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Pacing during an ultramarathon running event in hilly terrain

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ABSTRACT

Purpose. The dynamics of speed selection as a function of distance, or pacing, are used in recreational, competitive, and scientific research situations as an indirect measure of the psycho-physiological status of an individual. The purpose of this study was to determine pacing on level, uphill and downhill sections of participants in a long ($>$ 80 km) ultramarathon performed on trails and in hilly terrain.
Methods. Fifteen ultramarathon runners competed in a $\approx$173 km event (five finished at $\approx$103 km) carrying a Global-Positioning System (GPS) device. Using the GPS data, we determined the speed, relative to average total speed, in level (LEV), uphill (UH) and downhill (DH) gradient categories as a function of total distance, as well as the correlation between overall performance and speed variability, speed loss, and total time stopped.
Results. There were no significant differences in normality, variances or means in the relative speed in 173-km and 103-km participants. Relative speed decreased in LEV, UH and DH. The main component of speed loss occurred between 5% and 50% of the event distance in LEV, and between 5% and 95% in UH and DH. There were no significant correlations between overall performance and speed loss, the variability of speed, or total time stopped.
Conclusions. Positive pacing was observed at all gradients, with the main component of speed loss occurring earlier (mixed pacing) in LEV compared to UH and DH. A speed reserve (increased speed in the last section) was observed in LEV and UH. The decrease in speed and variability of speed were more important in LEV and DH than in UH. The absence of a significant correlation between overall performance and descriptors of pacing is novel and indicates that pacing in ultramarathons in trails and hilly terrain differs to other types of running events.

Keywords: Running, Performance, Global Positioning System, Elevation Gain and Loss, Digital Elevation Model

INTRODUCTION

Paragraph 1. The dynamics of speed during self-paced locomotor exercise, or pacing, are used in recreational, competitive and scientific settings as an indicator of the use of energetic resources and relative metabolic load (Abbiss and Laursen, 2008). Three general types of pacing (negative, even, positive) are commonly identified in the analysis of running performance, using the direction of the changes in time per km or speed, as a function of distance or exercise duration. Even pacing has often been suggested to optimise the rate and type of energy transfer and improve exercise performance (Foster et al., 1993; Firth, 1998), but has not been observed in self-paced and racing situations. Negative pacing (increasing speed) has been observed in high-level championship races in middle (800-3,000 m) to long distances ($>$ 5,000 m) up to the marathon distance (42.2 km) where racing strategies often include the conservation of metabolic reserves in preparation for the later stages of the race (Tucker et al., 2004). Positive pacing (decreasing speed) is the main type of pacing used in long distance events across all levels of performance (Abbiss and Laursen, 2008). A subset of these three main types of pacing is referred to as mixed pacing, in which at least two main types of pacing are combined.

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Paragraph 2. Events longer than the marathon (ultramarathons, UM) performed on trails are increasingly popular, including for scientific research, where they permit the study of the regulation of physiological, biomechanical, psychological adaptations as a function of the development of fatigue (Millet, 2011; Millet and Millet, 2012). Positive pacing was observed in UM events, such as during a short (45 km) trail UM in recreational runners (Angus and Waterhouse, 2011), a 100 km event on a level, multi-loop course in elite runners (Lambert et al., 2004), a 105 km mountain trail UM in competitive runners (Kerhervé et al., 2015), and a 161 km mountain trail UM in the five fastest runners over a 28 year period (Hofmann, 2014). Positive pacing has also been observed in other forms of ultra-endurance exercise, such as treadmill simulations of UM (Davies and Thompson, 1979, 1986; Millet et al., 2011), or during an ultra-endurance triathlon event consisting of ten consecutive Ironman distance triathlons (10 x 3.8 km swimming, 180 km cycling, 42 km running) in 10 days (Herbst et al., 2011). Pacing is also characterised by the magnitude of speed loss and the variability of speed (using the coefficient of variation of speed), which were found to be lower in faster compared to slower participants during UM running events (Angus and Waterhouse, 2011; Lambert et al., 2004; Hofmann, 2014), in agreement with what has been observed in events up to the marathon distance (Ely et al., 2008; Haney and Mercer, 2011).

Paragraph 3. In contrast to these findings, we measured a higher magnitude of speed loss in faster compared to slower runners, no significant relationship between the variability of speed and performance level, and a novel significant negative relationship between the total time stopped and performance level, in a long mountain UM (Kerhervé et al., 2015). Additionally, speed on level, uphill and downhill sections increased in the last 10% of the event. These results indicate that pacing may have been regulated conservatively in anticipation of topographic difficulties, and that faster runners paced less conservatively than slower runners.

Paragraph 4. The determination of pacing is dependent on the measure of time or speed, which can be relatively inexpensive using chronometry over a known distance, and highly accurate using automated systems (timing gates, radar technology, high speed chronophotography). However, these measures are not applicable for monitoring individuals in conditions of trail UM events, which can be performed on uneven surfaces in remote areas and hilly terrain for durations of multiple hours. Applications relying on the measurement of spatio-temporal behaviour of single devices outside of controlled conditions, including during UM running, commonly use a service for geo-location by satellite such as the Global Positioning System (GPS). Therefore, the aim of this study was to record the individual geographical positions (latitude, longitude, elevation) of participants in a long trail UM in hilly terrain, in order i) to measure the dynamics of speed selection as a function of terrain (level, uphill and downhill sections), and ii) to further investigate the relationship between performance and pacing characteristics (speed loss, speed variability, total time stopped). Based on the literature specific to pacing during UM and ultra-endurance exercise, speed was expected to decrease in all participants and at all gradients as a function of the distance and duration of the event.

METHODS

Paragraph 5. This study was approved by the university research ethics committee (Queensland University of Technology, project 0900001233). The study participants were recruited using advertisements on a specialised forum and researchers networks, from individuals already registered to compete in a long (≈173 km) and hilly UM running event including 6 checkpoints and a total elevation gain and loss of approximately 3,000 m. This event offered the opportunity to receive an official classification and time for participants failing to complete the entire event if they reached the 4^{th} checkpoint at ≈103 km, which we included in the study. Both distances are presented in this article as 173-km and 103-km. After providing written informed consent, 19 participants were equipped with a commercially-available GPS device (BT-Q1000, Qstarz International, Taiwan) fitted to their clothing or pack.

Paragraph 6. The GPS devices used in this study were selected for their light weight (≈100 g including the battery) and long battery life (tested to record for more than 40 continuous hours at a sampling rate of 0.2 Hz). The accuracy of measures of geographical position and speed were tested following published procedures (Townshend et al., 2008). Positional accuracy was found to be within the range provided by the manufacturer (100% of measures within 3 m of a known geodetic survey landmark, 84.5% of observations measured within 2 m, and had a mean distance of 1.57 ± 0.43 m). The calculated velocity (see following section) was found to be in excellent agreement (95% limits of agreement = 0.24±0.12, typical error expressed as a of CV = 1.2, standardised error of the estimate = $0.03\,\mathrm{km\,h^{-1}}$) and perfectly correlated to speed determined using chronometry over a known distance (100 m) over 50 trials (r = 1.00; $p < 0.001$).

Distance and Speed

Paragraph 7. The point-to-point distances were obtained from an internet-based utility (GPS Visualizer; www.gpsvisualizer.com) using geographical positions (latitude and longitude). We found the distances obtained were in exact agreement (r = 1.00, $p < 0.001$) with our preliminary measures of point-to-point distances using the Vincenty formulae (Vincenty, 1975) performed on 10 data sets. Therefore, we used the internet-based calculations of the formulae as a simple and generalisable procedure to obtain point-to-point distances.

Paragraph 8. Point-to-point speed was subsequently calculated using the ratio of point-to-point distances and time (one data point every 5 s) between each datum. Preliminary calculations revealed that GPS devices did not discriminate for speeds slower than $1\,\mathrm{km\,h^{-1}}$ ($0.28\,\mathrm{m\,s^{-1}}$ or 1.39 m in 5 s) based on the typical error in speed in a static position (drift, when a device will record speed values due to the non geo-synchronous nature of the constellation of satellites). At the other end of the speed spectrum, it was considered that speeds higher than $20\,\mathrm{km\,h^{-1}}$ ($5.56\,\mathrm{m\,s^{-1}}$ or 27.8 m in 5 s) were not expected during a long UM and originated in signal jamming (which can occur due to the signal from a satellite being too weak which forces the ground based receiver to pair to another satellite). These erroneous distance and speed data were assigned a value of zero, and all speed values were then smoothed in order to further increase the signal-to-noise ratio. For smoothing, a 9-pt weighted average was graphically compared with 3-pt and 15-pt weighted averages and considered satisfactory as it provided a balanced sensitivity to individual observations for slow and high speeds. This procedure permitted the decrease of the effect of signal drift and jamming (higher distance and speed due to erroneous values). This procedure was sensitive to periods of zero speed values, which corresponded to the location, via expected relative distances, of checkpoints in the race.

Elevation changes

Paragraph 9. GPS-based elevation is considered to be inaccurate (Townshend et al., 2008) due to differences between the model of reference of the earth used for calculations and the actual shape of the earth, and therefore an independent source was used to increase the quality of the elevation data. Due to the size of a typical file containing UM data at the relatively high recording rates of GPS devices (24 h of data recording at 5 s equals 17280 observations), a digital elevation model (DEM) was used in order to automate the treatment procedure. The online utility (GPS Visualizer; gpsvisualizer.com) was used to match the recorded geographical positions (determined by latitude and longitude) to a DEM elevation datum from the National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission (SRTM) database. As the resolution of DEM is relatively low for the study of human locomotion (90 m, only the SRTM3 was available where the current study was conducted), the procedure can create a series of steps when increasing or decreasing elevation every time a contour line is crossed. Likewise, it can also mean that actual changes in elevation are not detected when data points were recorded inside the same contour line. In the absence of an existing method to reconstruct accurate elevation data, we applied the same 9-point weighted average smoothing procedure we used in the speed data to calculate more realistic elevation data. Gradient was then calculated as the change in elevation divided by the horizontal distance between two points.

Variables and statistical analyses

Paragraph 10. The identification of relevant data was performed for each participant using official race results, GPS time-stamps and variations of speed (increase or decrease) indicating changes in position at the start and finish lines. Speed and gradient values were computed as a function of relative distance for each participant, where total individual distance represents 100% of the distance completed for the 173-km, and 60% for the 103-km event participants. Relative distance was used instead of the actual distance values because of the difference in total distances across participants. The dynamics of speed were determined relative to each participant's average speed over the entire event (100%) in order to increase the relevance of inter-individual comparisons. The mean relative speed values corresponding to

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level (LEV; -2.5 to 2.5% gradient), uphill (UH; 2.5 to 100% gradient), and downhill (DH; -100 to -2.5% gradient) were computed in sections of 5% of the total distance completed, which ensured a sufficient amount of data points in each section in the three gradient categories. The minimal amount of data points within one section occurred at 25% of total distance in the level gradient category (64 observations for one participant, which corresponded to 2.76 km for the participant), for an average number of observations in each gradient category of 360 ± 98 (LEV), 439 ± 60 (UH) and 386 ± 67 (DH).

Paragraph 11. We initially assessed the normality (Kolmogorov-Smirnov test) and homogeneity of variances (Fisher's F test) of the 173-km and 103-km participants for LEV, UH, DH and overall relative speeds. We then used independent t-tests to evaluate whether differences in relative speed existed between the 173-km and 103-km participants in the same categories. Due to varying lengths of data sets (173-km and 103-km distances), we investigated the dynamics of pacing within each gradient category using a one-way ANOVA on ranks (Kruskal-Wallis test) and a pairwise multiple comparison (Dunn's method) when required, to determine and locate potentially significant differences between sections of relative distance.

Paragraph 12. The relationship between the level of performance (individual average speed) and the variability of speed (coefficient of variation of speed), the magnitude of speed loss (slope of the linear regression of speed over the entire event) and the total time stopped (assumed to correspond to resting, eating, clothing and gear change, toilet, other), were assessed using correlations. Assumptions of normality were first tested using a Shapiro-Wilk test, and Pearson's product-moment correlation was used to calculate each relationship.

Paragraph 13. All statistical analyses were performed using the computing program and its associated packages R (R Core Team, 2015). The level of significance was set at $p < 0.05$.

RESULTS

Paragraph 14. The datasets from four participants were not included in the analysis, due to either not completing the event, or discrepancies between official results and GPS data (difference in finish time greater than 5%). A total of 15 GPS datasets were used for analysis (see Figure 1): ten participants completed the 173-km distance averaging 32.9 ± 3.6 h (26.5–36.3 h), with a mean total distance of 173.0 ± 4.0 km (5.68 ± 1.51 $\mathrm{km\,h^{-1}}$), and five participants completed the 103-km distance averaging 18.9 ± 2.3 h (15.6–21.1 h) with a mean total distance of 101.9 ± 2.3 km (5.91 ± 1.48 $\mathrm{km\,h^{-1}}$).

Paragraph 15. The initial testing for normality and homogeneity of variances did not reveal any significant differences between 173-km and 103-km participants. There were no significant differences in means in the relative speed of the 173-km and 103-km participants for all categories of gradients (overall: F = -1.38, p = 0.17; LEV: F = -0.99, p = 0.32; UH: -1.37, p = 0.18; DH: F = -0.27, p = 0.79). Therefore, all remaining analysis include the 173-km and 103-km participants.

Paragraph 16. Positive pacing was observed in all participants and in all gradient categories, except in one participant in negative gradients. The mean decrease in speed was -4.35 ± 3.0 $\mathrm{km\,h^{-1}}$ (LEV), -2.26 ± 1.4 $\mathrm{km\,h^{-1}}$ (UH) and -4.36 ± 2.2 $\mathrm{km\,h^{-1}}$ (DH). Relative speed was the most variable in LEV (coefficient of variation: 0.32) and reached a minimum at 50% of total distance (significantly lower than all observations between 5% and 40%). The relative speed increased from 50% to 60%, 85%, 90%, and 100%, and did not significantly decrease between any observations before 50% and 100% (Figure 2.A). Relative speed was the least variable in UH (coefficient of variation: 0.22) and reached a minimum at 95% of total distance. Relative speed increased from 35%, 40%, 45% and 50% to 60%. Relative speed increased from 95% to 100%, which was not different to any other observation (Figure 2.B). Relative speed in DH reached a minimum at 95% of total distance (coefficient of variation: 0.26). The relative speed at 20% increased compared to 15%, but no other significant increase was observed. The relative speed at 60% was not significantly different to any other observation, and the relative speed at 100% was significantly lower than 5%, 10%, 15%, 20%, 30% and 35% (Figure 2.C).

Paragraph 17. There were no significant correlations observed between overall performance and variables of pacing (Table 1). The dynamics of total time stopped as a function of relative distance are presented in Figure 3.

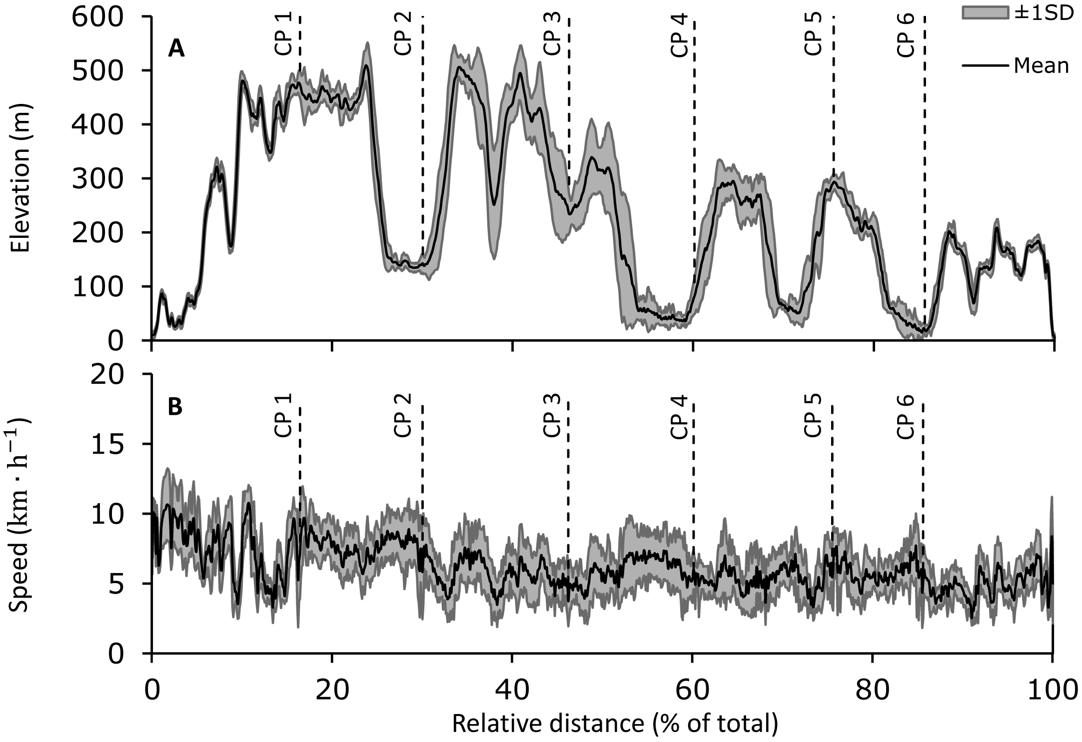

Figure 1. **Elevation and speed.** (A) Mean (± SD) group DEM data from geographical positions. (B) Mean (± SD) group calculated speed. Abbreviation: CP are official race checkpoints.

Table 1. Correlation between race performance and pacing characteristics.

	All participants	103-km	173-km
Speed variability	-0.23 (0.42)	-0.24 (0.70)	-0.25 (0.48)
Speed loss	-0.24 (0.39)	-0.43 (0.47)	0.00 (1.00)
Time stopped	-0.35 (0.21)	-0.15 (0.81)	-0.45 (0.20)

Note: Values are presented as: coefficient of correlation (p-value).

DISCUSSION

Paragraph 18. In this study, we reported the longest systematic description of pacing of runners in a long, hilly UM running event, using a method that generated no disturbances to normal running event situations.

Paragraph 19. The primary finding of this study was that positive pacing (slowing down overall) was used in all gradient categories, with three direct observations. Firstly, the variability of speed was higher in LEV, and, unlike in UH and DH, the main component of speed loss was the greatest in the first half of the event. These observations are characteristic of a subset of the three main types of pacing referred to as mixed pacing, with a positive pacing strategy during the first half of the event, and more evenly pace for the remainder of the event. Secondly, a speed reserve (increase in the last stage of an event) was measured in LEV and UH. Thirdly, the decrease in speed was greater in DH and LEV compared to UH, and the decrease in relative speed continued until the last section in DH only. Together, these findings clearly indicate that despite slowing down overall, LEV, UH and DH were paced differentially. A secondary finding of this study was that neither the characteristics of relative speed (no significant differences in normality, variances or means), nor the characteristics of pacing (no differences in speed loss, variability of speed or total time stopped) were different in the 103-km and 173-km distances. This allowed us to

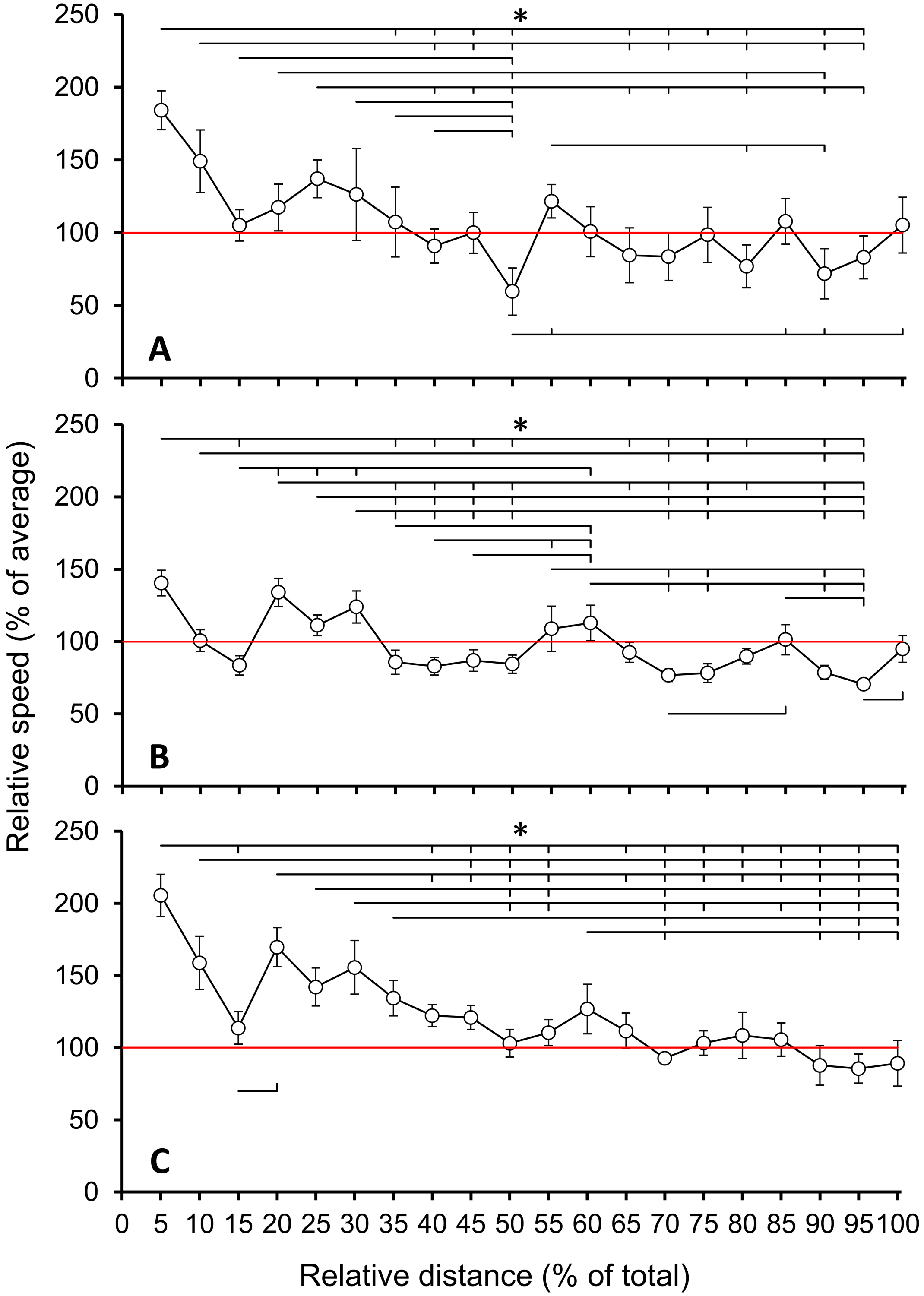

Figure 2. Dynamics of pacing. Group level (Panel A), uphill (Panel B), and downhill (Panel C) speed relative to average, respectively. Symbols * and brackets are used to denote and locate significant differences ($p < 0.05$).

compare the two groups and increase the relevance of our findings, but this finding also introduces the possibility that the additional ≈70 km did not significantly alter pacing in an ultramarathon performed in

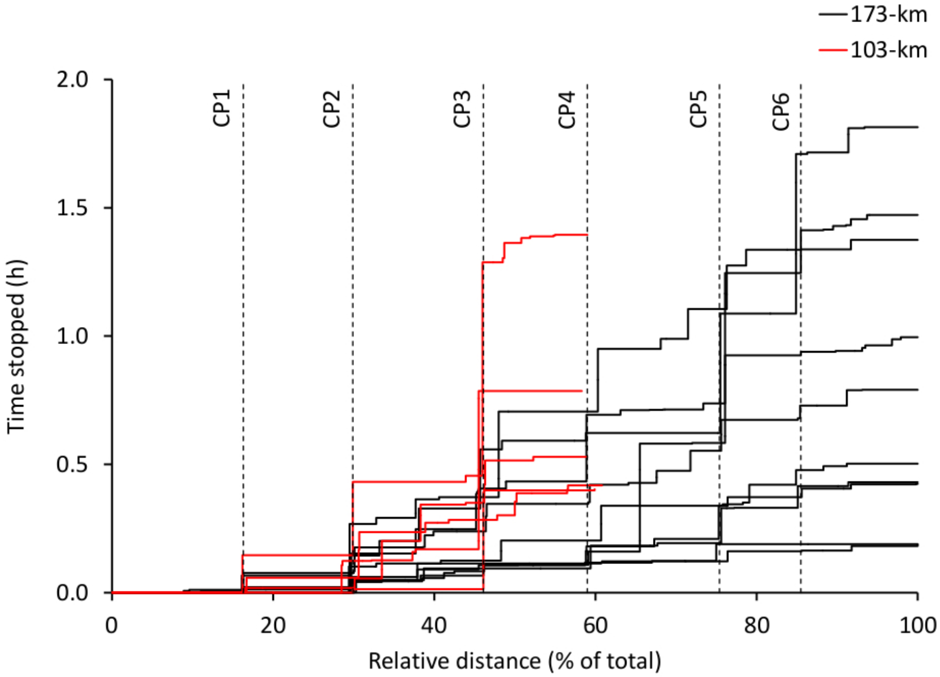

Figure 3. **Total time stopped.** Time stopped as a function of relative distance in all study participants, using the cumulated durations associated with speed <1 km/h

a hilly terrain.

Paragraph 20. A recent study from our group also reported mixed pacing during a 105 km mountain UM, characterised by a decrease of speed at all gradient categories in the later stages of the event (70-90% of total event duration), and by a final increase in speed in the last 10% of the event (Kerhervé et al., 2015). The presence of an increase in speed in the last 10% section of the event was discussed as an indicator of conservative pacing strategies in anticipation of upcoming topographic difficulties, and the use of a speed reserve (Millet, 2011) when the last topographic difficulty was passed. In the current study, both the longer distance and smaller elevation gain and loss could potentially explain the absence of a speed reserve in the level and downhill gradients. Alternatively, this finding could also potentially highlight the selective alteration of running economy (Morin et al., 2011; Vernillo et al., 2015) in gradient categories where speed is higher than during uphill locomotion.

Paragraph 21. The absence of significant correlations between overall performance and indicators of speed variability, speed loss and total time stopped are novel. While speed loss and total time stopped were found to be significantly correlated with performance in a mountain UM (Kerhervé et al., 2015), speed loss and speed variability were found to be significantly correlated with performance obtained in marathon (Ely et al., 2008; Haney and Mercer, 2011) and UM (Lambert et al., 2004; Angus and Waterhouse, 2011) running. Therefore, additional research is required to determine if those pacing characteristics are useful predictors of performance in long UM. Additionally, it has been proposed that the correlation between the level of performance and a more even pace is due to learning (Foster et al., 1993; Green et al., 2010), and that the previous practice of a specific distance produces more even pacing (Ansley et al., 2004; Green et al., 2010). However, ultra-endurance events require longer recovery periods than shorter events and hence, the opportunities to practice a specific distance are relatively less than for shorter events, which could partly explain both the relative lack of data on longer events (Abbiss and Laursen, 2008), and the lack of a significant correlation of these variables in the current study.

Paragraph 22. There were two direct limitations to this study. First, the findings related to the variations of speed within sections of relative distance used binary results (different or not), but do not provide an estimation of the magnitude of differences. A simple level of analysis is not only acceptable, but also warranted, for the type of data used in this study. Future studies are required to describe more accurately the direction and magnitude of changes. Second, the inclusion of participants from both the 103-km and 173-km distances could have implications for the results, due to any differences in pacing strategies across the two distances. For example, the five participants who had entered the 173-km event and stopped at the 103-km distance might have done so due to an inappropriate pacing strategy, or to a deliberate strategy. Irrespective, we reported the outcomes of pacing, which incorporate both inappropriate and deliberate strategies, and provided evidence that the general patterns of pacing did not differ across groups.

CONCLUSION

Paragraph 23. In conclusion, in this study we determined the dynamics and characteristics of speed of UM runners in an actual event, which provides a basis for future studies of ultra-long duration exercise. While the speed of all participants decreased as a function of distance over the entire event in all gradient categories, pacing was not comparable in those categories. Finally, overall performance was not correlated to expected predictors of overall running performance (variability of speed, speed loss), or to the total time stopped. Future studies are required to study the dynamics of speed during multiple formats of UM, to determine the effects of distance, and elevation gain and loss, on pacing. As has been done in other ultra-endurance disciplines (Herbst et al., 2011), future studies are also warranted to investigate the importance of variables related to participant experience (number of years of practice, number of starts at a certain distance) in order to further characterise pacing and performance in UM events.

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AUTHOR CONTRIBUTIONS

Conceived and designed the experiment and analyses: CS, HK. Performed the experiment: CS, T C-H. Analysed the data: HK, CS, AW. Wrote the paper: HK, CS, TC-H, AW

CONFLICT OF INTEREST

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