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Spontaneous pacing during overground hill running

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Abstract

Purpose: To investigate speed regulation during overground running on undulating terrain. **Methods:** Following an initial laboratory session to calculate physiological thresholds, eight experienced runners completed a spontaneously paced time trial over 3 laps of an outdoor course involving uphill, downhill and level sections. A portable gas analyser, GPS receiver and activity monitor were used to collect physiological, speed and stride frequency data. **Results:** Participants ran 23% slower on uphills and 13.8% faster on downhills compared with level sections. Speeds on level sections were significantly different for 78.4 ± 7.0 seconds following an uphill and 23.6 ± 2.2 seconds following a downhill. Speed changes were primarily regulated by stride length which was 20.5% shorter uphill and 16.2% longer downhill, while stride frequency was relatively stable. Oxygen consumption averaged 100.4% of runner's individual ventilatory thresholds on uphills, 78.9% on downhills and 89.3% on level sections. 89% of group level speed was predicted using a modified gradient factor. Individuals adopted distinct pacing strategies, both across laps and as a function of gradient. **Conclusions:** Speed was best predicted using a weighted factor to account for prior and current gradients. Oxygen consumption (VO2) limited runner's speeds only on uphill sections, and was maintained in line with individual ventilatory thresholds. Running speed showed larger individual variation on downhill sections, while speed on the level was systematically influenced by the preceding gradient. Runners who varied their pace more as a function of gradient showed a more consistent level of oxygen consumption. These results suggest that optimising time on the level sections after hills offers the greatest potential to minimise overall time when running over undulating terrain.

Key Words: Global Positioning System; field; gait; speed regulation; gradient.

Introduction

Paragraph 1 The capacity to manage energy resources optimally by matching locomotion speed to terrain and distance may have its origins in the early history of hominids. Recently, biologists have proposed that the ability of humans to run long distances has played an important role in our evolution, enabling successful hunting and scavenging (5). Minimizing the time to cover distances on foot would also have allowed early humans to locate and transport food and water, and aided them in escaping from predators, adverse weather conditions, and other threats to survival.

Paragraph 2 Given this long-standing evolutionary advantage for optimal speed regulation, it could be assumed that humans retain the ability to select locomotion speeds in a near-optimal manner without external pacing, provided that they have adequate fitness levels and experience of running in varying conditions and for a range of distances. Indeed, the optimal management of resources is essential if an endurance event is to be completed in the least possible time. For this reason numerous studies of athletic performance have focussed on pacing and the factors which affect it. One common issue arising from these studies, which have been well reviewed by Abbiss and Laursen (1), is the need for runners to select an optimal speed and vary it to meet environmental conditions, including changes in surface, direction and gradient. Of these factors, changes in gradient pose a special challenge as they involve the largest changes in energy expenditure, and any misjudgements of pace carry high performance costs. While the self-selected speed of walking in natural environments has been investigated extensively (6, 9, 14 & 16), a number of factors, including limitations of the available measurement technology, have hindered a comparable analysis of running.

Paragraph 3 The use of laboratory treadmills to simulate running over hills poses significant technical challenges, in particular by limiting the runner's ability to regulate speed freely and continuously. These problems notwithstanding, treadmill studies have been used to confirm that selected running speeds were inversely associated with gradient (23,26), and have demonstrated that runners were unable to maintain a constant energy expenditure due to an inability to increase speed sufficiently on downhill gradients (26).

Paragraph 4 In contrast to the relatively constant rate of energy expenditure achievable on straight and level courses (29), the only study so far to investigate speed regulation over an undulating off-road course found that gradient accounted for only 40% of the variation in speed (20). In contrast to the findings of Staab et al (26) subjects appeared to maintain a steady rate of energy expenditure across different grades, while relative effort, determined indirectly from heart rates using a heart rate-oxygen consumption regression, was found not to be related to gradient.

Paragraph 5 To more fully understand the determinants of and constraints on the selection of speeds during distance running on undulating terrain, the physiological profiles of subjects from the laboratory should be combined with a field study in which runners are completely free to regulate speed. The course should include a range of gradients and level sections, with each of sufficient length that the time course of speed changes can be observed. Ideally, the continuous measurement of physiological, kinematic and trajectory variables would be included so that a more comprehensive account of factors affecting speed regulation can be achieved. The current study was designed to accomplish this, using experienced runners on a three-lap course, and employing a portable gas analyser, heart monitoring, accelerometry to measure stride length and frequency, and a Global Positioning System (GPS) receiver to provide continuous velocity and location data.

Methods

Paragraph 6 *Participants*. Eight healthy male distance runners (age 28.1 ± 9 years, height 178.9 ± 7.3 cm, weight 70.2 ± 7.6 kg) were recruited for this study from local running clubs. All runners had completed a 10000m race in less than 40 mins in the previous 12 months (or a longer distance at an equivalent pace) and were free from any musculo-skeletal injuries of the lower limbs. Written informed consent was obtained from all participants and the study was approved by the Human Research Ethics Committee of the Queensland University of Technology.

Paragraph 7 *Laboratory test*. All participants completed both a laboratory and a field trial. At the initial session, participants completed an incremental exercise test to exhaustion on a motorized treadmill. After a brief warm up at a speed of their choice, runners commenced the incremental test at a speed between 12 and 14km/hr. The treadmill speed was increased by 0.3km/hr each minute while the grade was held constant at 1% to simulate the oxygen consumption of outdoor running (17). Respiratory gas-exchange data was collected breath by breath and averaged for every 15 second period using a portable gas analyser (details in equipment section) which was calibrated beforehand according to the manufacturer's instructions. Heart rate was measured continuously using a single-lead ECG monitor (Alive Technologies, Australia). Achievement of at least two of the following variables was taken to indicate that a participant had performed a maximal test: heart rate ± 10 beats per minute of age-predicted maximum, respiratory exchange ratio > 1.10, and an increase in oxygen consumption of less than 150mls.min^{-1} with an increase in workload. Maximum oxygen consumption (VO_2 max) was determined by averaging the four highest successive 15 second values. If a plateau in oxygen uptake was not clearly evident, a supra-maximal test was performed after an adequate rest period to confirm that the participant's highest VO_2 had been attained. Maximal oxygen consumption (VO_2 max) was defined as the highest value achieved in either the laboratory or field test. Ventilatory threshold was determined using the ventilatory equivalent method (3) and velocities at this threshold (vVT) recorded from the treadmill speed.

Paragraph 8 *Field test*. Within 14 days of their laboratory trial participants completed a field time-trial consisting of three laps of a 3175m circuit (Figure 1). This was divided into four sections completed in the following order: level section (765m), uphill (820m), level (770m), downhill (820m). (NB: The uphill/downhill portion of the course used the same section of road completed in opposite directions). The initial level section utilised a compacted dirt road which was free of loose gravel while the other sections consisted of bitumen roads and concrete footpaths. Each section was further divided into 8 sub-sections of equal distance for subsequent analysis. Gradients for each subsection for the uphill (in order) were as follows: 6.3%, 9.3%, 11.2%, 6.8%, 11.7%, 10.7%, 1.5%, and 7.8%. Gradients and distances were calculated by reference to topographic survey data, following the route measured using the GPS receiver.

Paragraph 9 At the end of the third lap, participants completed an additional level section of 380m. This section reduced risks to the participant by finishing on a level section rather than a downhill and minimised the effects of any finishing sprint - as this was likely to include a high anaerobic component and not be representative of the pacing throughout the remainder of the trial. Despite small differences in finishing speeds, this section had only a negligible effect on overall mean speeds (average change: 0.02m/sec or 0.55%), and did not alter the finishing order of the participants. This section was not included in subsequent analyses.

Paragraph 10 On laps 2 and 3 participants were provided with a drink stop at the midpoint of the 2^{nd} level section (following the downhill). As the gas analyser had to be partly unclipped from the headgear to enable drinking, participants were held stationary for a set 30 second period while this took place. Accordingly, data for that sub-section (all variables) and the following sub-section (HR and VO_2 only) have been replaced with estimates through subject-by-subject linear interpolation from values for the adjacent sections. This correction applied to either one or two of the 96 sub-sections only and allowed a fully balanced statistical analysis to be performed.

Paragraph 11 Participants were asked to adhere to their normal training and dietary schedules between sessions but to abstain from vigorous exercise, caffeine and alcohol in the preceding 24 hours. All trials were held between 6-7 am to avoid large variations in temperature. To familiarize each participant with the nature and length of the course, they were driven over it by car before each trial. Sessions were run as individual trials and runners were given the explicit goal of trying to minimise their overall time, but were free to select their own pacing strategy. No watches were worn by participants and no feedback was given so as to prevent any form of external pacing.

Paragraph 12 *Apparatus*. For the field trials, runners were equipped with a GPS receiver, activity monitor and portable metabolic analyser (described below) to provide physiological, speed and stride frequency data. Information from the GPS and activity monitor were wirelessly streamed (Bluetooth ™) to a smart phone (i-mate SP3, i-mate, Dubai) which was attached to the arm with a Velcro strap while the metabolic analyzer transmitted and logged information to its own internal memory for subsequent analysis.

Paragraph 13 *GPS*. Each runner wore a cap containing a lightweight, non-differential GPS receiver (GPS-BT55, Wonde Proud, Taiwan). The GPS receiver was used to provide speed, position and displacement values once each second and has been previously validated (28).

Paragraph 14 *Activity Monitor*. An activity monitor (Alive Technologies, Australia), containing a single lead ECG recorder and a tri-axial accelerometer, was attached to the participant's dorsal lumbar spine with double sided tape. ECG data was collected at 300Hz and R-R intervals used to determine heart rate. Electrodes were placed as for a standard limb lead II position. The tri-axial piezo-electric accelerometer (rated to ± 2.4g) concurrently logged body accelerations in the sagittal, frontal and transverse planes. Acceleration data were sampled at 75Hz and converted to earth acceleration units (g) based on a prior calibration. Peaks in the vertical acceleration data were used to detect steps in a manner similar to previous reports for walking (18, 30) and stride frequencies were subsequently calculated using a custom written program.

Direct interpolation from GPS speed data was then used to derive average stride lengths based on speed and stride frequency.

Paragraph 15 *Metabolic Analyzer*. Participants were fitted with a portable metabolic analyzer ($K4b^2$, Cosmed, Italy) which provided information on oxygen consumption, carbon dioxide production and ventilation. Values were collected breath by breath and averaged over 15 second intervals.

Data reduction and analysis

Paragraph 16 Data from the different systems (smart phone and gas analyser) were synchronised and converted to a common file format using spreadsheets (Excel 2003, Microsoft, Redmond, Washington) and a customised program. For each of the five dependent variables (speed, oxygen uptake, heart rate, stride frequency and stride length), mean values were calculated for each of the 96 sub-sections separately for each runner. These values were then used for subsequent statistical analyses.

Statistics

Paragraph 17 A three way repeated measures analysis of variance was used to characterize performance and determine the effects of the independent variables of gradient, lap and section (portion of each gradient- divided into 8 equal parts by distance).Tukey's post-hoc tests and planned comparisons were used to further examine the dependent variables where appropriate.

Paragraph 18 Multiple regression was used to develop prediction equations for self-selected running speed based on gradient and lap, first at the Group level (i.e. for each of the 96 sub-sections by averaging across subjects), and then at the individual level (i.e. by predicting speeds of the whole data-set (96 sub-sections x 8 runners). The Group level analyses facilitated comparison with the report by Mastroianni et al (20) and removed variance attributable to individual pacing strategies, while the individual analyses include alternative measures of physiological capacity obtained in the earlier laboratory testing as predictor variables.

2. Results

Paragraph 19 *Laboratory test*. Maximal oxygen consumption (VO_2 max) was defined as the highest value achieved in either the laboratory or field test. These tests yielded the following physiological measures: VO_2 max, 69.8 ± 5.4 mls. kg. min $^{-1}$; velocity at VO_2 max (vVO_2 max), 4.87 ± 0.40 m/s (17.5 ± 1.4 km/hr) ; ventilatory threshold (VT), 88.2 ± 6.4 % VO_2 max; speed at ventilatory threshold (vVT), 4.40 ± 0.21 m/s (15.8 ± 0.8 km/hr).

Paragraph 20 *Field test*. The results are divided into three parts. First the effect of lap, gradient and section on group level performance is outlined for each dependent variable. Secondly, the regulation of speed as a function of gradient is explored through multiple regression analysis, and finally, individual pacing strategies are outlined. All dependent variables are depicted in Figure 1, together with a profile of the course.

Paragraph 21 *2.1a Speed*. Speeds varied significantly between both laps and gradients. The lap effect was confined to Lap 1 which was run faster than Laps 2 or 3

(55 seconds and 51 seconds difference respectively, $p < 0.05$), while Laps 2 and 3 did not differ from one another ($p = 1.0$). Runners varied their speed significantly between different gradients, running 13.8% faster on the downhill and 23.0% slower on the uphill when compared with the level sections ($p< 0.001$). Table 1 illustrates mean values as a function of lap and gradient.

Paragraph 22 While speed varied across the 8 sub-sections as a main effect ($p < 0.001$), this can only be interpreted in light of its significant interaction with gradient ($p < 0.001$). A strong effect was a persistence of speed from the preceding gradient. This is most clearly evident on the two level sections which showed a deceleration following a downhill gradient and an acceleration following an uphill. This is shown in Figure 2. One difference between the two level sections was that speed stabilised rapidly after a downhill, reaching an asymptote after just one sub-section, whereas this did not occur until the fourth sub-section after an uphill. This was confirmed by planned comparisons within each series. Following a downhill, the first and second subsections were the only two adjacent sections which differed significantly ($p < 0.05$). Following an uphill, each of the first three sub-sections were significantly slower than the last four ($p < 0.05$). Therefore runners took some time to adjust their speeds to a new gradient, and this adjustment took much longer after an uphill.

Paragraph 23 *2.1b Stride Frequency*. Stride frequency was remarkably stable across all sections of the course (Table 1). None of the three independent variables (lap, gradient, sub-section) reached significance as main effects ($p = 0.52$, $p= 0.08$, $p= 0.08$, respectively). There was, however, a significant interaction between gradient and sub-section ($p<0.001$). Runners decreased their cadence from level to uphill, an effect that became significant only after the first two uphill sub-sections (uphill sub-sections 1&2 = 86.9 strides/min, subsections 3-8 = 84.7 strides/min, $p<0.001$, planned comparison). They maintained this lower cadence throughout the first half of the following level section, after which it slightly but significantly increased again (level after uphill subsections 1-4 = 85.1 strides/min, subsections 5-8 = 85.7 strides/min, $p <.05$).

Paragraph 24 *2.1c Stride length*. In contrast to the relatively stable stride frequency values, it was clear that speed was predominantly regulated by stride length. Accordingly, changes across laps and gradients closely mirrored changes in speed. Stride length on lap 1 was longer than lap 2 or lap 3 ($p<0.05$), while laps 2 and 3 did not differ from one another ($p = 1.0$). While there were no difference in stride lengths between the two level sections ($p = 0.79$), stride lengths were 20.5 % shorter uphill and 16.2% longer downhill when compared with the level ($p< 0.05$).

Paragraph 25 *2.1d Oxygen uptake (VO_2)*. As with speed, VO_2 varied across laps and gradients (Table 1). Variation across laps was primarily due to lap 1 which was higher than either lap 2 or lap 3 ($p<0.05$) while there was no difference between oxygen consumption on laps 2 and 3 ($p = 0.93$). VO_2 was significantly higher uphill and lower downhill compared with level sections ($p< 0.05$). Relative to individual thresholds, these values were below VT for both downhill and level sections. On the uphill sections, runners slightly exceeded VT on lap 1(105.2 ± 13.1%), but reduced speeds on subsequent laps such that VO_2 was in line with individual thresholds on subsequent uphill sections (97.7 ± 11.5% - Lap 2, 98 ± 9.6%- Lap 3).

Paragraph 26 *2.1e Heart rate*. All three independent variables (lap, gradient, section) and their interactions had a significant effect on heart rate (HR). Values were significantly lower on lap 1 (170 ± 17 bpm), than lap 2 (180 ± 12 bpm) and lap 3 (184 ± 11 bpm; $p < 0.05$) as the subject started from rest. As HR increases only relatively slowly on starting to run, the effects of gradient can be better appreciated in Lap 2. Analyzed separately, this shows HR averaging 186.1 ± 1.9 bpm uphill, 179.5 ± 2.1 bpm on the level, and 175.5 ± 2.4 bpm downhill.

2.2 Prediction of speed

Paragraph 27 We sought to characterise how well running speed can be predicted from gradient data and lap, using multiple regression analyses. The outcomes of these regressions are presented in Table 2. Group level analyses showed a high adjusted R^2 of 0.825 in which gradient was by far the more important term. This value increased to 0.891 when we substituted a modified gradient factor for the gradient of each section. This took into account the influence of the immediately preceding sub-section gradients on speed, using a geometric decay function to weight gradients of the current and seven preceding sub-sections as follows: Modified gradient = $(0.5 \times g_n + 0.25 \times g_{n-1} + 0.125 \times g_{n-2} \ldots + 0.003906 \times g_{n-7})$ where g = gradient and n = current sub-section. As this modified gradient improved prediction and can be readily calculated for any course, it was used in the subsequent individual level regressions. As individual regressions could not account for differences in pacing strategies, R^2 values were slightly lower than for Group level predictions (Table 2).

2.3 Individual pacing strategies

Paragraph 28 As stated above; mean speeds were fastest for lap 1, while there was no significant difference between laps 2 and 3 for the group (Table 1). Within the group however, there were large inter-individual differences in pacing strategies adopted across the three laps. Runners fell into two distinct groups. As seen in Figure 3a, four of the runners slowed monotonically across the three laps (lap one: 4.10 ± 0.34 m/s, lap two: 3.77 ± 0.33 m/s, lap three: 3.64 ± 0.28 m/s; $p < 0.0001$). Conversely, the other four runners significantly increased speeds from lap 2 to lap 3 (3.57 ± 0.36 v 3.72 ± 0.34 m/s; $p < 0.05$). These apparently distinct strategies are discussed later.

Paragraph 29 Figure 3b also shows that individual runners differed considerably in their modulation of pace as a function of gradient. In general, those who decreased speed more uphill (relative to level speed) ran faster downhill, and vice versa, and differences in downhill running speed were notably larger than those for the uphill sections. To gauge the degree to which these differences may have stemmed from more or less effective energy consumption optimisation, we correlated the range of running speed (downhill – uphill) with the range of oxygen consumption (downhill – uphill), expressing all values relative to level. The r of -0.775 suggests that those runners who minimised fluctuations in their oxygen consumption across the gradients achieved this by varying their speed more (i.e., by running slower on uphills and faster on downhills).

Discussion

Paragraph 30 Walking or running speed has long been considered a key variable to either measure or to control when studying the physiology of human locomotion, in part because of its strong association with energy expenditure. Generally, investigators conducting treadmill studies have been restricted to controlling speed, or both speed and gradient, so that the corresponding physiological processes are the dependent variables. While this procedure has been highly informative, it prevents the subject from spontaneously changing speed in response to changes in gradient (a very small number of studies in which the treadmill's speed is changed to match the subject's preferred speed are exceptions (23, 26). Similarly, the overwhelming majority of studies that have specifically examined spontaneous pacing have used data from track events or experimental trials on flat and level courses, thus excluding one of the most crucial determinants of speed in undulating terrain, namely changing gradient. It is largely for these reasons that spontaneous speed regulation in hilly terrain remains a poorly understood process, as does the concomitant regulation in the gait cycle, oxygen consumption and other physiological variables.

Paragraph 31 The current study extends this knowledge in several ways, firstly by characterising the gradient/speed relationship in more detail than previous studies, secondly by showing how speed regulation on hills co-varies with physiological measures and aspects of the gait cycle, and finally, by allowing some new insights into optimal pacing strategies in hilly terrain.

Effects of gradient on running speed

Paragraph 32 In the only previous study that examined the speed/gradient relationship on an undulating overground course, running speed was reported to change by 0.034 $m.s^{-1}$ for every one percent change in gradient (20), while in our study; this figure was substantially higher at 0.082 $m.s^{-1}$. This substantially greater predictive power of gradient was true even when the raw (not modified) gradient values were used. The reason for the better predictions obtained by substituting the modified gradient values are addressed in a following section- here we outline possible reasons for the differences between these studies. The runners in our study were fitter (69.8 ± 5.4 vs. 61.2 ± 6.9 mls. kg. min $^{-1)}$, and could therefore run about 18% faster on the level than this earlier study, but the most likely reason for this nearly two-and-a-half-fold greater degree of speed change is the length and order of the various uphill, level and downhill sections in each study. While the runners in the study by Mastrioanni et al (20) changed between uphill and downhill running 23 times in just under 9 km, ours made only 11 transitions in 9.5 km, and half of these were between level and uphill or level and downhill rather than downhill to uphill or vice versa. Our runners attained a steady state on each gradient, while the runners in Mastrioanni et al's (20) study had some more abrupt transitions (including one steep ascent of 90m in between two downhill sections), which will have attenuated some of the speed changes.

Paragraph 33 A similar explanation may underlie the fact that, while Mastrioanni et al (20) reported that gradient accounted for 40% of the variation in running speed, we found higher values, ranging from 65% to 89%, depending on whether individual or group data is examined. Because gradient transitions represented a smaller proportion of the course in our study, running speed was more closely associated with gradient magnitude. Thus we suggest that Mastroianni et al's (20) conclusion that terrain characteristics other than gradient (such as the nature of the soil and the trail) may be of similar significance to gradient in determining speed may apply only if gradients change frequently or if the surface conditions impede gait. However, there are also very clear - though relatively short-lived – lags in speed changes at these transitions.

Modified gradient, transition effects and lags

Paragraph 34 A novel finding in the current study was that by substituting for raw gradient values a modified gradient index that included a diminishing influence of the gradients prior to the current one, we improved the prediction of speed further. We believe that this superior prediction reflects a set of transition and lag effects as runners encounter a change in gradient. For example, although runners immediately accelerated following an uphill and slowed after a downhill, the effect of the preceding section persisted and only gradually diminished across the next section (Figure 2). While Staab et al. (26) has previously reported that runners slowed on a 0% treadmill gradient following an uphill of 5% grade, their use of mean speeds for the two gradients prevented any analysis of the time-course of this effect. Following the uphill section of 820m (gradient 6.3-11.7%) speeds were significantly different for each of the first three subsections on the level which corresponded to a time delay of 78.4 ± 7.0 seconds. As suggested by Staab et al (26), this lag in returning to the prior level speed is likely to be a result of runners being forced to recover from the high anaerobic cost of uphill running.

Paragraph 35 Our study found that in addition to diminished speeds on level sections after an *uphill*, speeds also remained elevated following a *downhill.* This decrease in speed however, was noticeably shorter and was complete by the end of the first subsection (23.6. ± 2.2 seconds or approximately 95 metres) for these runners. While a small component of this higher initial speed may be a simple momentum effect, this is likely to be confined to only a few seconds. The second phase of slowing probably reflects the gradual return of oxygen consumption as a limiting factor.

O2 not a limitation downhill

Paragraph 36 The ventilatory threshold (VT) has previously been reported to be the strongest physiological predictor of endurance performance during running on level ground (25). Accordingly, it seems likely that runners on a hilly course may also adjust their efforts in response to intrinsic cues in order to prevent exceeding this threshold. Runners in this study appeared to regulate their efforts in line with their threshold on uphill sections. After a faster uphill on lap 1 where VO_2 averaged ≈ 105% of VT, runners subsequently reduced speeds such that VO_2 was just under VT on the uphill sections of laps 2 and 3.

Paragraph 37 While this tendency is consistent with a physiological limitation on uphill running speed, this was not the case on the downhills. Firstly, overall downhill speed was increased substantially less than uphill speed was reduced– a 13.8% increase compared to a 23% reduction uphill. Despite this increase, downhill speeds were not limited by physiological cost as, as oxygen consumption was substantially less than VT (Table 1). This suggests that other factors limited runners' downhill speeds, confirming findings from earlier laboratory studies. Minetti et al (24) has previously shown that speed estimates based on energy cost compare favourably with actual performances in uphill races, but overestimate performance in downhill only competitions. Similarly, Staab et al (26) reported that runners were unable to run fast enough downhill to completely compensate for their slower pace uphill. These findings are in contrast to studies on level courses which have reported that runners spontaneously vary their pace to maintain a relatively constant level of effort as evidenced by a low variance in heart rates (11, 29). In this study, it was evident that speeds on downhill sections were not limited by the capacity to use oxygen.

Paragraph 38 Relative to the individual's ventilatory threshold, it was also apparent that there was a large range in the energy expended on the downhill section (equivalent to 64.5- 93.7 % of VT) showing that while some runners took full advantage of the downhills, others may have used this section for recovery from preceding sections. A recent study by Baron et al (2) has proposed that the degree of eccentric muscle loading may also influence pacing strategy. This may suggest that runners who did not increase speed as much downhill may have attempted to attenuate the shock of running downhill as an injury prevention mechanism. As the limiting factors on downhills are thus likely to be biomechanical rather than physiological, changes in variables such as stride length and stride frequency may represent some of these constraints on downhill speed.

Effects of gradient on stride length and cadence

Paragraph 39 While historically, analysis of stride parameters in distance running has often been confined to the treadmill or restricted to brief durations when conducted outdoors, the recent use of accelerometry to detect steps now allows the collection and analysis of data over longer periods and in more natural settings (19). Using this method we found that the mean stride frequency was not significantly different between level, uphill and downhill sections (Table 1) with changes in speed primarily regulated by changes in stride length. It has been suggested that this near independence of stride frequency observed with speed (8) and gradient (23) is a reflection of the "bouncy paradigm of running" (23). Although this concept was confirmed on a broad comparison between the overall mean for each gradient, analysis at the section level showed that after the first two sections of the uphill had been completed there was a small but statistically significant decrease in stride frequency which carried over to the first half of the subsequent level section.

Paragraph 40 Despite this small contribution from stride frequency to speed changes in these sections, speed was still primarily regulated by stride length. While improving speed on downhill sections offers a potential opportunity for improving performance in hilly races, other factors may limit the full utilisation of these strategies. It has previously suggested that individuals with musculoskeletal injuries may choose to forsake minimising energy cost in comparison to selecting gait parameters which maximize shock attenuation in order to protect the injured structures (15). This could also be expected in healthy individuals when running on downhill gradients, and both normal and shear forces have been shown to rise substantially (54% and 73% respectively), when running at 3 m/s on a -9% grade compared to the level, substantially increasing the likelihood of overuse injury (13). Shock attenuation has been shown to be altered primarily with changes in stride length rather than frequency (21, 22). The current study, where downhill speeds were not limited by physiological cost, suggests that on sufficiently steep downhill grades shock attenuation may be a stronger determinant of preferred stride length (and thus speed) than energy cost even within healthy individuals.

Pacing strategies-Lap effects

Paragraph 41 As shown in Figure 3b, runners in our study fell into two clear groups, with half slowing continuously across the three laps while the other half were able to accelerate from lap 2 to lap 3. A “positive split” pacing strategy (first half faster than second half) has been shown to be effective in events lasting less than 2 mins where the accompanying anaerobiosis can be tolerated for the duration of the event, however, there is no clear consensus as to the optimal strategy over more prolonged durations (1).

Paragraph 42 Despite a wealth of literature on pacing in athletic events, studies involving distance running are scarce with the majority of research dominated by studies of cycling or running events of less than 2 mins duration (1). Based on studies of swimming and cycling as well as mathematical modelling, it has been suggested that endurance athletes may benefit most from a more even distribution of their energy expenditure (10, 27).

Paragraph 43 Conversely, from the few studies of running, there is evidence that variable pacing may be more optimal. Billat et al (4) has demonstrated that runners constrained to a constant pace (on the level) incur a higher physiological cost (↑ VO_2, HR and blood lactate), when compared with a freely paced run at the same mean speed. Comparison of different pacing strategies has also shown that running the first 1/3 of a 5km race 3-5% faster than the mean speed resulted in faster times during a treadmill trial when compared with even pacing (12). While all of these studies took place on level ground, many athletes engage in road races which involve positive and negative gradients. As such, speed is likely to vary naturally in response to changes in terrain, so it is less clear as to how this variation should be managed to optimise performance.

Pacing strategies-Gradient effects

Paragraph 44 Our results show large individual variations in pacing with respect to gradient (Figure 3a). In general, those runners who varied their pace more as a function of gradient showed smaller changes in oxygen consumption, and we propose that this is indicative of a more effective pacing strategy. Downhill running speed showed particularly wide individual variation. It is noteworthy that distinct strategies have been observed in downhill running kinematics (7), attributed to the conflict between the need to attenuate shock and the requirements of controlling the stability of the head, arms and trunk. Resolving this conflict in different ways may in part determine why some runners are capable of much faster downhill running than others.

Paragraph 45 A final note concerning pacing strategies is that there was little if any relationship between pacing over the three laps and pacing over the varying gradients, that is, those who adopted a conservative strategy with respect to laps (minimising lap-to-lap energy expenditure fluctuations by keeping average speed consistent) did not necessarily do so over hills (minimising uphill vs. downhill energy expenditure fluctuations by *increasing* speed differences on these sections) (Figure 3a & 3b). If confirmed in larger studies this would suggest that different factors can influence pacing at the macro (whole distance) and micro (component section) levels.

Paragraph 46 Optimal pacing over a hilly course may thus require a more fine-grained analysis with strategies varying throughout to take account of the length, type and gradient of any hills. This study has shown that runners tended to limit uphill running to a speed which resulted in oxygen consumption values in line with their ventilatory threshold. Conversely, there was a large potential to improve time on downhill sections as runners were not limited by physiological cost. Despite this, runners may be unable or unwilling to greatly increase speeds on these sections due to biomechanical or psychological factors already discussed. As reported earlier, speeds on level sections have been shown to be affected by a preceding uphill or downhill. In this study speeds on level sections following an uphill were lower than mean level speeds for almost 80 seconds.

Paragraph 47 Conversely, while speeds were elevated for a short time on levels after a downhill, the VO_2 on these sections was still well below their ventilatory threshold. One possible suggestion for minimising time then on hilly courses may be to balance the time cost of running slightly slower uphills, with the potential time saving if runners can return to a faster speed on the level in a shorter time frame. Similarly, runners should take full advantage of running faster on level sections following a downhill but limit increases to keep VO_2 just below their ventilatory threshold.

Summary

Paragraph 48 In summary, this study is the first to characterise how runners regulate their speeds during a time trial on a hilly course through the provision of continuous metabolic, kinematic and speed data. Speed was shown to be strongly predicted using a weighted gradient factor which accounted for the influence of prior and current gradients. This was supported by our findings on the effect of hills on subsequent level sections where a lag effect on speed persisted for almost 80 seconds. This research has suggested that these level sections following hills represent the most likely source of potential improvements for runners wishing to minimise their overall time in distance races on hilly courses. Future studies should test the feasibility of athletes adopting these strategies. The limits on downhill running speed and the efficiency of various gradient-speed trade-offs hills also warrant further investigation, not only to enhance performance, but, more broadly, to understand the optimisation principles that account for the spontaneous choice of running speed in humans.

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Table 1- Kinematic and physiological variables across sections and laps

Section/Lap	Speed (m/s)	Stride frequency (strides/min)	Stride length (m)	VO_2 (L/min)	VO_2 (% of VT)
Level	3.83 ± 0.43	86.1 ± 3.0	2.76 ± 0.29	3.81 ± 0.64	89.3 ± 13.8
Uphill	2.95 ± 0.40*	85.2 ± 3.5	2.19 ± 0.28*	4.28 ± 0.51*	100.4 ± 11.9*
Downhill	4.36 ± 0.62*	86.0 ± 3.8	3.20 ± 0.36*	3.38 ± 0.59*	78.9 ± 11.3*
Lap 1	3.88 ± 0.67	85.6 ± 3.5	2.79 ± 0.45	3.98 ± 0.75	92.5 ± 17.4
Lap 2	3.67 ± 0.63**	86.1 ± 3.3	2.68 ± 0.45**	3.75 ± 0.61**	87.2 ± 13.2**
Lap 3	3.68 ± 0.76**	86.0 ± 3.3	2.68 ± 0.51**	3.72 ± 0.63**	88.6 ± 12.8**

Values are means ± SD. VO_2, oxygen consumption;VT, individual ventilatory threshold.
*   significantly different compared with level, $p < 0.05$.
** significantly different compared with Lap 1, $p < 0.05$.

Table 2- Summary of regression weightings for group and individual subjects

Group					
Variable	**Beta**	**B**	**Intercept**	**Adjusted R^2**	**SEE**
Gradient	-0.898	-8.265	3.948	0.825*	0.239
Lap	-0.147	-0.103			
Modified gradient	-0.934	-9.743	3.979	0.891*	0.189
Lap	-0.164	-0.114			
Individual					
Variable	**Beta**	**B**	**Intercept**	**Adjusted R^2**	**SEE**
Modified gradient	-0.765	-9.743	2.340	0.651*	0.411
Lap	-0.134	-0.114			
VO_2 max	0.228	0.024			
Modified gradient	-0.765	-9.743	2.003	0.656*	0.408
Lap	-0.134	-0.114			
VT	0.239	0.032			
Modified gradient	-0.765	-9.743	0.649	0.733*	0.360
Lap	-0.134	-0.114			
vVO_2 max	0.365	0.684			
Modified gradient	-0.765	-9.743	-1.504	0.721*	0.368
Lap	-0.134	-0.114			
vVT	0.349	1.247			

VO_2 max, maximal oxygen consumption; VT, ventilatory threshold; vVO_2 max, speed at maximal oxygen consumption; vVT, speed at ventilatory threshold.
* $p < 0.001$
NB: All individual variables significant, $p < 0.001$.

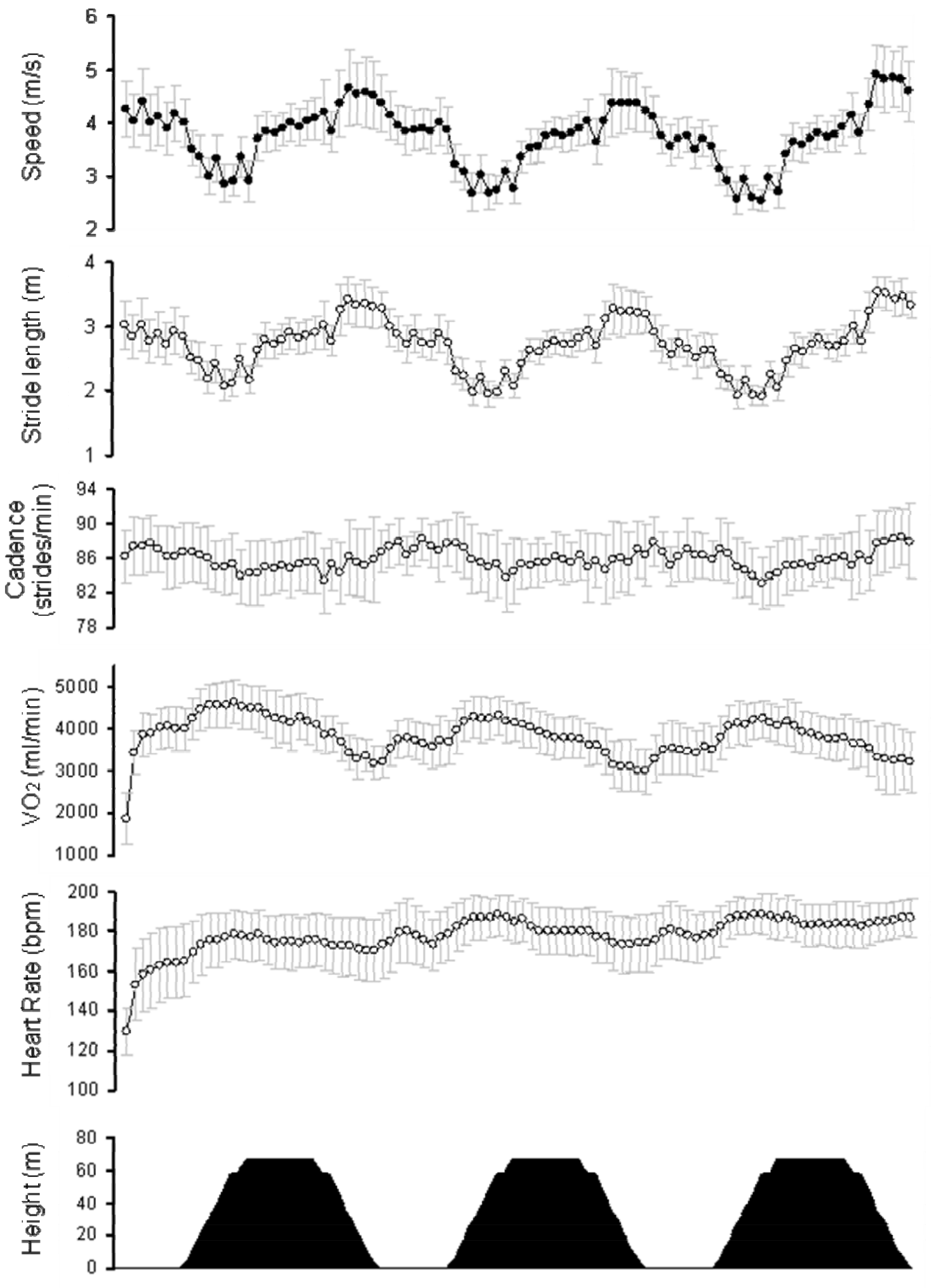

Figure 1: Changes in speed, kinematics and physiological variables across 3 laps of an undulating course. Individual graphs represent (top to bottom): Speed, stride length, cadence, oxygen consumption, heart rate and course profile.

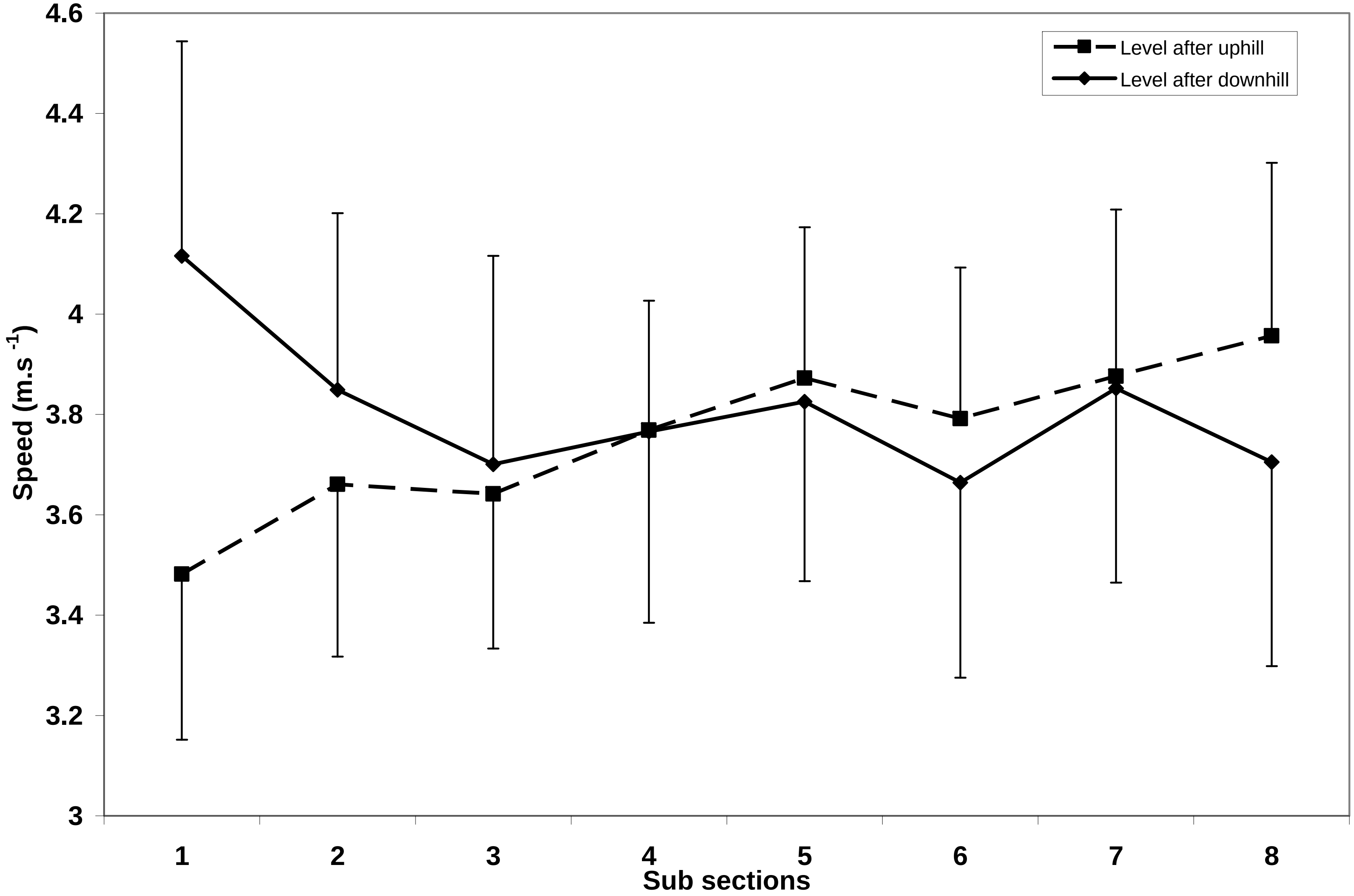

Figure 2: Speed changes on level sections following uphill or downhill running.

* significantly different from all other level subsections after downhill, $p < 0.05$

** subsections 1-3 after uphill significantly different from subsections 5-8, $p < 0.05$

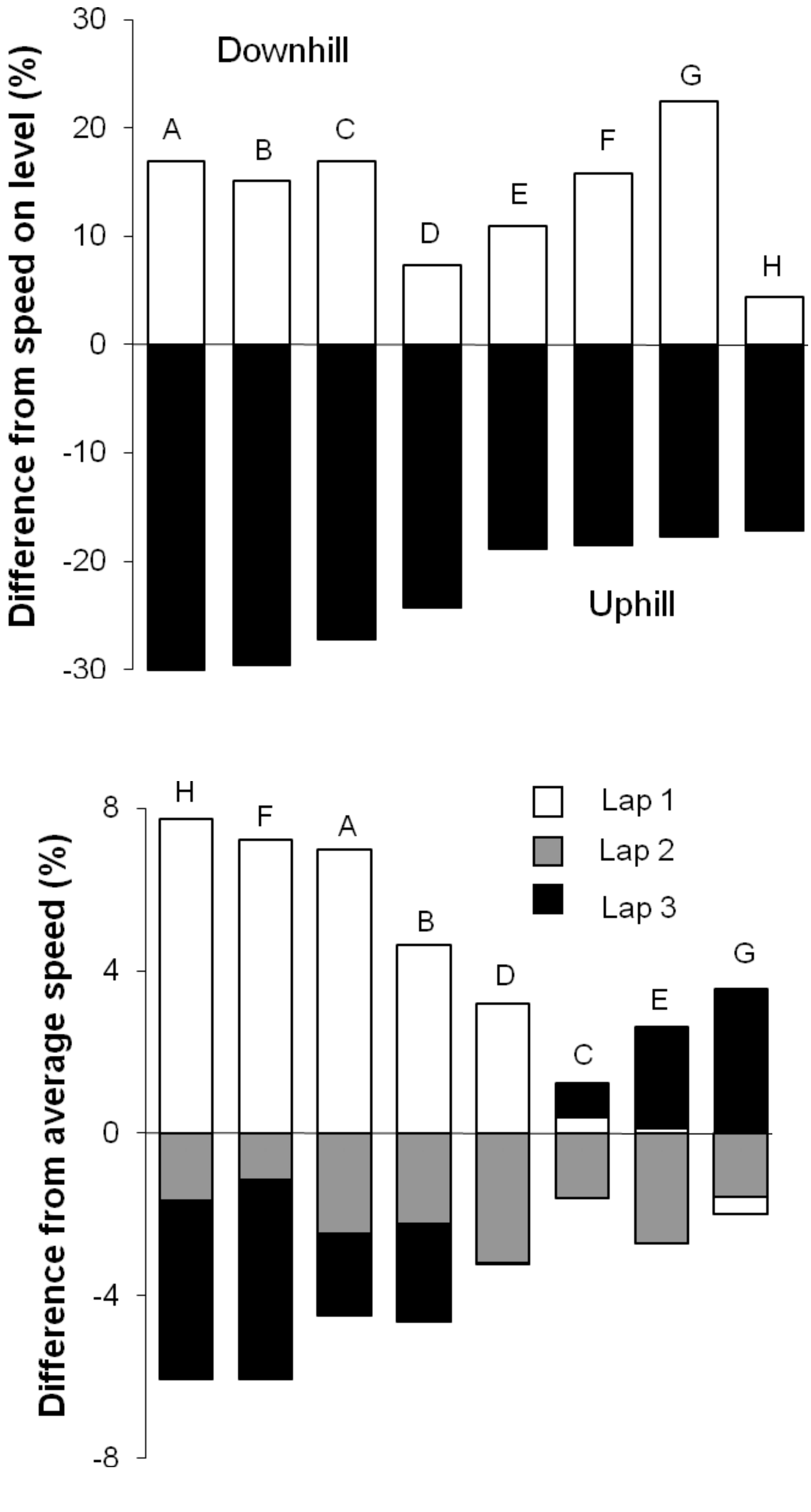

Figure 3: Individual pacing strategies showing relative differences in speeds across gradients (top panel) and laps (bottom panel). Columns and identifier numbers represent individual runners. NB: in bottom panel values for all laps are read from zero.