Géants ([TdG]) (Valle D'Aosta, Italy), on inflammation,[19] neuromuscular fatigue,[19] postural responses,[25] energy cost,[6] and lung function.[26] In this MUM, the maximal allowed time is 150 hours. Since there are no mandatory stops, most runners experience severe sleep deprivation. This factor has been assessed in previous studies.[19,25]

However, to date no study has assessed the consequences of such an extreme event on running patterns and spring-mass behavior. The experimental design of these TdG studies included a measurement during the race (ie, MID-TdG) of interest to understand the kinetics of responses. The observed changes during the first and second halves of the TdG seem to be very specific to each physiological function. For instance, there was minimal strength loss in knee extensors and plantar flexors[19] in the first half, whereas most of the postural alterations[25] were observed at midrace. Conversely, lung function tended to decrease throughout the same MUM.[26]

The aim of the current study was to investigate running mechanics and spring-mass behavior of experienced runners during the TdG, the world's most challenging MUM. By using data recorded before, during, and after the event on both runners and nonexercising control participants submitted to comparable levels of sleep deprivation, we also aimed to better dissociate the alterations induced by muscle fatigue/damage from the alterations induced by sleep deprivation. We hypothesized that running mechanics and spring-mass behavior would be more altered than on shorter-duration MUMs (eg, Ultra-Trail du Mont-Blanc, 166 km) and would not be a direct consequence of sleep deprivation.

Table 1 Main Characteristics of the Runners and the Control Group (Mean ± SD)

Group	Age (y)	Mass (kg)	Sleep duration (h)
Runners, n = 16			
PRE	44.7 ± 11.0	67.9 ± 5.4	—
MID		67.3 ± 5.0	1.0 ± 1.5
POST		67.4 ± 0.7	8.8 ± 5.1
Control, n = 8			
PRE	29.3 ± 8.1***	70.9 ± 9.3	—
MID		70.7 ± 8.9	1.2 ± 1.8
POST		71.0 ± 8.4	12.3 ± 5.4

Abbreviations: PRE, before; MID, during; POST, after.

***$P < .001$ compared with runners.

Materials and Methods

This experiment is part of a large research project incorporating running-mechanics and neuromuscular-fatigue assessment. Thus, some parts of the methods and results have been reported elsewhere,[19] but they are repeated here for the convenience of the reader.

Experimental Design

The race supporting this study was the TdG. It comprises running/walking 330 km with a total positive and negative elevation of 24,000 m (Figure 1). This race is considered the world's most challenging single-stage MUM. The maximum and minimum altitudes are 3300 m and 322 m, respectively, with 25 passes over 2000 m. The distance is divided into 7 sections, with 6 interspersed aid stations where sleeping is allowed. However, the participants do not have to make any compulsory stop and therefore can pace themselves and manage their stops as they wish. Because the recovery time (nutrition, hydration, sleep, etc) is not subtracted from the race time, the influence of pacing and sleep deprivation is of paramount importance. This race is therefore different from other MUMs of shorter distances (eg, Ultra-Trail du Mont-Blanc, 166 km[27]) and from road ultramarathons over longer distances but with several stages (eg, the 2009 Trans Europe Foot Race, 4487 km in 64 stages from southern Italy to North Cape, Norway[28]), where sleep management is of less importance.

The runners and control participants were tested 3 times: before the run (PRE, Courmayeur, Italy, altitude 1224 m, km 0), during the run (MID, Donnas, Italy, altitude 322 m, km 148.7), and during the 30 minutes after completion of the run (POST, Courmayeur, Italy, altitude 1224 m, km 330). Note that MID is approximately as long and as difficult in terms of elevation changes as the Ultra-Trail du Mont-Blanc race, which was among the longest MUMs hitherto studied.

Participants

Sixteen male runners participated in this study. They were 44.7 ± 11.0 years old, measured 174.0 ± 5.0 cm, and weighed 67.9 ± 5.4 kg at the start of the race. From the 25 initially engaged participants, 16 participated in the 3 testing sessions. All participants were experienced in ultramarathon/trail running, trained 7.5 ± 4.7 h/wk, and had 8.4 ± 6.1 years of experience in trail running. Six had already finished the previous TdG. In addition, a control group of 8 nonrunner participants was included in this study. They were 29.3 ± 8.1 years of age (significantly different from the runners group, $P < .05$), measured 174.1 ± 5.6 cm, and weighed 70.9 ± 9.3 kg. The control group underwent the same sleep deprivation and the same tests as the runners. The instructions for sleep deprivation to the control group were as follows: "Sleep as little as possible, and if you sleep, record your sleeping duration." All changes in weight during the race/study are presented in Table 1.

Ethics Statement

All participants were fully informed of the procedure and the risks involved. They all provided written consent. They were allowed to

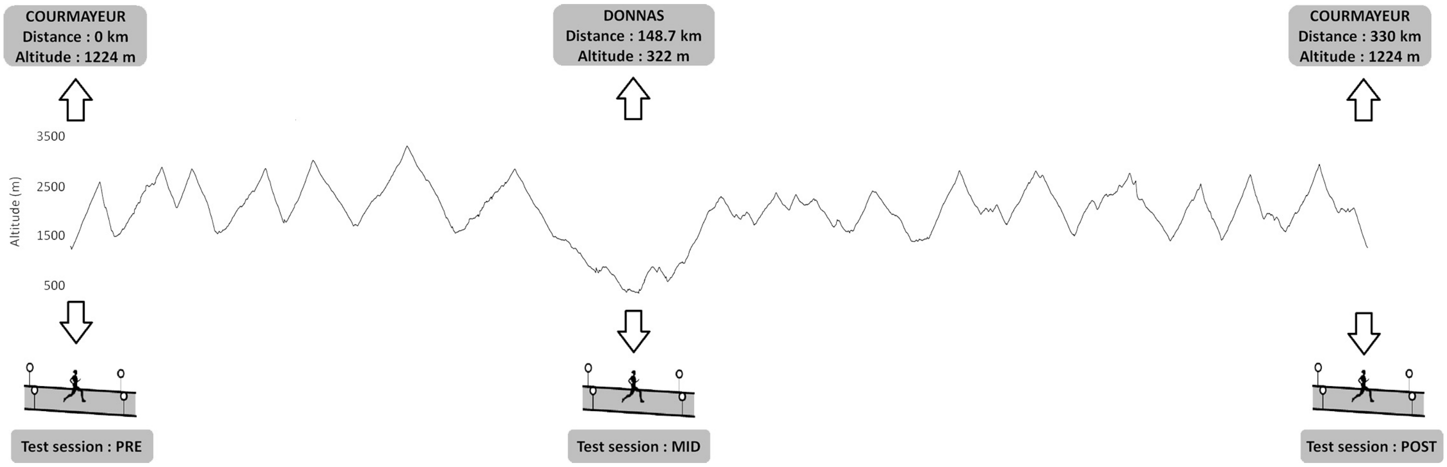

Figure 1 — GPS track of the entire run with the 3 test-session locations and the distance scale in kilometers.

stop the study at will and to refuse any of our tests. The study was approved by the institutional ethics committee of the University of Verona, Italy (Approval #152, Department of Neurological, Neuropsychological, Morphological and Motor Sciences). All participants provided written, voluntary, informed consent before participation. The experiment was conducted according to the Declaration of Helsinki.

Experiments

Methods replicated those used on the Ultra-Trail du Mont-Blanc[7] for comparison purpose. Measurements were performed on a pressure mat set on the floor at a 12-km/h pace given by an experimenter running next to the participants. The 12-km/h velocity was chosen for comparison with previous studies using similar methods[3,7,29] and because we previously showed that there were no significant differences in the effects of fatigue on running mechanics between 12 and 10 km/h.[3] Finally, a higher velocity was not possible because it would have been too difficult for some runners in a fatigued state.

This running velocity was checked by means of 2 photocells placed 5 m apart, and any trial run 5% slower or faster than 12 km/h was repeated. Mechanical data were sampled for 2 consecutive valid trials at 12 km/h, allowing us to analyze 5 to 8 steps for each participant and condition. All measurements were performed indoors on the same mat and the same types of floor, ensuring similar measurement conditions PRE, MID and POST-TdG. Running velocities were 12.1 ± 0.2, 12.0 ± 0.3, and 12.0 ± 0.3 km/h for runners and 12.1 ± 0.2, 12.2 ± 0.1, and 12.0 ± 0.2 km/h for the control group at PRE, MID, and POST, respectively. No significant difference was observed between sessions and between groups.

Participants ran over an electronic 7.32-m-long and 0.61-m-wide walkway (GAITRite Gold, CIRSystems, Havertown, PA), comprising a series of pressure-sensor pads placed ~1.3 cm apart. This pressure mat was connected to a personal computer yielding contact (t_c) and aerial (t_a) times at a sampling rate of 80 Hz (for further details on the validity of this device for gait analysis, see references 30–32). Step frequency was calculated as $f = 1/(t_c + t_a)$. Participants' running velocity (v) was calculated from the electronic-walkway data and carefully checked to be within ±5% of the reference value of 12 km/h. Spring-mass parameters were calculated using the computation method[33] based on the following input variables: t_c, t_a (s), v (m/s), body mass (kg), and L (m), the lower-limb length. L was measured as the great-trochanter-to-ground distance in a standing position. This method, based on a modeling of the ground-reaction-force signal during the contact phase by a sine function, allows computation of vertical stiffness (k_{vert} in kN/m) as the ratio of the maximal estimated ground-reaction force (F_{max} in N) to the estimated maximal downward displacement of center of mass during contact (Δz in m):

$$k_{vert} = (F_{max}/\Delta z)$$

with

$$F_{max} = mg\frac{\pi}{2}\left(\frac{t_a}{t_c}+1\right)$$

and

$$\Delta z = -\frac{F_{max}}{m}\frac{t_c^2}{\pi^2} + g\frac{t_c^2}{8}$$

Leg stiffness (k_{leg} in kN/m) was calculated as the ratio of F_{max} to the peak displacement of the leg spring ΔL (in m) during contact:

$$k_{leg} = (F_{max}/\Delta L)$$

with

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta z$$

Statistical Analyses

Descriptive statistics are presented as mean ± SD for the 5 to 8 steps sampled in each participant and condition. Normal distribution of the data was checked by the Shapiro-Wilk normality test. The mechanical variables studied were compared by using a 2-way (group [runners vs control] × time [PRE, MID, POST]) repeated-measures ANOVA. In addition, the importance of the differences found between PRE, MID, and POST conditions was assessed through the effect size and Cohen d coefficient,[34] interpreted as follows: small difference, $0.15 \le d < 0.4$; medium difference, $0.40 \le d < 0.75$; large difference, $0.75 \le d < 1.10$; and very large difference, $d \ge 1.10$. The significance level was set at $P < .05$. Statistical analyses were performed using SigmaPlot (version 12.5, Systat Software Inc, San Jose, CA, USA).

Results

Performance and Sleep Duration

The average finishing time of the runners was 126 hours 40 minutes ± 16 hours 49 minutes (final rank from 7th to 243th position out of 301 finishers). The time between arrival (finish line) and the POST-TdG measurements was 18 ± 06 minutes. Sleep-duration values are presented in Table 1 and were not different between the controls and the runners either at MID or at POST-TdG.

Body mass was not significantly changed at MID and POST for both groups as shown in Table 1.

Running Mechanics

Significant decreases were observed in runners between PRE and MID-TdG for t_a ($P < .001$, $d = 1.23$—very large), F_{max} ($P < .001$), Δz ($P < .05$), and k_{leg} ($P < .01$) and a significant increase for f ($P < .05$, $d = 0.62$—medium) (Figure 2 and Table 2A). In the same group, significant decreases were observed between PRE and POST-TdG for t_a ($P < .001$, $d = 1.14$—very large) (Figure 2), F_{max} ($P < .001$), and Δz ($P < .05$) and a significant increase for f ($P < .05$, $d = 0.73$—medium) (Table 2A). Significant differences were observed in controls for t_a ($P < .01$, $d = 1.25$—very large) between PRE and MID-TdG, as well as between PRE and POST-TdG ($P < .05$, $d = 1.02$—large) (Figure 2 and Table 2B).

Discussion

The purpose of this study was to investigate the effects of the world's most challenging MUM on running mechanics and spring-mass behavior of experienced runners. The main results are that experienced runners modified their running pattern and spring-mass behavior mainly during the first half of the TdG, the running mechanics being no further modified from MID to the finish; overall, these changes were not higher than those previously observed on shorter MUMs, and the effects of sleep deprivation on running patterns were minimal.

The mechanical-parameter values reported in Figure 2 and Table 2A are similar to those previously reported in ultradistance runners.[6,7,20] In the current study, the runners modified their running patterns and spring-mass behavior mainly during the first half of the TdG. Indeed, we found significant changes in running patterns already at MID-TdG with an increase in f and a decrease of t_a. These changes are in line with several studies that investigated the effects of an MUM on running biomechanics.[6,7] Indeed, in the current study, the distance at MID-TdG was about same as the distance and positive and negative elevation as a shorter MUM (Ultra-Trail du Mont-Blanc). Morin et al[7] examined the changes in mechanics and spring-mass behavior induced by this shorter MUM.

The runners in these 2 experiments showed similar modifications in t_a, that is, decrease of about 18% versus 19% in the Ultra-Trail du Mont-Blanc and at MID-TdG, respectively. Similarly, when comparing Ultra-Trail du Mont-Blanc versus MID-TdG, the changes were found to be ~+6% versus +7% for f, ~–6% versus –8% for F_{max}, and ~–12% versus –11% for Δz. This occurred

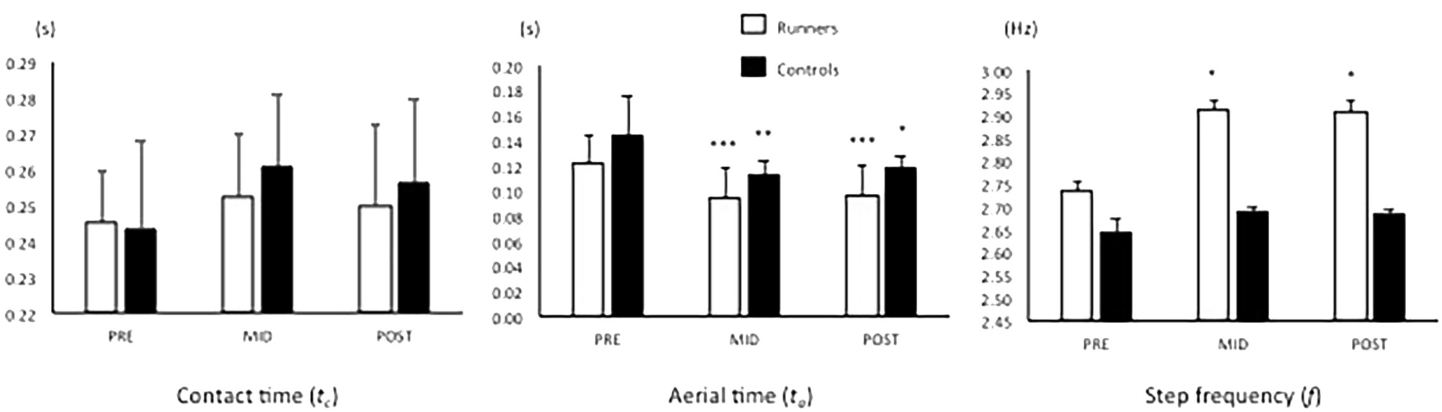

Figure 2 — Evolution of contact time, aerial time, and step frequency for runners and controls before (PRE), during (MID), and after (POST) the Tor des Géants.

Table 2A Spring-Mass Parameters of Runners Before (PRE), During (MID), and After (POST) the Tor des Géants, Mean ± SD

Parameter	PRE	MID	POST	PRE–MID % change	PRE–MID effect size	PRE–POST % change	PRE–POST effect size
F_{max} (× body weight)	2.36 ± 0.14	2.16 ± 0.15***	2.18 ± 0.18***	–8.4 ± 7.5	1.34 (very large)	–7.3 ± 8.1	1.1 (very large)
Δz (m)	0.067 ± 0.011	0.059 ± 0.011*	0.058 ± 0.009*	–10.9 ± 20.2	0.7 (medium)	–11.7 ± 18.2	0.87 (large)
ΔL (m)	0.164 ± 0.017	0.164 ± 0.016	0.157 ± 0.024	0.3 ± 11.7	0.1 (small)	–4.2 ± 13.4	6.95 (very large)
k_{vert} (kN/m)	23.51 ± 2.82	24.83 ± 5.36	25.23 ± 4.41	6.3 ± 21.5	0.3 (small)	8.2 ± 18.5	0.45 (medium)
k_{leg} (kN/m)	9.53 ± 0.79	8.69 ± 0.69**	9.36 ± 1.6	–7.8 ± 9.1	1.1 (very large)	–1.7 ± 14.8	0.13 (small)

*$P < .05$, **$P < .01$, ***$P < .001$: significantly different from PRE.

Table 2B Spring-Mass Parameters of Controls Before (PRE), During (MID), and After (POST) the Tor des Géants, Mean ± SD

Parameter	PRE	MID	POST	PRE–MID % change	PRE–MID effect size	PRE–POST % change	PRE–POST effect size
F_{max} (× body weight)	2.31 ± 0.14	2.25 ± 0.12	2.3 ± 0.12	–2.01 ± 7.58	0.43 (medium)	0.07 ± 6.23	0.07 (small)
Δz (m)	0.074 ± 0.01	0.068 ± 0.006§	0.069 ± 0.008§	–6.52 ± 13.85	0.69 (medium)	–5.66 ± 12.99	0.52 (medium)
ΔL (m)	0.171 ± 0.023	0.177 ± 0.016	0.175 ± 0.02	5.28 ± 15.68	0.29 (small)	3.31 ± 12.90	0.17 (small)
k_{vert} (kN/m)	23.37 ± 2.07	23.1 ± 4.33	22.81 ± 3.96	0.12 ± 23.94	0.05 (small)	–1.52 ± 20.88	0.17 (small)
k_{leg} (kN/m)	10.1 ± 1.5	8.92 ± 1.75	8.66 ± 1.75	–10.29 ± 19.41	0.68 (medium)	–13.12 ± 17.88	0.83 (large)

§$P < .05$: significantly different from runners.

despite the runners completing the Ultra-Trail du Mont-Blanc in 37.9 ± 6.2 hours while they needed 43.4 ± 7.2 hours to run a comparable distance and positive/negative elevation over the first half of the TdG. It therefore appears that the 14% lower speed at MID-TdG than the Ultra-Trail du Mont-Blanc[19] was not associated with lower mechanical alterations. We showed in a previous paper that strength loss in knee-extensor and plantar-flexor muscles was negligible at MID-TdG (see Figure 4 in reference 19), while significant foot/ankle and knee/thigh/hip pain (see Figure 6 in reference 19) existed. Therefore, the current data suggest that the observed changes in running biomechanics are associated with nociceptive feedback. However, since we did not find any correlation between increase in pain and mechanical changes, it is likely that this is a complex phenomenon probably combining different (eg, perceptive, metabolic, and mechanical) underlying mechanisms. Indeed, Morin et al[7] suggested that the increased f and decreased vertical oscillations of the spring-mass system (in terms of F_{max}, Δz, and k_{vert}) are associated with an overall lower force production, especially during the braking phase of each step. Morin et al[7] previously suggested that 2 principal hypotheses can explain this phenomenon. The first is a decrease in force capacities in lower-limb muscles. This was, for instance, the case in older runners[35] where the deficit in force would result in a lower push, causing reduced amplitude of the vertical oscillation. However, when high levels of fatigue were induced by a different type of exercise in a different study, that is, not inducing the pain that occurs in ultramarathons, the running mechanical changes were minimal. The second hypothesis is that the smoother running pattern is associated with a safer running technique. By using this technique, runners attempt to attenuate the potentially painful eccentric (braking) phase and overall load faced by their locomotor system at each step.

The changes observed in the current study clearly fit with the localized-pain hypothesis and be confirmed by Dutto and Braun[36] and Paschalis et al,[37] who explained that delayed-onset muscle soreness induced by eccentric exercise during the downhill phase of running induces significant alterations of running mechanics and kinematics.

However, the current results do not allow us to rule out the fact that these changes might have also been in part due to anticipatory strategies. Everything happened as if runners decreased their speed and modified their running technique by adopting a "safer" pattern to reduce pain, but they also might have tried to reduce further damages in the second half of the race, in agreement with the theory of the teleoanticipatory strategy aiming to protect body integrity and maintain homeostasis.[38,39] In the current study, there were no further alterations in running mechanics in the second half of the TdG; that is, the mechanical changes observed POST-TdG (except for k_{leg}, which seems to return to baseline value without significant difference) were not higher than at MID and were not higher than previously observed ones on shorter MUMs. This could be due to successful anticipatory strategies, but it is also likely due to the large reduction in running speed over the second half (–37% when compared with Ultra-Trail du Mont-Blanc[19]), which can be explained by the high level of general fatigue and sleep deprivation. Indeed, most of the runners alternated short periods of running with long bouts of walking, including on flat portions, from MID-TdG to the finish.

The current study also shows that sleep deprivation had only a small effect on running patterns. The 13% decrease in k_{leg} is mainly caused by a nonsignificant 3.3% increase in leg compression during contact while F_{max} did not change. It suggests that the alteration in stiffness induced by sleep deprivation might arise from factors different from those observed after the MUM (eg, reduction in both F_{max} and leg compression leading to an almost unchanged 1.7% leg stiffness). The mechanisms underlying this nonsignificant decrease in k_{leg} for the control subjects are unexplained since they did showed neither any significant neuromuscular peripheral or central fatigue[19] nor postural-control alteration.[25] These data suggest that severe sleep deprivation as experienced in the current study was not sufficient to induce the same magnitude of mechanical alteration as in runners. Since some changes were larger at MID than at POST in runners, it is difficult to isolate the sleep deprivation from the other factors experienced under extreme fatigue. It is known that sleep deprivation affects postural control by reducing levels of alertness[40] and affects executive functions and sensorimotor integration. The link between neurophysiological parameters and functional deficiencies (eg, ankle sprain) was shown by Doherty et al,[41] who found significant correlations between postural control strategy deficiencies (multisensory integrations) and ankle sprain. This may increase the risk of a fall, especially in trail running because of the uneven surface. Thus, despite the lack of major effects of sleep deprivation on running mechanics, proper management of sleep during an MUM is still required to reduce the risk of runner falls and injuries.[25]

Practical Applications

Although such challenging sport events (200-mile running races) are not currently performed by a substantial number of individuals, the recent increase in participants in shorter ultratrail races (100–160 km) could possibly result in increasing numbers of participants in longer races and the overall increase in such events. The main findings of this study show that runners adapt their running pattern to safely cover the entire distance by adjustments of the running stride mechanics already observable and complete at midrace, and to an extent that is not substantially higher than what is observed during races of half the duration of the one studied here. So we can, for instance, propose that 100- to 160-km races are sufficient for the subjects to learn and adapt their running pattern and that they might focus in their preparation on other features of running performance beyond these 100 to 160 km (food- and liquid-intake strategies, sleep management, psychological features), since basically almost nothing will change in their running mechanics between ultratrail races of 160 and 320 km such as those studied in this paper and in recently published ones.

One major limitation of the current study is that the assessment of running mechanics and spring-mass behavior was performed during level running only. That is not ecological, and one may question its validity in the context of MUMs, which are mainly (almost totally) characterized by uphill and downhill sections. Vernillo et al[6,42] reported specific mechanical and metabolic adaptations in uphill running that were not observed in level running.

Conclusion

During the TdG, the world's most challenging MUM, experienced runners modified their running pattern and spring-mass behavior mainly during the first half, and the observed changes were not higher than those previously measured on shorter MUMs. Overall, the current results suggest that the changes in running mechanics and spring-mass behavior in ultramarathons aim to minimize pain of the eccentric phase at each step. The switch to a "safer" technique, that is, a "smoother" running style, may also aim to anticipate further damages.

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