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Authors: Nicola Giovanelli[1,2], Paolo Taboga[1,2] and Stefano Lazzer[1,2]

Affiliations: [1] Department of Medical and Biological Sciences, University of Udine, Italy. [2]School of Sport Sciences, University of Udine, Italy.

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Changes in running mechanics during a six hours running race

Submission type: original investigation

Nicola Giovanelli[1,2], Paolo Taboga[1,2] and Stefano Lazzer[1,2]

[1.] Department of Medical and Biological Sciences, University of Udine, Italy

[2.] School of Sport Sciences, University of Udine, Italy

Corresponding Author:

Nicola Giovanelli,

University of Udine

Department of Medical and Biological Sciences

P.le Kolbe 4

33100 Udine, Italy

Phone: +39 0432 494330 - Fax: +39 0432 494301

e-mail: nicola.giovanelli@uniud.it

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ABSTRACT

PURPOSE: To investigate changes in running mechanics during a six hours running race. **METHODS:** Twelve ultra-runners (age: 41.9±5.8 years; body mass: 68.3±12.6 kg; stature: 1.72±0.09 m) were asked to run as many 874 m flat loops as possible in six hours. Running speed, contact (t_c) and aerial (t_a) times were measured in the first lap and every 30±2 minutes during the race. Peak vertical ground reaction force (F_{max}), stride length (SL), vertical downward displacement of the centre of mass (Δz), leg length change (ΔL), vertical (k_{vert}) and leg (k_{leg}) stiffness were then estimated. **RESULTS:** Mean distance covered by the athletes during the race was 62.9±7.9 km; compared to the first lap running speed decreased significantly starting from 4h30' onward (mean: -5.6±0.3%; p<0.05), while t_c increased after 4h30'of running, reaching the maximum difference after 5h30' (+6.1%, p=0.015). Conversely, k_{vert} decreased after 4h00' reaching the lowest value after 5h30' (-6.5%, p=0.008); t_a and F_{max} decreased after 4h30' throughout the end of the race (mean: -29.2% and -5.1%, p<0.05, respectively). Finally, SL decreased significantly (-5.1%, p=0.010) during the last hour of the race. **CONCLUSIONS:** These results show that most changes occurred after 4h continuous self-paced running, suggesting the possible existence of a "time threshold" that could affect performance regardless of absolute running speed.

Keywords: kinematics; ultra-endurance; ground reaction forces; pacing strategy; ultra-marathon

INTRODUCTION

Over the past few years some authors have focused their research on ultra endurance running, both in laboratory- and real- settings[1-10], and the mechanics of running have been studied extensively and in different contexts. Studying ultra-marathons provides information on the limits that can be achieved by humans. These performances allow to better explore the adaptive responses of humans undergo to extreme load and stress induced by severe and prolonged efforts[11].

In some of the above mentioned studies[1,2,4,8,10], the spring-mass model proposed by Blickhan[12] was used to investigate running mechanics and results showed a direct link between changes in running mechanics and the exercise duration. All authors agree that peak vertical ground reaction forces (F_{max}) decrease following a prolonged run (6-24 hours), but no consensus exists on contact (t_c) and aerial (t_a) times. For instance, some studies reported that t_c increased after a 65 km mountain ultra-marathon (MUM)[13] and after an uphill-only marathon[7,10], whereas others showed a decrease in t_c after a 5-h hilly[4] run and after a 24-h treadmill run[1]. In addition, t_c remained unchanged during performances protracted for several days[2,8,9,14]. Further, t_a decreased in some of these studies[2,8-10] and did not change in others[1,4,7,14]. Discrepancies can be also observed when other mechanical parameters were considered. Indeed, vertical displacement of the centre of mass (Δz) decreased while step frequency (SF) and vertical stiffness (k_{vert}) increased[1,2,4,8,9]. It has been suggested that this running pattern leads to a smoother and safer running style, in order to limit the overall loading on the lower limbs and the associated painful consequences, particularly during the braking phase of the step[2]. On the other hand, two studies[7,10] reported higher Δz as well as lower k_{vert} and SF which explain, at least in part, the higher energy cost of running due to the positive work[15,16] performed by athletes during an uphill-only race event. Moreover, Dutto and Smith[17], who reported similar trends for SF and k_{vert}, suggested that it is the inability of the system to maintain an optimal stiffness that leads to exhaustion.

Another important factor to take into account when analysing running mechanics is the "time-effect". Indeed, it seems that in long-lasting events some changes are time- rather than distance-induced[2,7]. Specifically, it was hypothesized that the spring-mass model parameters could be affected by fatigue between the third and fourth hour of exercise both in level treadmill and uphill running[1,7]. Despite the large number of studies on running mechanics, to our knowledge the present study is the first to specifically address the changes in running mechanics during an outdoor ultra-marathon event on flat terrain, which is a unique opportunity to study the continuous changes occurred during this type of race. Previous study[1] analysed the mechanical changes during an ultra-endurance event, but not in real setting and not during a competition. It is supposed that athletes express their maximal effort during competition since they may be positively influenced by the motivation to achieve the best result. Also, the study of the changes in physiological and mechanical parameters during real competition might lead to new insights into the pacing strategy and thus the training and race tactics[18].

The aim of the study was to analyse continuous changes in running mechanics during a six hours running race on an 874 m flat loop. As reported in a previous work[7] in which a race of similar duration was analysed, we hypothesized changes in running mechanics between the third and fourth hour of the race.

METHODS

Subjects

Nineteen healthy Italian male runners were enrolled in this study as participants in the "6 ore Città di Buttrio". The experimental protocol was conducted according to the Declaration of Helsinki and it was approved by the Ethics Committee of the University of

Udine. Before the study began, the purpose and objectives were carefully explained to each participant and written informed consent was obtained from all of them. The participants were recruited among experienced ultra-endurance runners (12.4±8.5 years of training history in running and 6.5±3.5 years of ultra-endurance running race experience; they reported to run on average 73.3±19.5 km every week). Athletes were asked to fill out a questionnaire on physical exercise activity, demographics, medical history and lifestyle[19]. All the nineteen athletes who were eligible for the study began the race but only 12 completed the entire competition (age: 41.9±5.8 years; body mass index: 22.3±2.1 $kg \cdot m^{-2}$). The athletes dropped out because of gastrointestinal problems (n=4) and muscular cramps (n=3). Therefore, only the runners who concluded the race were taken into account for the data analysis.

Experimental design

The athletes were required to run as many 874 m paved surface flat loops as possible in six hours. In the week preceding the race, the participants were asked to come to the laboratory to perform a graded exercise test on a treadmill to evaluate their maximal oxygen uptake ($\dot{V}O_2max$). Then, during the race, running mechanics in the first lap and every 30 minutes thereafter (±2 minutes, depending on the athlete's position along the circuit) were evaluated. Athletes were free to choose their own running speed during the competition to achieve their best performance (i.e. the highest distance covered).

Physiological measurements before the race

Body mass (BM) was measured by a manual weighing scale (Seca 709, Hamburg, Germany) and stature by standardized wall-mounted height board. Then, body mass index (BMI) was calculated. $\dot{V}O_2max$ ($mL \cdot kg^{-1} \cdot min^{-1}$) was measured by means of a graded exercise test on a treadmill (Saturn, HP Cosmos, Germany) as described elsewhere[10,14].

Mechanical measurements during the race

A digital camera with a sample frequency of 400 Hz (Nikon J1, Japan) was used to record participants during the race. The camera was placed perpendicular to the running direction of the athletes in a flat section of the loop, allowing the recording of a 10 m long section. Running speed was measured by means of two photocells placed 20 m apart (Figure 1). The height of the photocells was 1.50 m, according to Cronin et al.[20], and it was maintained constant during all the six hours.

Five subsequent complete steps (from foot strike of one foot to the foot strike of the contralateral foot) were analysed, these steps were gathered at the initial part of the 10 m corridor. Mean CV±s.d. for t_c and t_a were 0.023±0.003 s and 0.166 ±0.080 s, respectively. We used Kinovea 0.8.15 software (www.kinovea.org) in order to measure t_c (s) and t_a (s)[2,7], mean values of t_c and t_a over the 5 steps were then utilized in our calculations.

In particular, step frequency (SF, step·s^{-1}) was calculated as SF=$1/(t_c+t_a)$ and step length (SL, m) was calculated as SL=running speed/SF. Finally, the spring-mass model parameters (F_{max}, Δz, ΔL, k_{vert}, k_{leg}) were calculated using the method proposed by Morin et al.[21].

Statistical analyses

Statistical analyses were performed using PASW Statistic 18 (SPSS Inc., IL, USA) with significance set at $p<0.05$. All results are expressed as means and standard deviation (SD).

Normal distribution of the data was tested using the Kolmogorov-Smirnov test. Changes of speed and mechanical parameters during the race were studied with the General Linear Model (GLM) for repeated measures. When significant differences in the analysed parameters (speed, t_c, t_a, F_{max}, Δz, k_{vert} and SL) on within-subjects effects were found by GLM, a Bonferroni post-hoc test was used to determine the exact location of the difference.

All the changes are related to the first check point and the magnitude of the changes was assessed using the Cohen's effect size (ES) statistic and percentage change. The interpretation of effect size was as follows: <0.2 = trivial, 0.2–0.49 = small, 0.5–0.79 = medium, >0.80 = large[22].

RESULTS

The physical characteristics of the participants who completed the race are reported in Table 1, together with the distance covered and the running speed. The average running speed during the race was 2.91±0.37 $m \cdot s^{-1}$, which corresponds to 67.4±6.9% of $v\dot{V}O_2max$. Running speed decreased significantly starting from 4h30' onward, compared to the running speed measured at the first check point (first lap) (mean: -5.6±0.3%; $p<0.05$, ES=0.64, medium, Figure 2(a)).

Figure 2 shows the trends of mechanical parameters during the race. Contact time (Figure. 2(b)) increased significantly from 4h30' onward, reaching the maximum difference at 5h30, (+6.1%, p=0.015, ES=0.97, large). Aerial time (Figure 2(c)) and F_{max} (Figure 2(d)) decreased significantly from 4h30' throughout the end of the race (mean of the last four sections: -29.2% and -5.1%, $p<0.05$; ES= 0.55 and ES=0.72, medium; respectively). Whereas, Δz (Figure 2(e)) decreased only in the last check point (-6.5%, p= 0.02; ES=0.64, medium). k_{vert} (Figure 2(f)) decreased significantly after 4h00' reaching the lowest value after 5h30' (-6.5%, p=0.008; ES=0.33, small). Finally, SL (Figure 2(g)) decreased significantly from 5h00' throughout the end of the race (mean of the last three sections: -5.1%, p=0.010; ES=0.41, small) whereas SF did not change (Figure 2(h)).

DISCUSSION

The main result of the present study shows that running mechanics start to change after the fourth hour of exercise, regardless of absolute running speed.

Running mechanics did not significantly change in the first 2/3 of the race, therefore we reject our hypothesis that significant changes would be seen between the third and fourth hour of the race. Indeed, before the fourth hour we did not observe any significant change in the spring-mass model parameters, while at the fourth hour only k_{vert} changed. After $4^h30'$ of running, F_{max}, t_a, t_c and SL changed significantly, suggesting that before this moment running fatigue does not affect the gait.

The decrease observed in F_{max} was in agreement with all previous studies that analysed both shorter and longer events than six hours[1,2,4,7,8,10,14]. In our study, athletes decreased their F_{max} by -5.1%, a value similar to those already reported. Indeed, Morin et al. [1] showed a decrease by -4.4% after a 24h treadmill running. Other studies reported a decrease in F_{max} by -6.3% and by -7.3% after mountain ultra-marathons[2,8], while Degache et al. [4] showed a decrease by -2.4% after 5h hilly running. Therefore, our results are comparable to those reported for longer (≥24 hours) races. As previously pointed out[1], F_{max} seems to decrease in the first few hours of exercise reaching a plateau after a certain time (~4 hours) of running. The decrease in F_{max} could be due to functional and structural alterations of muscle fibres as well as to an increase in the inflammatory status occurring during these types of race, in particular when eccentric contractions are required (e.g. in the first part of stance phase)[3]. Indeed, the muscle fibres damaged by an eccentric exercise[23,24] generate lower force because the decreased sarcomeres functionality[23,24].

However, our results are not consistent with the findings of other studies[1,2,4,8] showing different trends for Δz, k_{vert}, k_{leg}, SF, t_c and t_a. These studies showed an increase in k_{vert} due to a higher decrease in Δz than in F_{max} explaining these changes as the result of a smoother and less traumatic way to run. However, in our study, k_{vert} decrease was due to a decrease in F_{max} without changes in Δz, suggesting the inability of the spring-mass system to maintain an optimal stiffness when the subject is running at constant speed in a fatigued state[17]. In addition, SF did not change significantly during the entire competition. Taylor [25] reported that an allometric relationship relating SF and body mass might exist. However, for technical issues we were not able to collect the BM after the race making it impossible to establish a relationship comparing the BM before and after the race with the SF. Nonetheless, the method[21] we used for calculating SF does not take into account the BM and we can exclude a direct influence to the SF.

Our results regarding the SF are in agreement with Lazzer et al.[10] who analysed running mechanics during an uphill-only race. Despite the fact that in uphill race the running pattern is different involving higher parallel peaks force[26], higher SF and shorter SL[27], we expected that similar results could be achieved because of the similar duration of the race (~six hours). Indeed, changes in all the measured parameters agree with the study of Lazzer et al.[10], even if after six hours of level running they are lower in magnitude if compared with uphill running (level *vs.* uphill running: F_{max}: -5.1 *vs.* -17.6%; Δz: -6.5 *vs.* +52.9%; ΔL: NS *vs.* +44.5%; k_{vert}: -6.4 *vs.* -45.6%; k_{leg}: -7.2 *vs.* -42.3%; t_c: +6.1 *vs.* +28.6%; t_a: -29.2 *vs.* -58.6%). These differences could be due to the work done to elevate the centre of mass during uphill running, which involves higher fatigue and bigger changes in running mechanics compared to level running. Also, Vernillo et al.[13] explained that changes in stiffness due to fatigue could induce the runners to generate force less rapidly compared to a non-fatigued state, thus having longer t_c as observed in the present study.

In sprint and middle-distance running events athletes start fast, then slow down[28] and then increase their speed again in the last part of the race[29]. Conversely, in endurance races, athletes try to keep a regular and comfortable pace for the whole duration of the event[30] or slowing down in the last part of the race[18]. Evidences suggest that during ultra-endurance events athletes tend to decrease their speed, adopting a positive pacing strategy[18,31,32]. Our results agree with this strategy although the strongest athlete (with a 100 km personal best of

7h29') adopted a negative pacing strategy, increasing the speed by mean ~3% in the last two hours of the race compared to the first check point. This could be explained by the great experience of this subject in the ultra-endurance events. It would be interesting to repeat this kind of analysis in different type of races, for example in races where distance, and not time, is fixed. Since the distance covered by the different subjects in our study varied a lot (range: ~47km to ~80 km) it is difficult to predict whether the result would be the same if, instead of a time-trial, runners were asked to cover a given distance as fast as possible. For example, if the strongest athlete who ran 80 km had to run 47 km, as the slowest participant did, it is fair to assume that he would have covered that distance at a faster pace than that maintained during the six hours race. Given that all the analyzed athletes were experienced ultra-endurance runners, it can be assumed that every athlete covered the maximum distance that was in his possibilities; however, for a distance-based race, the same athletes could adopt a different pacing strategy that could influence their running mechanics.

Considering the mean speed over six hours, the average speed was 2.91±0.37 $m \cdot s^{-1}$, which corresponds to 67.4 ± 6.9 % of the running speed at $\dot{V}O_2max$ measured during the graded test. This speed was slightly slower than the running speed at which the mechanical analysis was carried out because it actually includes also the rest time to enable athletes to feed during the six hours. Unlike other protocols[1,33,34], athletes organized their own feeding strategy, so that we did not control when and how long they rested during the race. However, since athletes informally reported to rest 1-3 minutes every hour, we supposed that these breaks did not affect running mechanics. Furthermore, we are aware that the method we used to calculate the spring-mass parameters[21] is dependent upon ground contact times. Nevertheless, previous studies considered this model for measuring the changes in running mechanics during both short[35] and long performance[1,2,7,10]. In addition, the changes in running speed (coefficient of variation 3.7±2.6%) observed in this study were not great enough to affect the computation of the F_{max} and k_{vert}. Indeed, in agreement with a previous study[10], a decrease of -5.6±0.3% in the running speed had only a partial effect on the changes in the mechanical parameters [21,36]. Further, the range of speed accepted by Morin et al.[2] for calculation of the mechanical parameters during running was ±5% the reference speed (3.33 $m \cdot s^{-1}$). In particular, Arampatzis et al.[36] showed that k_{vert} did not change significantly for speeds ranging from 2.5 to 3.5 $m \cdot s^{-1}$, which are very similar to the range of speeds that the athletes maintained throughout the whole race (min=2.4 $m \cdot s^{-1}$; max=3.9 $m \cdot s^{-1}$).

Practical applications

Changes in mechanical parameters observed in ultra-endurance runners could be related to minimizing damage to lower limb tissue, muscular fatigue, and symptoms associated with prolonged running to the detriment in the cost of running (Cr)[37]. Cr represents a key factor in defining performance in ultra-endurance runners[14] . Lesser changes in Cr have been observed in athletes with lower changes in some mechanical parameters (foot print index, k_{vert} and SF)[14] which were related to higher values of lower limbs muscle power[14] . Then, we support our belief[14] that ultra-endurance runners should include strength and power training sessions in their preparation.

Conclusions

In conclusion, we observed that, most mechanical changes happen after four hours of continuous running indicating that a "time threshold" may exists. This suggests that the duration of the race may affect the performance regardless of absolute running speed. Future studies should focus on the reason why spring-mass model changes after this "threshold", proposing some specific training to preserve the correct running mechanics for more hours.

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Disclosures

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

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FIGURE 1 – The experimental setup

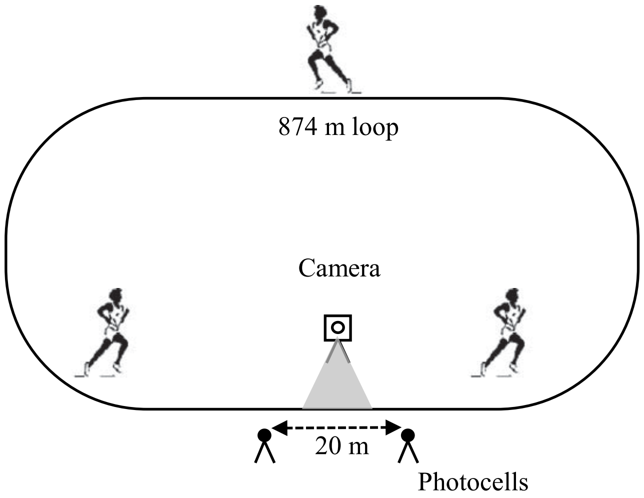
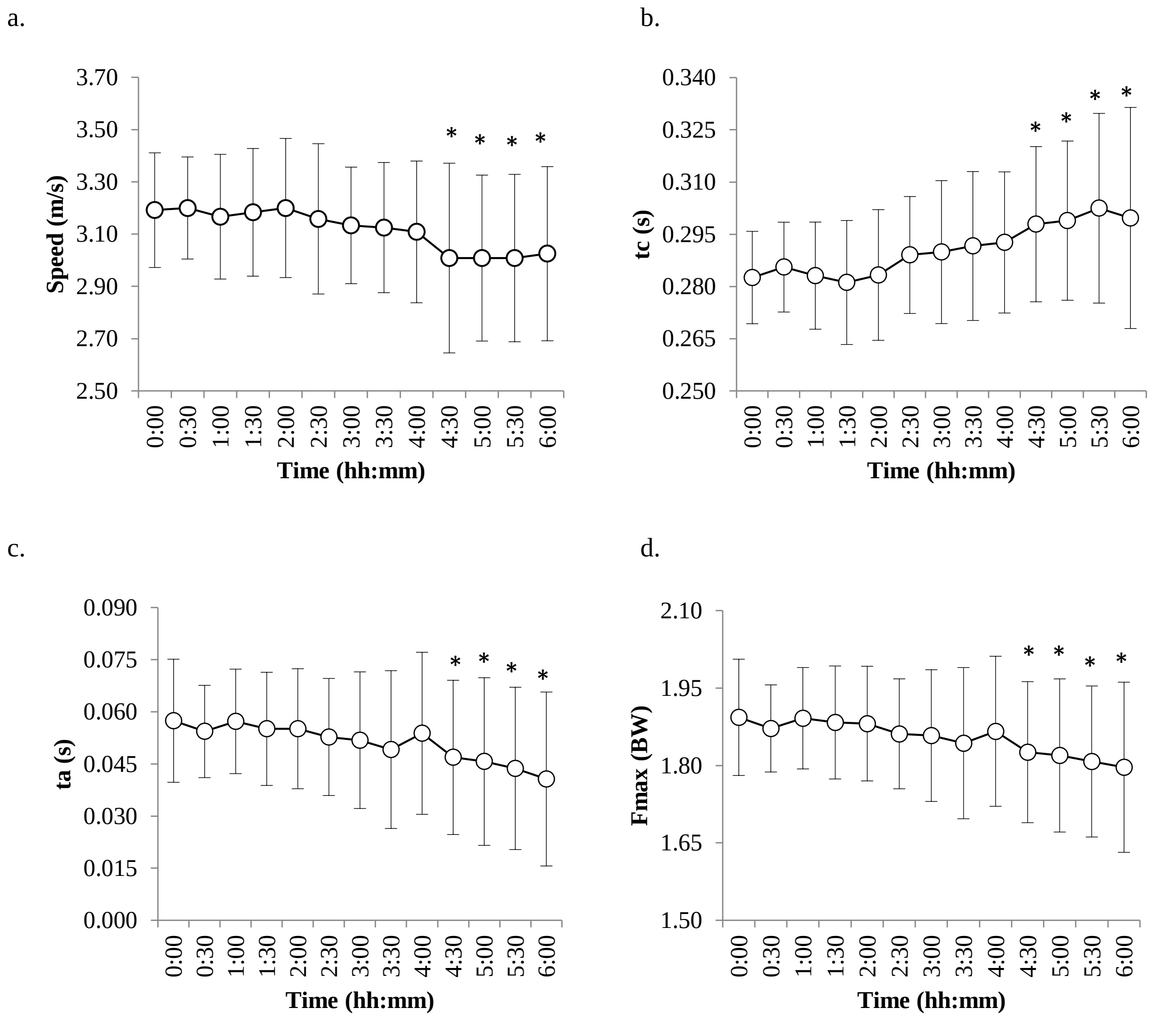


FIGURE 2 – Mechanical parameters measured every 30 minutes (a: running speed; b: contact time, t_c; c: aerial time, t_a; d: vertical ground reaction force, F_{max}; e: vertical displacement of the centre of mass, Δz; f: vertical stiffness, k_{vert}; g: step length, SL; h: step frequency, SF)

*: $p<0.05$, significantly different from the first point.



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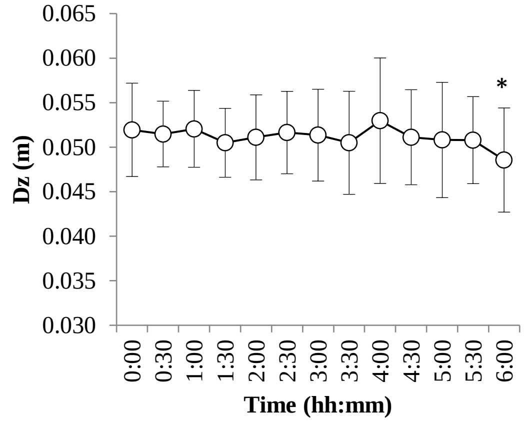

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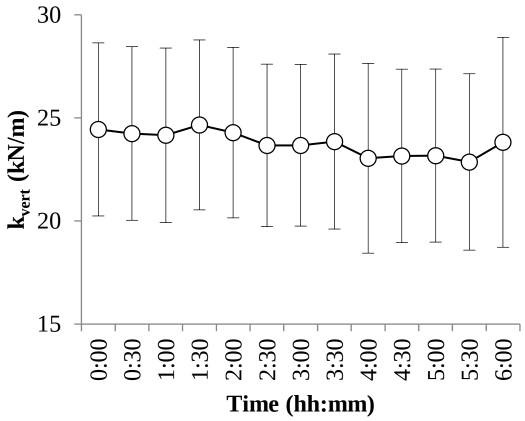

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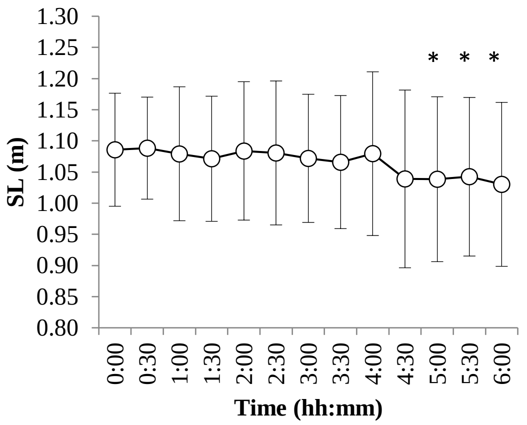

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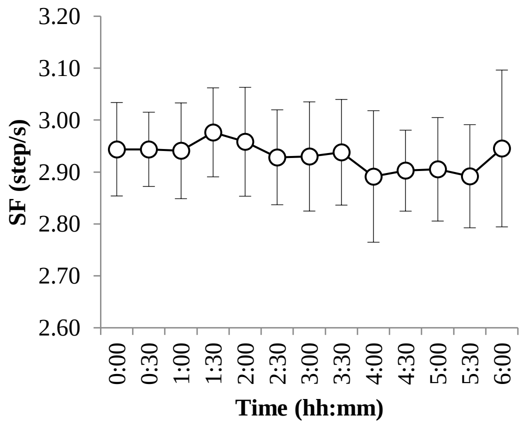

TABLE 1. Physical characteristics of participants measured before the race in the athletes who concluded the race (n: 12).

Age (years)	41.9 ± 5.8	[33.0 - 56.0]
Body mass (kg)	68.3 ± 12.6	[51.0 - 86.0]
Stature (m)	1.72 ± 0.09	[1.62 - 1.90]
Body mass index (kg·m^{-2})	22.3 ± 2.1	[19.4 - 25.6]
L (m)	0.91 ± 0.05	[0.83 - 0.99]
$\dot{V}O_2$max (mL·kg^{-1}·min^{-1})	52.7 ± 5.0	[45.0 - 60.0]
v$\dot{V}O_2$max (m·s^{-1})	4.32 ± 0.31	[3.83 - 4.92]
Race distance (km)	62.9 ± 7.9	[47.4 - 79.5]
Average running speed (m·s^{-1})	2.91 ± 0.37	[2.2 - 3.7]

All values are mean ± standard deviation (SD). Range in square brackets.

$\dot{V}O_2$max: maximal oxygen uptake; v$\dot{V}O_2$max: velocity at $\dot{V}O_2$max