Pacing during an ultramarathon running event in hilly terrain

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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 (>80km) ultramarathon performed on trails in hilly terrain. **Methods.** Fifteen ultramarathon runners competed in a ~173 km event (five finished at ~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.

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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 (~173 km) ultramarathon performed on trails in hilly terrain.

Methods. Fifteen ultramarathon runners competed in a ~173 km event (five finished at ~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 exercise intensity (Abbiss & Laursen 2008), and fatigue (Knicker et al. 2011). 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. Events longer than the marathon (ultramarathon, UM) are increasingly popular in recreational and competitive settings and are increasing being used in scientific research. However, there is a relative paucity of systematic descriptions of pacing in long (> 80 km) UM, especially those performed on trails and in hilly or mountainous terrain, which could be due to the difficulties associated with the monitoring of individual participants in remote areas and over long durations.

Paragraph #2. Positive pacing (decreasing speed) and a subset of positive pacing including a final end-spurt referred to as parabolic pacing (Abbiss & Laursen 2008), were observed in UM, such as during a short (45 km) trail UM in recreational runners (Angus & 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 (Hoffmann 2014). Positive pacing has also been observed in other forms of ultra-endurance exercise, such as a 24 h treadmill run (Gimenez et al. 2013), 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 (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 & Mercer 2011).

Paragraph #3. In contrast to these findings, we measured in a previous study on trained UM runners 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

73   the last 10% of the event. These results indicate that pacing may have been regulated

74   conservatively in anticipation of topographic difficulties, and that faster runners paced less

75   conservatively than slower runners. Overall, the literature specific to UM and ultra-endurance

76   exercise has highlighted the protective nature of fatigue in situations where the physical integrity

77   of participants could be compromised, such as greater neuromuscular (Millet et al. 2011b) or

78   biomechanical alterations (Morin et al. 2011b) in events with large elevation gain and loss

79   compared to UM events on level ground (Martin et al. 2010; Morin et al. 2011a).

80   **Paragraph #4.** Therefore, the aim of this study was to record the individual pacing of participants

81   in a long trail UM in hilly terrain, in order i) to measure the dynamics of speed selection as a

82   function of terrain (level, uphill and downhill sections), and ii) to further investigate the

83   relationship between performance and pacing characteristics (speed loss, speed variability, total

84   time stopped). Speed was expected to decrease in all participants and at all gradients as a function

85   of the distance and duration of the event.

86 Methods

87   **Paragraph #5.** This study was approved by the university research ethics committee (Queensland

88   University of Technology, project 0900001233). The study participants were recruited using

89   advertisements on a specialised forum and researchers networks, from individuals already

90   registered to compete in the Great North Walk 100s (NSW, Australia), a long (~173 km) and hilly

91   UM running event including 6 checkpoints and a total elevation gain and loss of approximately

92   3,000 m. This event offered the opportunity to receive an official classification and time for

93   participants failing to complete the entire event if they reached the 4th checkpoint at ~103 km,

94   which we included in the study. Both distances are presented in this article as 173-km and 103-

95   km. After providing written informed consent, 19 participants were equipped with a commercially-

96   available Global Positioning System (GPS) device (BT-Q1000, Qstarz International, Taiwan)

97   fitted to their clothing or pack.

98   **Paragraph #6.** The GPS devices used in this study were selected for their light weight (~100 g

99   including the battery) and long battery life (tested to record for more than 40 continuous hours at

100   a sampling rate of 0.2 Hz). The accuracy of measures of geographical position and speed were

101   tested following published procedures (Townshend et al. 2008). Positional accuracy was found to

102   be within the range provided by the manufacturer (100% of measures within 3 m of a known

103   geodetic survey landmark, 84.5% of observations measured within 2 m, and had a mean distance

104   of 1.57 ± 0.43 m). The calculated velocity (see following section) was found to be in excellent

105   agreement (95% limits of agreement = 0.24 ± 0.12, typical error expressed as a % of CV = 1.2,

106   standardized error of the estimate = 0.03 $km \cdot h^{-1}$) and perfectly correlated to speed determined

107   using chronometry over a known distance (100 m) over 50 trials (r = 1.00, p < 0.001).

Distance and Speed

109   **Paragraph #7.** The distance between points at the surface of a sphere can be calculated using

110   simple spherical trigonometry. However, the earth is not a sphere, but an oblate spheroid akin to

111   an ellipsoid with the following dimensions: equatorial radius ≈ 6,378.13 km, polar radius ≈

112   6,356.752 314 245 km and flattening $f \approx {}^{1}\!/_{298.257223563}$ (Defense Mapping Agency 1990).

113   The calculation of point to point distances at the surface of an ellipsoid can be improved compared

114   to spherical trigonometry using the inverse Vincenty formulae (Vincenty 1975). The point-to-point

115   distances were obtained from an internet-based utility (GPS Visualizer; www.gpsvisualizer.com)

116   using geographical positions (latitude and longitude). We found the distances obtained were in

117   exact agreement (r = 1.00, p < 0.001) with our preliminary measures of point-to-point distances

118   using the Vincenty formulae performed on 10 data sets. Therefore, we used the internet-based

119   calculations of the formulae as a simple and generalisable procedure to obtain point-to-point

120   distances.

121   **Paragraph #8.** Point-to-point speed was subsequently calculated using the ratio of point-to-point

122   distances and time (one data point every 5 s) between each datum. Preliminary calculations

123   revealed that GPS devices did not discriminate for speeds slower than 1 $km \cdot h^{-1}$ (0.28 $m \cdot s^{-1}$

124   or 1.39 m in 5 s) based on the typical error in speed in a static position (drift, when a device will

125   record speed values due to the non geo-synchronous nature of the constellation of satellites). At

126   the other end of the speed spectrum, it was considered that speeds higher than 20 $km \cdot h^{-1}$ (5.56

127    $m \cdot s^{-1}$ or 27.8 m in 5 s) were not expected during a long UM and originated in signal jamming

128   (which can occur due to the signal from a satellite being too weak which forces the ground based

129   receiver to pair to another satellite). These erroneous distance and speed data were assigned a value

130   of zero, and all speed values were then smoothed in order to further increase the signal-to-noise

131 ratio. For smoothing, a 9-pt weighted average was graphically compared with 3-pt and 15-pt

132 weighted averages and considered satisfactory as it provided a balanced sensitivity to individual

133 observations for slow and high speeds. This procedure limited the effect of signal drift and

134 jamming (higher distance and speed due to erroneous values). These procedures were sensitive to

135 periods of zero speed values, which corresponded to the location, via expected relative distances,

136 of checkpoints in the race.

Elevation changes

138 **Paragraph #9.** We used previously published procedures (Kerhervé et al. 2015) to alleviate the

139 inaccuracies in GPS-based elevation (Townshend et al. 2008). The online utility (GPS Visualizer;

140 gpsvisualizer.com) was used to match the recorded geographical positions (determined by latitude

141 and longitude) to a DEM elevation datum from the National Aeronautics and Space Administration

142 (NASA) Shuttle Radar Topography Mission (SRTM) database. As the resolution of DEM is

143 relatively low for the study of human locomotion (90 m, only the SRTM3 was available where the

144 current study was conducted), the procedure can create a series of steps when increasing or

145 decreasing elevation every time a contour line is crossed. Likewise, it can also mean that actual

146 changes in elevation are not detected when data points were recorded inside the same contour line.

147 In the absence of an existing method to reconstruct accurate elevation data, we applied the same

148 9-point weighted average smoothing procedure we used in the speed data to calculate more realistic

149 elevation data. Gradient was then calculated as the change in elevation divided by the horizontal

150 distance between two points.

Variables and statistical analysis

152 **Paragraph #10.** The identification of relevant data was performed for each participant using

153 official race results, GPS time-stamps and variations of speed (increase or decrease) indicating

154 changes in position at the start and finish lines. Speed and gradient values were computed as a

155 function of relative distance for each participant, where total individual distance represents 100%

156 of the distance completed for the 173-km, and 60% for the 103-km event participants. Relative

157 distance was used instead of the actual distance values because of the difference in total distances

158 across participants. The dynamics of speed were determined relative to each participant's average

159 speed over the entire event (100%) in order to increase the relevance of inter-individual

160 comparisons. The mean relative speed values corresponding to level (LEV; -2.5 to 2.5% gradient),

161 uphill (UH; 2.5 to 100% gradient), and downhill (DH; -100 to -2.5% gradient) were computed in

162 sections of 5% of the total distance completed, which ensured a sufficient amount of data points

163 in each section in the three gradient categories. The minimal amount of data points within one

164 section occurred at 25% of total distance in the level gradient category (64 observations for one

165 participant, which corresponded to 2.76 km for the participant), for an average number of

166 observations in each gradient category of 360 ± 98 (LEV), 439 ± 60 (UH) and 386 ± 67 (DH).

167 **Paragraph #11.** We initially assessed the normality (Kolmogorov-Smirnov test) and homogeneity

168 of variances (Fisher's F test) of the 173-km and 103-km participants for LEV, UH, DH, and overall

169 relative speeds. We then used independent t-tests to evaluate whether differences in relative speed

170 existed between the 173-km and 103-km participants in the same categories. Due to varying

171 lengths of data sets (173-km and 103-km distances), we investigated the dynamics of speed within

172 each gradient category using a one-way ANOVA on ranks (Kruskal-Wallis test) and a pairwise

173 multiple comparison (Dunn's method) when required, to determine and locate potentially

174 significant differences between sections of relative distance.

175 **Paragraph #12.** The relationship between the level of performance (individual average speed) and

176 the variability of speed (coefficient of variation of speed), the magnitude of speed loss (slope of

177 the linear regression of speed over the entire event) and the total time stopped (assumed to

178 correspond to resting, eating, clothing and gear change, toilet, other), were assessed using

179 correlations. Assumptions of normality were first tested using a Shapiro-Wilk test, and Pearson's

180 product-moment correlation was used to calculate each relationship.

181 **Paragraph #13.** All statistical analyses were performed using the computing program and its

182 associated packages R (R Core Team 2015). The level of significance was set at $p < 0.05$.

183 # Results

184 **Paragraph #14.** The datasets from four participants were not included in the analysis, due to either

185 not completing the event, or discrepancies between official results and GPS data (difference in

186 finish time greater than 5%). A total of 15 GPS datasets were used for analysis (see Figure 1): ten

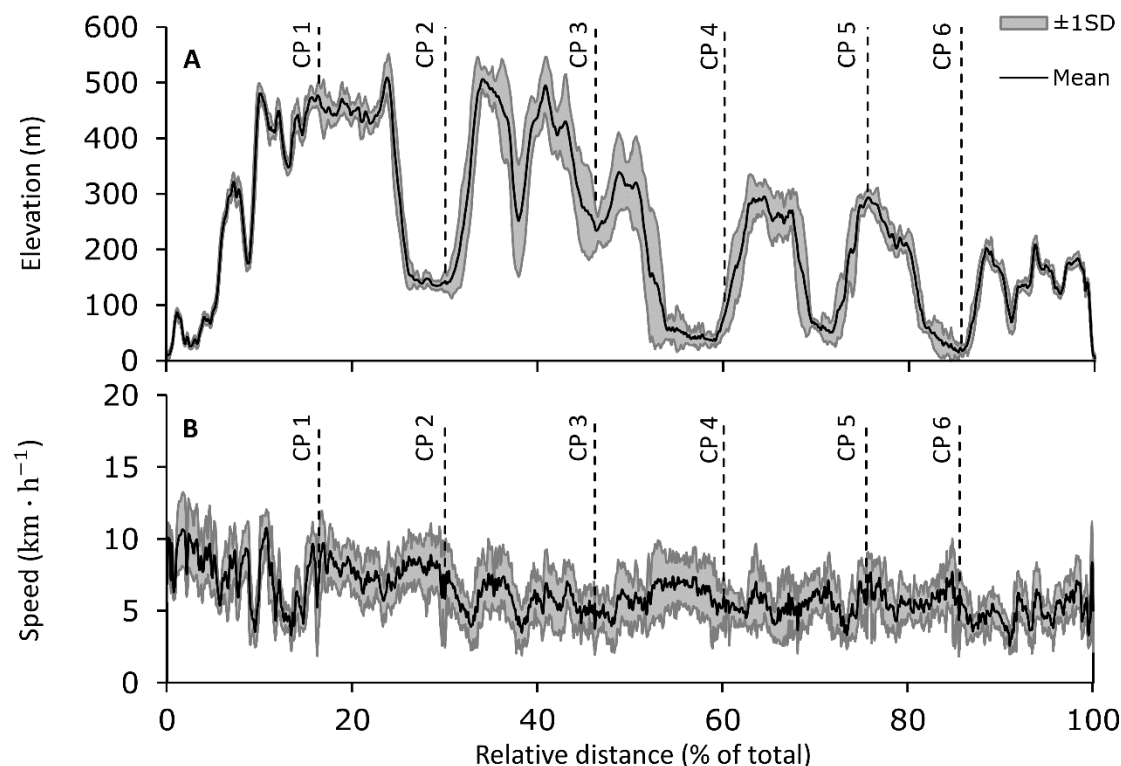
187 participants completed the 173-km distance averaging 32.9 ± 3.6 h (range $26.5 - 36.3$ h), with a

188   mean total distance of 173.0 ± 4.0 km (5.68 ± 1.51 km $\cdot$ h^{-1}), and five participants completed the

189   103-km distance averaging 18.9 ± 2.3 h (range $15.6 - 21.1$ h) with a mean total distance of 101.9

190   ± 2.3 km (5.91 ± 1.48 km $\cdot$ h^{-1}). Weather conditions on race day were dry (no precipitations), the

191   temperatures ranged 14.9-22.8 ℃ at the start point, 10.2-29.1 ℃ at the 103-km checkpoint, and

192   11.4-26.8 ℃ at the finish line, respectively.

193

194   **Figure 1. Elevation and speed.** (A) Mean (SD) group DEM data from geographical positions. (B)

195   Mean (±SD) group calculated speed. Abbreviation: CP are official race checkpoints.

196

197   **Paragraph #15.** The initial testing for normality and homogeneity of variances did not reveal any

198   significant differences between 173-km and 103-km participants. There were no significant

199   differences in means in the relative speed of the 173-km and 103-km participants for all categories

200   of gradients (overall: F = -1.38, p = 0.17; LEV: F = -0.99, p = 0.32; UH: -1.37, p = 0.18; DH: F =

201   -0.27, p = 0.79). Therefore, all remaining analysis include the 173-km and 103-km participants.

202   **Paragraph #16.** Positive pacing was observed in all participants and in all gradient categories,

203   except in one participant in negative gradients. The mean decrease in speed was -4.35 ± 3.0

204 $km \cdot h^{-1}$ (LEV), -2.26 ± 1.4 $km \cdot h^{-1}$ (UH), and -4.36 ± 2.2 $km \cdot h^{-1}$ (DH). Relative speed was

205 the most variable in LEV (coefficient of variation: 0.32) and reached a minimum at 50% of total

206 distance (significantly lower than all observations between 5% and 40%). The relative speed

207 increased from 50% to 60%, 85%, 90%, and 100%, and did not significantly decrease between any

208 sections before 50% and 100% (Figure 2.A). Relative speed was the least variable in UH

209 (coefficient of variation: 0.22) and reached a minimum at 95% of total distance. Relative speed

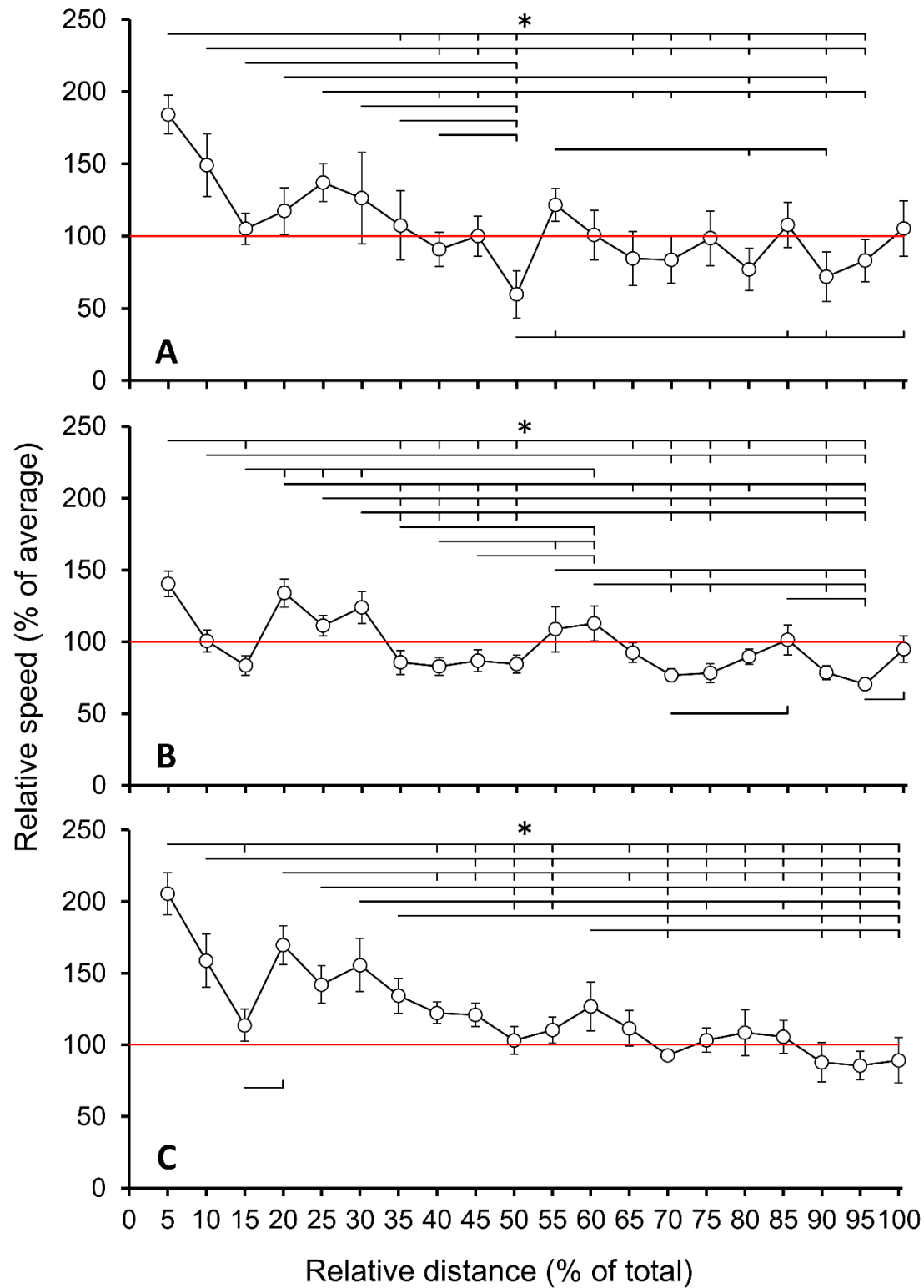
210 increased from 35%, 40%, 45% and 50% to 60%. Relative speed increased from 95% to 100%,

211 which was not different to any other observation (Figure 2.B). Relative speed in DH reached a

212 minimum at 95% of total distance (coefficient of variation: 0.26). The relative speed at 20%

213 increased compared to 15%, but no other significant increase was observed. The relative speed at

214 60% was not significantly different to any other observation, and the relative speed at 100% was

215 significantly lower than 5%, 10%, 15%, 20%, 30% and 35% (Figure 2.C).

216

217 **Figure 2. Dynamics of speed.** Group level (Panel A), uphill (Panel B), and downhill (Panel C)

218 speed relative to average, respectively. Symbols * and brackets are used to denote and locate

219 significant differences (p < 0.05).

220

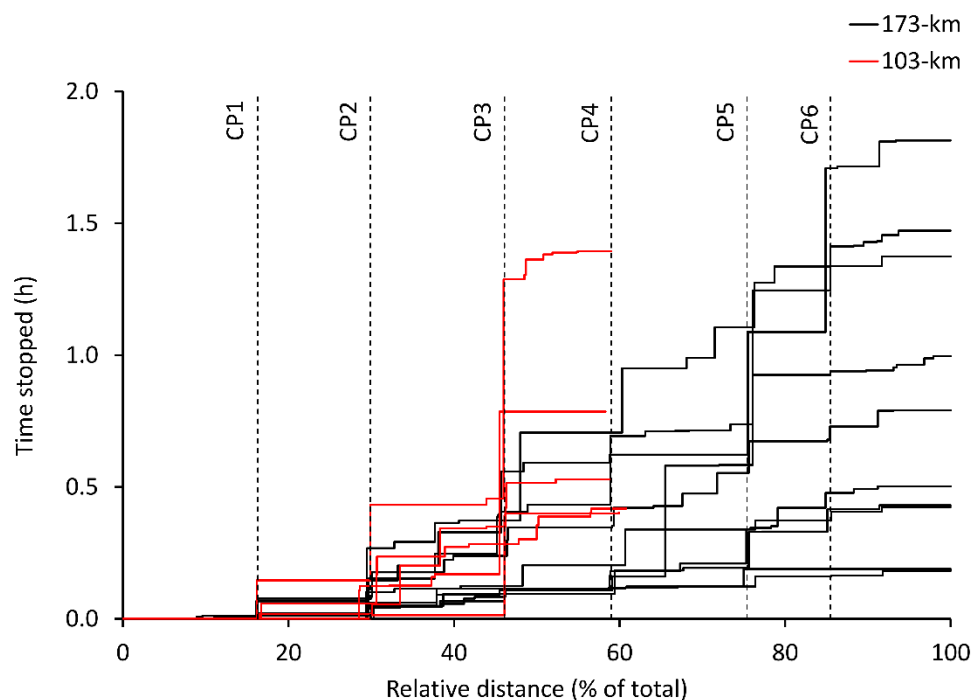
221 **Paragraph #17.** There were no significant correlations between overall performance and variables

222 of pacing (Table 1). The dynamics of total time stopped as a function of relative distance are

223 presented in Figure 3.

224

225 **Table 1.** Correlation between race performance and pacing characteristics.

	All participants		103-km		173-km	
	r	P	r	p	r	p
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
Total time stopped	-0.35	0.21	-0.15	0.81	-0.45	0.20

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227 **Figure 3. Total time stopped.** Time stopped as a function of relative distance in all study

228 participants, using the cumulated durations associated with speed $< 1 \ \mathrm{km \cdot h^{-1}}$.

229

Discussion

231 **Paragraph #18.** In this study, we collected and reported the longest systematic description of

232 pacing of runners in a long, hilly UM running event, using a method that created no disturbances

233 to normal running event situations.

234 **Paragraph #19.** The primary finding of this study was that positive pacing (overall decrease in

235 speed) was used in all gradient categories, with three direct observations. Firstly, the variability of

236 speed was higher in LEV, and, unlike in UH and DH, speed loss was the greatest in the first half

237 of the event. These observations are characteristic of a subset of the three main types of pacing

238 referred to as parabolic or mixed pacing, with a positive pacing strategy during the first half of the

239 event, and more evenly pace for the remainder of the event. Secondly, a speed reserve (increase in

240 the last stage of an event) was measured in LEV and UH. Thirdly, the decrease in speed was greater

241 in DH and LEV compared to UH, and the decrease in relative speed continued until the last section

242 in DH only. Together, these findings clearly indicate that despite slowing down overall, LEV, UH

243 and DH were paced differentially. A secondary finding of this study was that neither the

244 characteristics of relative speed (no significant differences in normality, variances or means), nor

245 the characteristics of pacing (no differences in speed loss, variability of speed or total time stopped)

246 were different in the 103-km and 173-km distances. This allowed us to compare the two groups

247 and increase the relevance of our findings, but this finding also introduces the possibility that the

248 additional ~70 km did not significantly alter pacing in an ultramarathon performed in hilly terrain.

249 **Paragraph #20.** A recent study from our group also reported parabolic pacing during a 105 km

250 mountain UM, characterised by a decrease of speed at all gradient categories in the later stages of

251 the event (70-90% of total event duration), and by a final increase in speed in the last 10% of the

252 event (Kerhervé et al. 2015). The presence of an increase in speed in the last 10% section of the

253 event was discussed as an indicator of conservative pacing strategies in anticipation of upcoming

254 topographic difficulties, and the use of a speed reserve (Millet 2011) when the last topographic

255 difficulty was passed. In the current study, both the longer distance and smaller elevation gain and

256 loss could potentially explain the absence of a speed reserve in DH. Other research have noted the

257 determinant role of elevation gain and loss in the type and magnitude of fatigue on neuromuscular

258 (Martin et al. 2010; Millet et al. 2011b) and biomechanical alterations (Millet et al. 2011a; Morin

259 et al. 2011b). Alternatively, this finding could also potentially highlight the selective effects of

260 fatigue as a function of gradient category, specifically to limit the effect of the transmission of

261 force or vibrations to the musculo-skeletal systems, as previously indicated by the alteration of

262 running economy in LEV and DH gradient categories, but not in UH (Morin et al. 2011b; Vernillo

263 et al. 2015).

264 **Paragraph #21.** The absence of significant correlations between overall performance and

265 indicators of speed variability, speed loss and total time stopped are novel. While speed loss and

266 total time stopped were found to be significantly correlated with performance in a mountain UM

267 (Kerhervé et al. 2015), speed loss and speed variability were found to be significantly correlated

268 with performance obtained in marathon (Ely et al. 2008; Haney & Mercer 2011) and UM

269 (Hoffmann 2014; Lambert et al. 2004) running. Therefore, additional research is required to

270 determine if specific pacing characteristics are useful predictors of performance in long UM, and

271 whether other variables currently not measured could be better predictors of pacing, including but

272 variables of gait kinematics (stride frequency, stride length, ground contact and aerial times) or

273 gait biomechanics (leg and vertical stiffness), which are known to be influenced by fatigue and

274 gradient (Morin et al. 2011a; Morin et al. 2011b; Vernillo et al. 2016; Vernillo et al. 2015; Vernillo

275 et al. 2014). Additionally, it has been proposed that the correlation between the level of

276 performance and a more even pace is due to learning (Foster et al. 1994; Green et al. 2010), and

277 that the previous practice of a specific distance produces more even pacing (Ansley et al. 2004;

278 Green et al. 2010). However, ultra-endurance events require longer recovery periods than shorter

279 events and hence, the opportunities to practice a specific distance are relatively less than for shorter

280 events, which could partly explain both the relative lack of data on longer events (Abbiss &

281 Laursen 2008), and the lack of a significant correlation of these variables in the current study.

282 **Paragraph #22.** There were three direct limitations to this study. First, the findings related to the

283 variations of speed within sections of relative distance used binary results (different or not), but do

284 not provide an estimation of the magnitude of differences. A simple level of analysis is not only

285 acceptable, but also warranted, for the type of data used in this study. Future studies are required

286 to describe more accurately the direction and magnitude of changes. Second, the inclusion of

287 participants from both the 103-km and 173-km distances could have implications for the results,

288 due to any differences in *a priori* pacing strategies across the two distances, or information relative

289 to the decision to stop for the 103-km group. For example, the five participants who had entered

290 the 173-km event and stopped at the 103-km distance might have done so due to an inappropriate

291 pacing strategy, or to a deliberate strategy. Irrespective, we reported the outcomes of pacing, which

292 incorporate both inappropriate and deliberate strategies, and provided evidence that the general

293 patterns of pacing did not differ across groups. Third, there are potential carry-over effects at

294 transitions between types of gradients during running (Townshend et al. 2009). However, the

295 spatial and temporal resolutions permitted by non-differential GPS do not currently allow

296 sufficient accuracy for this level of analysis during UM events, and future studies using alternative

297 methodologies are necessary to investigate these effects.

298 Conclusion

299 **Paragraph #23.** In conclusion, in this study we determined the dynamics and characteristics of

300 speed of UM runners in an actual event, which provides a basis for future studies of ultra-long

301 duration exercise. While the speed of all participants decreased as a function of distance over the

302 entire event in all gradient categories, pacing was not comparable in those categories. Finally,

303 overall performance was not correlated to expected predictors of overall running performance

304 (variability of speed, speed loss), or to the total time stopped. Future studies are required to study

305 the dynamics of speed during multiple formats of UM, to determine the effects of *a priori* pacing

306 strategies, distance, and elevation gain and loss, on pacing. As has been done in other ultra-

307 endurance disciplines (Herbst et al. 2011), future studies are also warranted to investigate the

308 importance of variables related to participant experience (number of years of practice, number of

309 starts at a certain distance) in order to further characterise pacing and performance in UM events.

310 Acknowledgements

311 The authors would like to thank Dr. Andrew Townshend for his valuable comments in the

312 conception of the study.

313 **Figure legends**

314 **Figure 1. Elevation and speed.** (A) Mean (SD) group DEM data from geographical positions.

315 (B) Mean (±SD) group calculated speed. Abbreviation: CP are official race checkpoints.

316 **Figure 2. Dynamics of speed.** Group level (Panel A), uphill (Panel B), and downhill (Panel C)

317 speed relative to average, respectively. Symbols * and brackets are used to denote and locate

318 significant differences ($p < 0.05$).

319 **Figure 3. Total time stopped.** Time stopped as a function of relative distance in all study

320 participants, using the cumulated durations associated with speed $< 1 \ km \cdot h^{-1}$.

321

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