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Changes in spatio-temporal gait parameters and vertical speed during an extreme mountain ultra-marathon

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Original Investigation

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Abstract

The aim of the present study was to investigate the effects of altitude and distance on uphill vertical speed (VS) and the main spatio-temporal gait parameters during an extreme mountain ultra-marathon. The VS, stride height (SH) and stride frequency (SF) of 27 runners were measured with an inertial sensor at the shank for two different altitude ranges (low 1300-2000 m vs high 2400-3200 m) of 10 mountains passes distributed over a 220 km course. There was a significant interaction ($F(4,52) = 4.04$, $p < 0.01$) for the effect of altitude and distance on VS. During the first passes, the mean VS was faster at lower altitudes, but this difference disappeared at a quarter of the race length, suggesting that neuromuscular fatigue influenced the uphill velocity to a larger extent than the oxygen delivery. The average VS, SH and SF were 547±135 m/h, 0.23±0.05 m and 0.66±0.09 Hz. The individual VS change for each uphill portions was more strongly correlated with the changes in SH ($r = 0.80$, $P < 0.001$, $n = 321$) than SF ($r = 0.43$, $P < 0.001$, $n = 321$). This suggests a large effect of the knee extensors strength loss on the diminution of VS.

Keywords: ultra-endurance, fatigue, altitude, uphill walking

Introduction

Mountain ultra-marathons (MUMs) have gained popularity in recent years.[1] These events are of interest to better understand how healthy subjects cope - from both physiological and biomechanical points of view - with extreme loads and fatigue.[2]

Similarly to running events of shorter duration, maximal oxygen uptake (VO_{2max}) and the fraction of its utilization are important determinants of ultra-marathon performance.[3] However, the measurement of the energy demand over the complete course of a MUM is difficult if not impossible and the results of laboratory studies can hardly be extrapolated to a mountainous environment.[4] Altitude, exercise duration, elevation changes and temperatures are making the determination of the energy cost of locomotion particularly difficult in the case of a MUM.[5] At the moderate altitudes (2000 to 3000m a.s.l) often encountered during a MUM, VO_{2max} is reduced by 7-8% per 1000 meters above sea level.[6] Additionally, exposure to moderate hypoxia exacerbates the development of peripheral fatigue.[7,8] Therefore, the negative effect of altitude on uphill performance should be greater the further an athlete gets on the race course during a MUM.

MUMs provide opportunities to assess the effects of prolonged uphill and downhill walking/running periods over extremely long distances on biomechanical parameters.[9,10] Previous studies have measured running mechanics either at set points during a race[9,11] or after the completion of the event.[10,12-14] Beside a case study,[4] there is a paucity of data collected during real racing conditions, thereby limiting our understanding of the changes in running mechanics during MUMs. Recording the gait parameters with an inertial sensor in the context of going up a mountain pass would broaden our knowledge in this area.

An increased stride frequency (SF) – or reduced stride length (SL) – at a constant speed is known to diminish the impact shock and the energy absorbed at the ankle, knee and hip.[15] Despite some debate regarding the importance of the cost of running in MUM performance,[5] preferred SF and optimal SF remained the same following a 6-hour trail run suggesting that, despite fatigue, athletes optimize their running gait to preserve energetic efficiency.[16] Furthermore, the muscle preservation strategies used during a MUM of extreme duration did not lead to a modification of SL or SF from pre to post race when tested at the same speed.[12] However, the speed loss expected during the climbs of a MUM[17] must be related to a reduction of the SF and/or SL. As the speed of locomotion is expressed vertically in this study, the amplitude of the strides will be referred to as stride height (SH) rather than SL. Considering that knee extensors (KE) force loss during a MUM was shown to be correlated with performance time[18] and that SF was not affected by an improvement in maximal strength,[19] loss of strength over the course of MUM should primarily affect SH. Consequently, one may hypothesize that the expected decrease in vertical speed (VS) throughout the race is mostly correlated with a decrease in the SH rather than a reduction of the SF.

To our knowledge, the combined effects of altitude and distance on uphill running/walking performance and biomechanics have never been studied to date. Therefore, the evolution of VS and other spatio-temporal gait variables during the climbs of a MUM remains unclear and would provide novel insights into the respective influence of 1) physiological factors, i.e. the convective oxygen transport altered by altitude, compared to 2) neuromuscular factors, i.e. KE muscle fatigue induced by prolonged exercise, on the performance and pacing during MUMs. The primary aim was to use an inertial sensor to investigate the effect of altitude and fatigue on VS during a MUM of extreme duration. The secondary aim was to assess the relationship between VS and SH and SF. We hypothesized that VS would be lower at higher altitude and that the decrease in VS would be greater for the highest portion of each mountain pass.

Methods

Participants

Twenty-seven athletes (3 women and 24 men) volunteered to participate in this study. Their characteristics are presented in table 1. All subjects were experienced MUM athletes, 15 of them had finished a previous edition of the race studied. The participants were informed of the procedure and the risks involved. They gave their consent and could refuse to take part in any of the tests. The study was approved by the Institutional Ethics Committee of the University of Verona, Italy (Department of Neurosciences, Biomedicine and Movement Sciences) and carried according to the Declaration of Helsinki.

Design

The international race supporting the study was the 2015 Tor des Géants® (TdG). Considered as one of the world's most challenging mountain ultra-marathon,[20] it covers a total of 330 km and includes 24 000 meters of elevation gain and loss. The maximum and minimum altitudes are 3300 m and 322 m, respectively, with 25 passes over 2000 m. The distance is divided by six major aid stations where sleeping is allowed. Ten mountain passes were divided in sections of 147 to 368 meters of elevation gain and categorized as in high altitude (2392 to 3204 m a.s.l.) and low altitude (640 to 2086 m a.s.l.) portions (Table 2). Each section was selected to avoid flat portions or aid stations and did not start immediately after an aid station. The race was stopped a few hours after the 80-hour mark due to bad weather conditions – athletes normally have 150 hours to cover the distance. Therefore, only the measurements up to the ascent of Col Pinter, which correspond to pass number 10 (figure 1), were used and only the first 5 passes with both a low and a high altitude section were used for the comparison of the VS between low and high altitudes.

Methodology

Movement was recorded using Physilog® 4 Silver device (Gait up SA, Lausanne, Switzerland). The 19 g device was attached to each participant's shank close to the ankle, encapsulated in a waterproof elastic band and securely placed over the lateral malleoli. The device was recording tri-axial acceleration at 100 Hz, tri-axial angular velocity at 100 Hz and the barometric pressure at 50 Hz. First, altitude was estimated using the barometric pressure signals as in the ICAO Standard Atmosphere model and then linearly corrected using the 10 passes as altitude landmarks. A calibration process was designed to align the technical frame of the sensors with the functional frame of the shank.[21] Knowing the time ($Time_k$) spent in each section k of the pass and the elevation difference between the lowest ($Altitude_{low}^{k}$) and highest limits ($Altitude_{high}^{k}$) of the section, average vertical velocity of each portion was estimated by Eq.1:

$$\frac{Altitude_{high}^{k} - Altitude_{low}^{k}}{Time_k} \qquad (1)$$

For each section stride frequency (SF_k) was estimated using a 4 seconds sliding-window and was set as the fundamental frequency component of the medio-lateral angular velocity of the shank obtained by Fast Fourier Transform (FFT).[22] We then used this fundamental frequency f0 to set the cut-off frequency (fc = 1.5 f0) of the low-pass Butterworth filter applied on the sagittal plane angular velocity signal. We used this highly filtered signal (almost a sinusoid) to find the local peaks which we assumed correspond to the mid-swing moment. Finally, we detected initial contact within each midswing-to-midswing period and use the detection results to compute the stride frequency. [23] There was no need to apply a high-pass filter. The determination of stride frequency using step by step detection is more accurate than using FFT that gives only a rough estimation. Stride height SH_k within each pass section was defined as Eq.2:

$$SH_k = \frac{Altitude_{high}^{k} - Altitude_{low}^{k}}{N_{strides}^{k}} \qquad (2)$$

Where $N_{strides}^{k}$ is the number of strides detected in the kth section.

Statistical Analysis

The statistical analysis was performed using the R software (R foundation for Statistical Computing, Vienna, Austria) using a significance level of 0.05. A Two-way repeated measures analysis of variances (ANOVA) was used to determine the effect of altitude (low vs. high section of mountain passes) and distance covered (number of mountain pass during the race) on VS. Sphericity was tested using Mauchly's test and Greenhouse-Geisser correction was applied when sphericity was violated. Normality was confirmed with the Shapiro-Wilks test. Post hoc comparisons were made using Tukey honestly significant difference. Pearson's correlations were calculated to evaluate the association between VS, SH and SF.

Results

Of the 27 athletes participating in this study, 4 withdrew from the race before it was stopped. None of the 23 remaining athletes completed the whole 330 km. Only 6 athletes who were not involved in the study reached the finish line before the race was stopped.

For the five first passes with both a low-altitude (1300-2000 m) and a high-altitude (2400-3200 m) portions, there was a significant interaction [F (4,52) = 4.04, $p < 0.01$]. Figure 2 shows the Tukey HSD post hoc comparison for the low and high-altitude sections of each mountain pass analyzed.

The average VS, SH and SF were 547±135 m/h, 0.23±0.05 m and 0.66±0.09 Hz. As shown in figure 2, VS was more strongly correlated with SH than SF .

Discussion

The purpose of this study was to investigate the effects of altitude and distance on VS during an extreme mountain ultra-marathon (the Tor des Geants®). The main findings were: 1) VS was progressively diminished with race progression and this decrease in speed was greater at low than at high altitude; 2) the reduction in VS throughout the race is mainly related to a reduction in stride height (SH).

The VS was lower at higher altitude for the first and third pass, but the deceleration was greater at low altitude, which is contrary to the initial hypothesis. After the third mountain pass, there was no more difference in VS between the two altitude portions studied. A case study about an experienced athlete showed no metabolic fatigue during the major climbs of the TdG.[4] The large decrease of speed in the second half of TdG has previously been associated with sleep deprivation and fatigue.[17] Maximal aerobic speed was shown to be more strongly related to performance in a MUM than KE force or KE force loss.[18] These results were obtained during a shorter race (75 km with 3930 m of elevation gain). They do not contradict our findings, as the reduced VS at higher altitudes in the first quarter of TdG indicates that the effect of aerobic capacity on performance is only reduced beyond 75 km. Also, it is worth pointing out that there were no effects of the slope on VS ($p = 0.279$).
One may argue that central or neuromuscular fatigue may be different between the low-altitude (at the beginning of the pass) and the high-altitude (at the upper part of the pass) sections. In such an ecological set-up, it was impossible to measure fatigue at the bottom and at the summit of each pass. This can be seen as a confounding factor since the differences between low and high altitudes may be due to other factors than the altitude-induced changes in aerobic capacity.

As expected, the reduction in VS was more strongly correlated with the reduction of SH than the reduction of SF. Changes in running biomechanics during the TdG have been associated with nociceptive feedback and the use of a smoother running pattern, which involved an increase in SF.[9] In that case, the measurements were made on a treadmill at 12 km/h before and after the race. With the speed being constant, the increased in SF was accompanied by a reduction in stride length. However, the etiology of neuromuscular fatigue differs between level and graded running where the decrease in maximal voluntary force observed for uphill running is associated with metabolic fatigue whereas it is associated with mechanical damages for downhill running.[24] A reduction in the strength of the KE and the plantar flexors (PF) have previously been reported for the TdG and could explain the reduction in SH observed in the present study.[11] We have previously shown a large fatigue in plantar flexors during hilly running.[25] Strength loss is similar in PF and in KE during MUM[17] while during level ultra-running, a greater stress occurs on PF compared with KE (24-h running exercise on a treadmill).[26] Despite that there are no data available on hip flexors/extensors during or after MUM, it is likely that a strength loss of the hip flexors or extensors could also be involved. Moreover, the present results are in line with the previously reported decrease in uphill energy cost following the TdG that was associated with a modification of the uphill running mechanics presumably caused by a decrease in KE strength.[12] Considering that the preferred SF seems to be adjusted to be metabolically optimal despite the fatigue encountered during a prolonged trail running exercise,[16] the reduction in SF observed may not be detrimental to the energy cost of movement. Taken together, our results indicate that the speed loss observed is likely related to a loss of KE strength, however, a voluntary reduction of intensity could also explain the reduction in VS observed.

A positive pacing strategy, where the speed progressively decreases, is the most common during ultra-endurance events[27] and is the one adopted, consciously or not, by every athletes of this study. Participants with a higher performance level generally show greater speed loss during ultra-marathon events.[28-30] The observed reduction in speed could have been partly related to the athletes' perceived exertion[31] which – based on the psychobiological model of endurance performance - plays a crucial role in the self-regulation of pacing.[32] Future studies regarding MUM should consider the role of motivation and rate of perceived effort in the regulation of pace and their effects on performance. Because of the cancellation of the event before its completion, it was not possible to determine if the athletes would increase their speed in the last part of the race and whether or not this increase in speed would be influenced by the altitude.

Practical Applications

Considering the main finding of the present study, we do confirm that acclimatization to altitude is paramount for MUM since there was a lower VS at higher altitudes in the first quarter of TdG. However, the effect of fatigue is progressively becoming more important than the oxygen delivery for explaining the deceleration throughout this extreme MUM.

Regarding the biomechanical changes, the fact that the change in SH is highly correlated to the decrease in VS suggests that strengthening exercises targeting the KE could help reduce the speed loss observed during a MUM.

Conclusions

During the TdG, pacing was different between low and high altitudes only in the first quarter of the race suggesting that exertion influenced the uphill velocity to a larger extent than the oxygen delivery. The reduction in VS was more strongly correlated to the decrease in SH than SF and implies an effect of the KE strength loss.

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Figures and Tables

Figure 1. Average vertical speed for the low (1298 to 2086 m) and high (2392 to 3204 m) portions of the first 5 mountain passes with both a low and high altitude portions (A). *P < 0.05 for differences with high altitude. #P < 0.05 for differences with previous pass. Values are mean ± SD. Mountain passes used for the measurement of vertical speed, stride height and stride frequency (B).

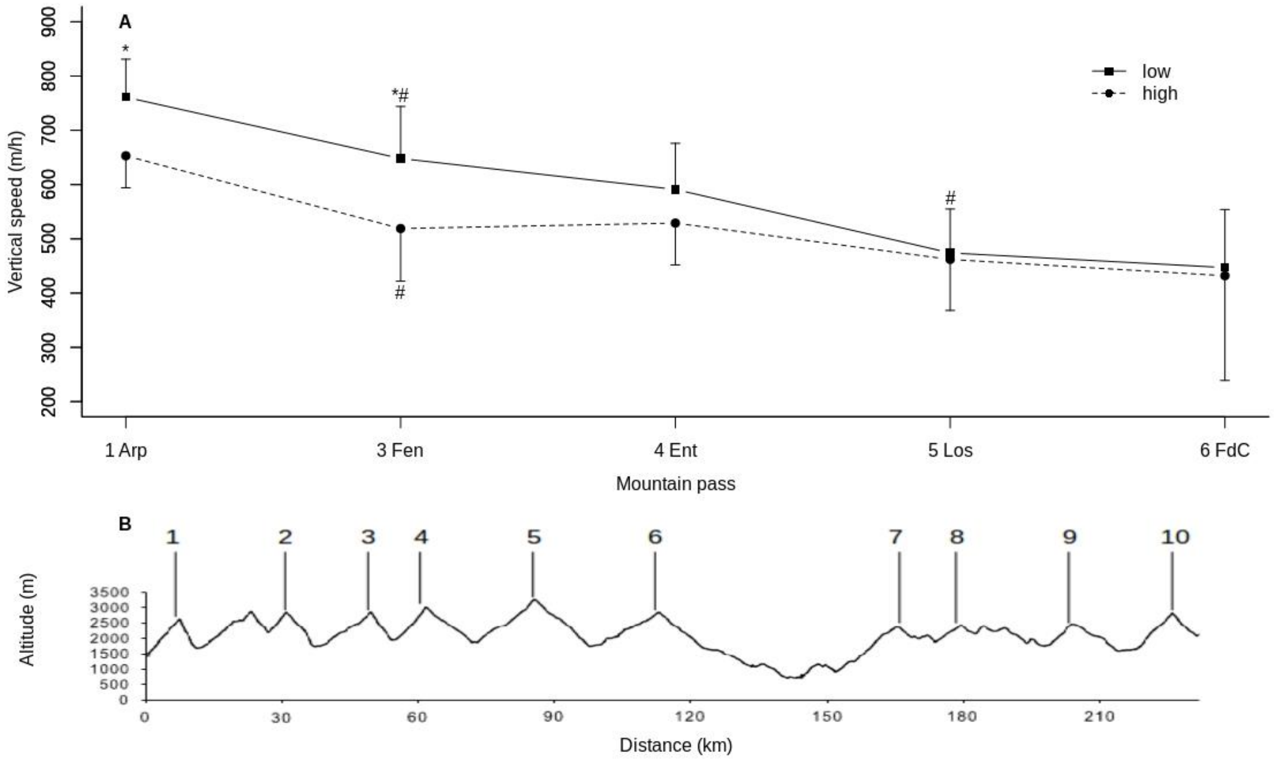
Figure 2. Correlation between vertical speed and stride height (A) or stride frequency (B) for the selected uphill portions of the mountain passes.

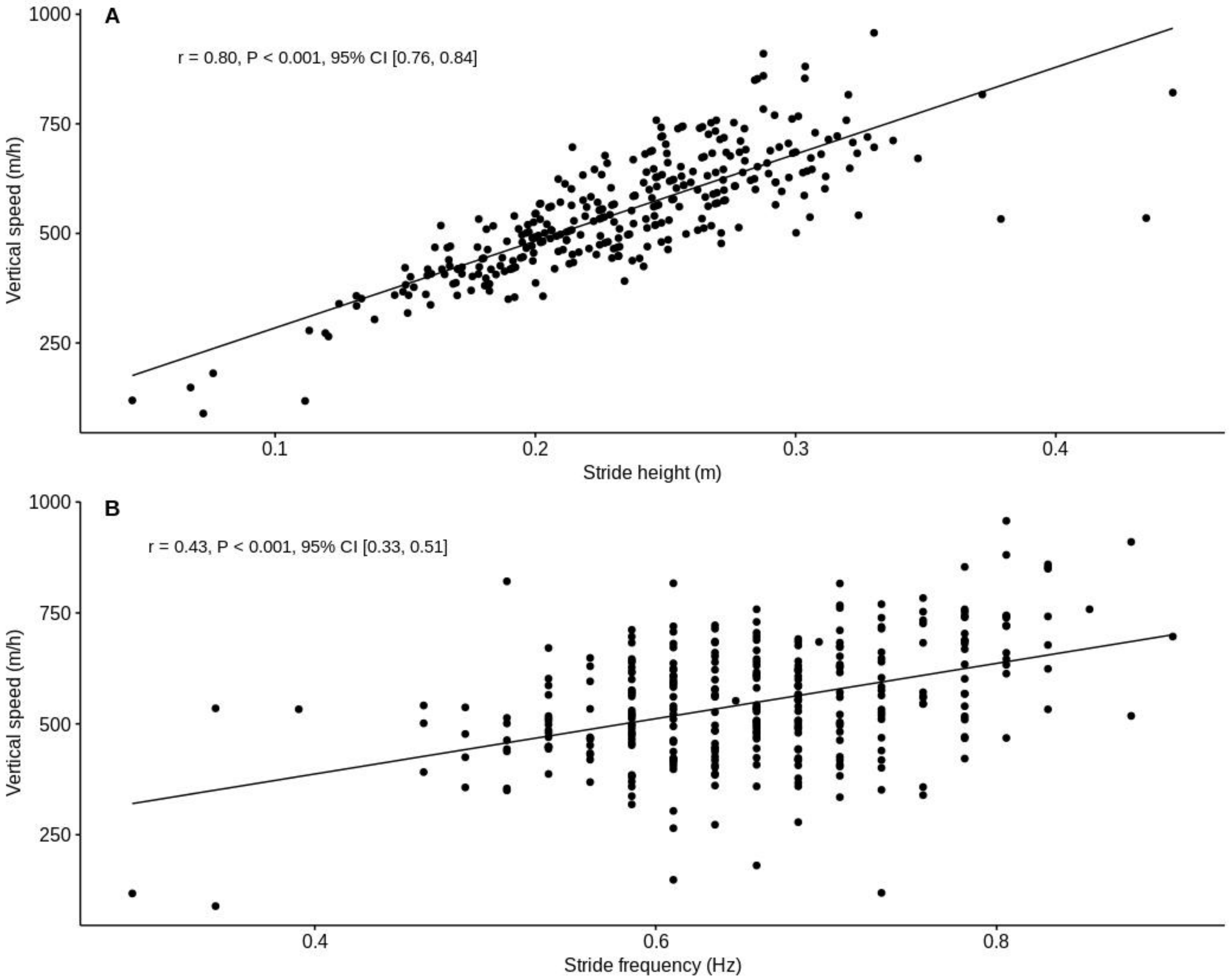
Table 1 Age, height, weight, body mass index and the International Trail Running Association performance index of the participants.

n =27	**Age (y)**	**Height (cm)**	**Weight (kg)**	**BMI (kg m^{-2})**	**Performance index**
Mean	45.3	176.7	72.8	23.3	549
SD	9.5	8.0	9.0	2.4	76.6
Range	22-64	158-193	59.8-93	19.7-28.7	412-743

Table 2. Characteristics of the portions of the mountain passes used for the analysis of vertical speed, stride height and stride frequency.

	Low				**High**			
	Altitude (m)			**Slope (%)**	**Altitude (m)**			**Slope (%)**
	Start	**End**	**Gain**		**Start**	**End**	**Gain**	
1. Arp	1298	1639	341	23.7	2392	2539	147	20.1
2. Crosatie	-	-	-	-	2506	2828	322	29.8
3. Fenêtre	1681	2032	351	21.7	2576	2815	239	19.1
4. Entrelor	1756	2086	330	23.2	2529	2822	293	32.2
5. Loson	1757	2010	253	13.8	2948	3204	256	23.3
6. F. di Champorcher	1614	1818	204	22.4	2508	2813	305	15.4
7. Coda	640	818	178	16.3	-	-	-	-
8. Marmontana	1683	1936	253	16.4	-	-	-	-
9. Lasoney	1707	2031	324	24.9	-	-	-	-
10. Pinter	1422	1790	368	33.5	2573	2765	192	29.1


A
Vertical speed (m/h)
900
800
700
600
500
400
300
200
*
*#
#
#
low
high
1 Arp
3 Fen
4 Ent
5 Los
6 FdC
Mountain pass
B
1
2
3
4
5
6
7
8
9
10
Altitude (m)
3500
3000
2500
2000
1500
1000
500
0
0
30
60
90
120
150
180
210
Distance (km)


A
r = 0.80, P < 0.001, 95% CI [0.76, 0.84]
Vertical speed (m/h)
1000
750
500
250
0.1
0.2
0.3
0.4
Stride height (m)
B
r = 0.43, P < 0.001, 95% CI [0.33, 0.51]
Vertical speed (m/h)
1000
750
500
250
0.4
0.6
0.8
Stride frequency (Hz)