Spontaneous Pacing during Overground Hill Running

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Spontaneous Pacing during Overground Hill Running

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ABSTRACT

TOWNSHEND, A. D., C. J. WORRINGHAM, and I. B. STEWART. Spontaneous Pacing during Overground Hill Running. *Med. Sci. Sports Exerc.*, Vol. 42, No. 1, pp. 160–169, 2010. **Purpose**: To investigate speed regulation during overground running on undulating terrain. **Methods**: After an initial laboratory session to calculate physiological thresholds, eight experienced runners completed a spontaneously paced time trial over three laps of an outdoor course involving uphill, downhill, and level sections. A portable gas analyzer, global positioning system 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 s following an uphill and 23.6 ± 2.2 s following a downhill. Speed changes were primarily regulated by stride length, which was 20.5% shorter uphill and 16.2% longer downhill, whereas 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. Approximately 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 ($\dot{V}O_2$) 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, whereas 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 optimizing time on the level sections after hills offers the greatest potential to minimize overall time when running over undulating terrain. **Key Words:** GLOBAL POSITIONING SYSTEM, FIELD, GAIT, SPEED REGULATION, GRADIENT

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.

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 focused 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 misjudgments of pace carry high performance costs. Whereas the self-selected speed of walking in natural environments has been investigated extensively (6,9,14,16), several factors, including limitations of the available measurement technology, have hindered a comparable analysis of running.

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

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speeds were inversely associated with gradient (23,26) and have demonstrated that runners were unable to maintain a constant energy expenditure because of an inability to increase speed sufficiently on downhill gradients (26).

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 seemed to maintain a steady rate of energy expenditure across different grades, whereas relative effort, determined indirectly from heart rate (HR) using an HR–oxygen consumption regression, was found not to be related to gradient.

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 using a portable gas analyzer, an HR monitor, an accelerometer to measure stride length and frequency, and a global positioning system (GPS) receiver to provide continuous velocity and location data.

METHODS

Participants. Eight healthy male distance runners (age = 28.1 ± 9 yr, 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 10,000-m race in less than 40 min in the previous 12 months (or a longer distance at an equivalent pace) and were free from any musculoskeletal 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.

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 14 $\text{km}\cdot\text{h}^{-1}$. The treadmill speed was increased by 0.3 $\text{km}\cdot\text{h}^{-1}\cdot\text{min}^{-1}$, whereas the grade was held constant at 1% to simulate the oxygen consumption of outdoor running (17). Respiratory gas exchange data were collected breath by breath and averaged for every 15-s period using a portable gas analyzer (details in apparatus section), which was calibrated beforehand according to the manufacturer's instructions. HR was measured continuously using a single-lead ECG monitor (Alive Technologies Pty Ltd, Australia). Achievement of at least two of the following variables was taken to indicate that a participant had performed a maximal test: HR ± 10 bpm of age-predicted maximum, respiratory exchange ratio >1.10, and an increase in oxygen consumption of less than 150 $\text{mL}\cdot\text{min}^{-1}$ with an increase in workload. Maximum oxygen consumption ($\dot{V}O_{2\text{max}}$) was determined by averaging the four highest successive 15-s values. If a plateau in oxygen uptake was not clearly evident, a supramaximal test was performed after an adequate rest period to confirm that the participant's highest $\dot{V}O_2$ had been attained. Maximal oxygen consumption ($\dot{V}O_{2\text{max}}$) was defined as the highest value achieved in either the laboratory or the field test. Ventilatory threshold was determined using the ventilatory equivalent method (3), and velocities at this threshold (vV_T) recorded from the treadmill speed.

Field test. Within 14 d of their laboratory trial, participants completed a field time trial consisting of three laps of a 3175-m circuit (Fig. 1). This was divided into four sections completed in the following order: level section (765 m), uphill (820 m), level (770 m), and downhill (820 m). (NB: The uphill/downhill portion of the course used the same section of road completed in opposite directions.) The initial level section used a compacted dirt road that was free of loose gravel, whereas the other sections consisted of bitumen roads and concrete footpaths. Each section was further divided into eight subsections 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.

At the end of the third lap, participants completed an additional level section of 380 m. This section reduced risks to the participant by finishing on a level section rather than on a downhill and minimized the effects of any finishing sprint—because 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: 0.02 $\text{m}\cdot\text{s}^{-1}$ or 0.55%) and did not alter the finishing order of the participants. This section was not included in subsequent analyses.

On laps 2 and 3 participants were provided with a drink stop at the midpoint of the second level section (following the downhill). As the gas analyzer had to be partly unclipped from the headgear to enable drinking, participants were held stationary for a set 30-s period while this took place. Accordingly, data for that subsection (all variables) and the following subsection (HR and $\dot{V}O_2$ only) have been replaced with estimates through subject-by-subject linear

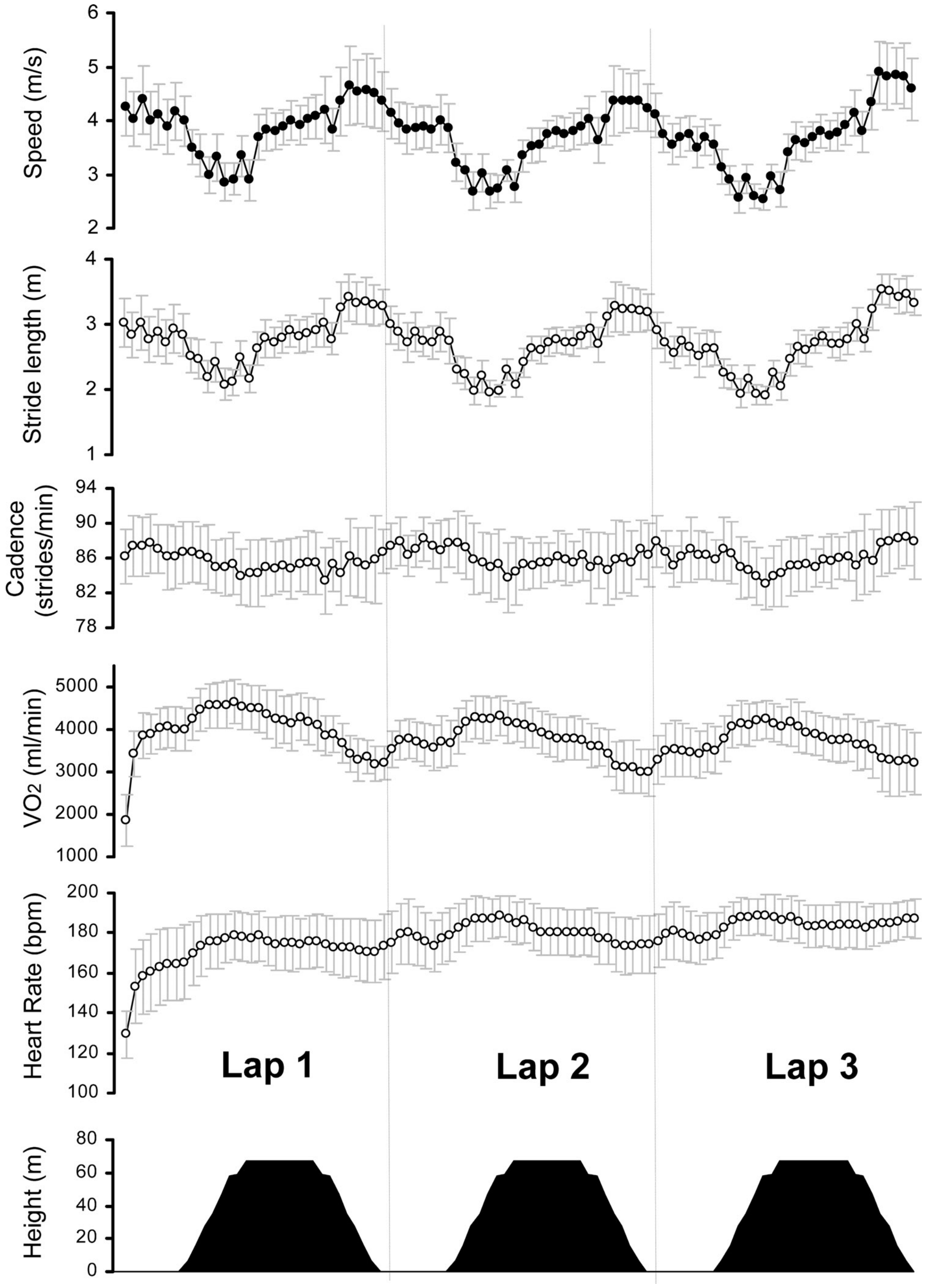

FIGURE 1—Changes in speed, kinematics and physiological variables across three laps of an undulating course. Individual *graphs* represent (*top to bottom*): speed, stride length, cadence, oxygen consumption, HR, and course profile.

interpolation from values for the adjacent sections. This correction applied to either one or two of the 96 subsections only and allowed a fully balanced statistical analysis to be performed.

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 h. All trials were held between 6 and 7 a.m. 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 minimize 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.

Apparatus. For the field trials, runners were equipped with a GPS receiver, activity monitor, and portable metabolic analyzer (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) that was attached to the arm with a Velcro strap, whereas the metabolic analyzer transmitted and logged information to its own internal memory for subsequent analysis.

GPS. Each runner wore a cap containing a lightweight, nondifferential 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).

Activity monitor. An activity monitor (Alive Technologies), containing a single-lead ECG recorder and a triaxial accelerometer, was attached to the participant's dorsal lumbar spine with double-sided tape. ECG data were collected at 300 Hz and R–R intervals were used to determine HR. Electrodes were placed as for a standard limb lead II position. The triaxial piezoelectric accelerometer (rated to ±2.4*g*) concurrently logged body accelerations in the sagittal, frontal, and transverse planes. Acceleration data were sampled at 75 Hz and converted to earth acceleration units (*g*) on the basis of 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 on the basis of speed and stride frequency.

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 during 15-s intervals.

Data reduction and analysis. Data from the different systems (smart phone and gas analyzer) were synchronized and converted to a common file format using spreadsheets (Excel 2003; Microsoft, Redmond, WA) and a customized program. For each of the five dependent variables (speed, oxygen uptake, HR, stride frequency, and stride length), mean values were calculated for each of the 96 subsections separately for each runner. These values were then used for subsequent statistical analyses.

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

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

RESULTS

Laboratory Test

Maximal oxygen consumption ($\dot{V}O_{2\max}$) was defined as the highest value achieved in either the laboratory or the field test. These tests yielded the following physiological measures: $\dot{V}O_{2\max}$ = 69.8 ± 5.4 mL·kg^{-1}·min^{-1}, velocity at $\dot{V}O_{2\max}$ (v$\dot{V}O_{2\max}$) = 4.87 ± 0.40 m·s^{-1} (17.5 ± 1.4 km·h^{-1}), ventilatory threshold (V_T) = 88.2 ± 6.4% $\dot{V}O_{2\max}$, and speed at ventilatory threshold (vV_T) = 4.40 ± 0.21 m·s^{-1} (15.8 ± 0.8 km·h^{-1}).

Field Test

The results are divided into three parts. Firstly, 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.

Speed. Speeds varied significantly between both laps and gradients. The lap effect was confined to lap 1, which was run faster than lap 2 or 3 (55- and 51-s difference, respectively; $P < 0.05$), whereas 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

TABLE 1. Kinematic and physiological variables across sections and laps.

Section/Lap	Speed (m·s^{-1})	Stride Frequency (Strides per minute)	Stride Length (m)	$\dot{V}O_2$ (L·min^{-1})	$\dot{V}O_2$ (% of V_T)
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.
* Significantly different compared with level, $P < 0.05$.
† Significantly different compared with lap 1, $P < 0.05$.
$\dot{V}O_2$, oxygen consumption; V_T, individual ventilatory threshold.

compared with the level sections ($P < 0.001$). Table 1 illustrates mean values as a function of lap and gradient.

Whereas speed varied across the eight subsections 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 stabilized rapidly after a downhill, reaching an asymptote after just one subsection, whereas this did not occur until the fourth subsection 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 that differed significantly ($P < 0.05$). Following an uphill, each of the first three subsections 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.

Stride frequency. Stride frequency was remarkably stable across all sections of the course (Table 1). None of the three independent variables (lap, gradient, and subsection) reached significance as main effects ($P = 0.52$, $P = 0.08$, and $P = 0.08$, respectively). There was, however, a significant interaction between gradient and subsection ($P < 0.001$). Runners decreased their cadence from level to uphill, an effect that became significant only after the first two uphill subsections (uphill subsections 1 and 2 = 86.9 strides per minute, subsections 3–8 = 84.7 strides per minute, $P < 0.001$, 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 per minute, subsections 5–8 = 85.7 strides per minute, $P < 0.05$).

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 that on lap 2 or 3 ($P < 0.05$), whereas that on laps 2 and 3 did not differ from one another ($P = 1.0$). Although 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 ($P < 0.05$).

Oxygen uptake ($\dot{V}O_2$). As with speed, $\dot{V}O_2$ 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 ($P < 0.05$), whereas there was no difference between oxygen consumption on laps 2 and 3 ($P = 0.93$). $\dot{V}O_2$ was significantly higher uphill and lower downhill compared with level sections ($P < 0.05$). Relative to individual thresholds, these values were below V_T for both downhill and level sections. On the uphill sections, runners slightly exceeded V_T on lap 1 (105.2 ± 13.1%) but reduced speeds on subsequent laps such that $\dot{V}O_2$ was in line with individual thresholds on subsequent uphill sections (lap 2 = 97.7 ± 11.5%, lap 3 = 98 ± 9.6%).

HR. All three independent variables (lap, gradient, and section) and their interactions had a significant effect on HR. Values were significantly lower on lap 1 (170 ± 17 bpm) than on lap 2 (180 ± 12 bpm) and lap 3 (184 ± 11 bpm; $P < 0.\ 05$) as the subject started from rest. Because HR increases only relatively slowly on starting to run, the

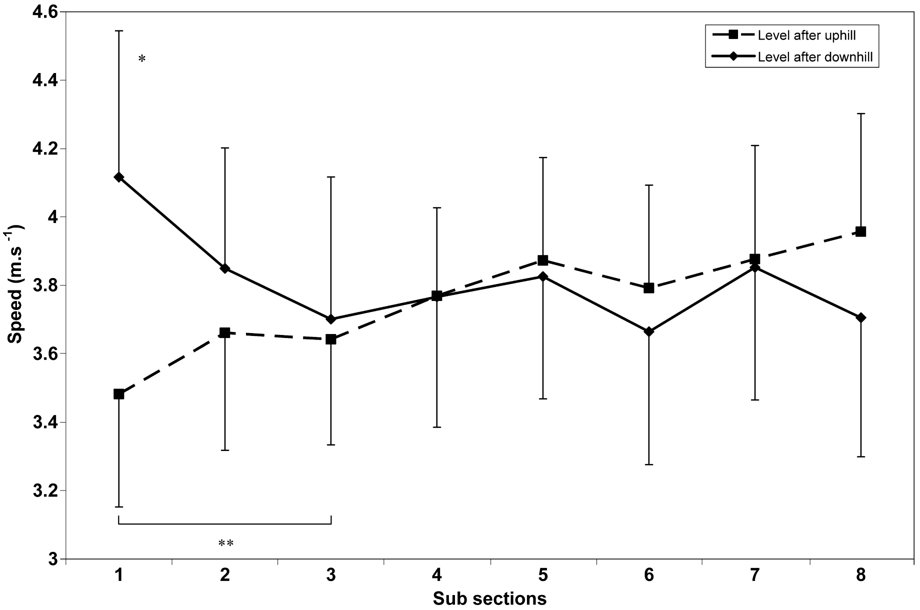

FIGURE 2—Speed changes on level sections following uphill or downhill running. *Significantly different from all other level subsections after downhill, $P < 0.05$. **Subsections 1–3 after uphill significantly different from subsections 5 to 8, $P < 0.05$.

TABLE 2. Summary of regression weightings for group and individual subjects.

Variable	β	B	Intercept	Adjusted R^2	SEE
Group					
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					
Modified gradient	−0.765	−9.743	2.340	0.651*	0.411
Lap	−0.134	−0.114			
$\dot{V}O_{2max}$	0.228	0.024			
Modified gradient	−0.765	−9.743	2.003	0.656*	0.408
Lap	−0.134	−0.114			
V_T	0.239	0.032			
Modified gradient	−0.765	−9.743	0.649	0.733*	0.360
Lap	−0.134	−0.114			
$v\dot{V}O_{2max}$	0.365	0.684			
Modified gradient	−0.765	−9.743	−1.504	0.721*	0.368
Lap	−0.134	−0.114			
vV_T	0.349	1.247			

All individual variables are significant, $P < 0.001$.

* $P < 0.001$.

$\dot{V}O_{2max}$, maximal oxygen consumption; V_T, ventilatory threshold; $v\dot{V}O_{2max}$, speed at maximal oxygen consumption; vV_T, speed at ventilatory threshold.

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.

Prediction of Speed

We sought to characterize 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 subsection gradients on speed, using a geometric decay function to weight gradients of the current and seven preceding subsections as follows: modified gradient = $(0.5g_n + 0.25g_{n-1} + 0.125g_{n-2} + \cdots + 0.003906g_{n-7})$, where g = gradient and n = current subsection. As this modified gradient improved prediction and can be readily calculated for any course, it was used in the subsequent individual level regressions. Because individual regressions could not account for differences in pacing strategies, R^2 values were slightly lower than for group-level predictions (Table 2).

Individual Pacing Strategies

As stated in previous sections, mean speeds were fastest for lap 1, although there was no significant difference between laps 2 and 3 for the group (Table 1). Within the group, however, there were large interindividual differences in pacing strategies adopted across the three laps. Runners fell into two distinct groups. As seen in Figure 3 (right panel), four of the runners slowed monotonically across the three laps (lap 1 = 4.10 ± 0.34 $m \cdot s^{-1}$, lap 2 = 3.77 ± 0.33 $m \cdot s^{-1}$, lap 3 = 3.64 ± 0.28 $m \cdot s^{-1}$, $P < 0.0001$). Conversely, the other four runners significantly increased speeds from lap 2 to lap 3 (3.57 ± 0.36 vs 3.72 ± 0.34 $m \cdot s^{-1}$, $P < 0.05$). These apparently distinct strategies are discussed later.

Figure 3 (left panel) 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 optimization, 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 minimized fluctuations in their oxygen consumption across the

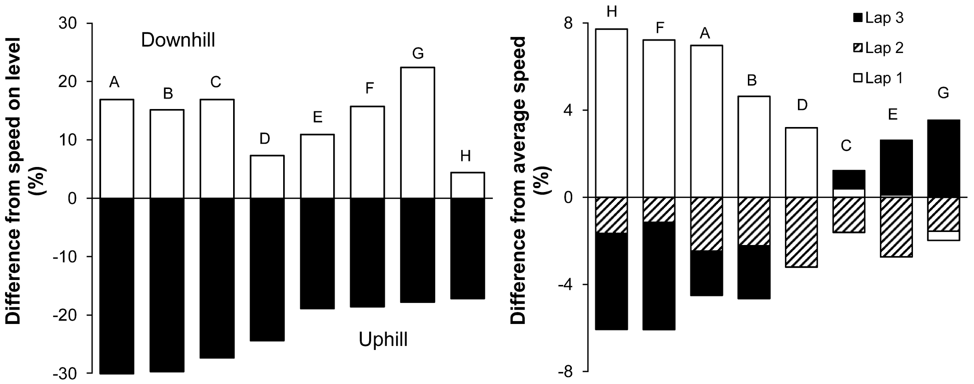

FIGURE 3—Individual pacing strategies showing relative differences in speeds across (*left panel*) gradients and (*right panel*) laps. *Columns* and *identifier letters* represent individual runners. In the *right panel*, values for all laps are read from 0.

gradients achieved this by varying their speed more (i.e., by running slower on uphills and faster on downhills).

DISCUSSION

Walking or running speed has long been considered a key variable either to 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. Although 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, most 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.

The current study extends this knowledge in several ways, firstly by characterizing the gradient–speed relationship in more detail than previous studies, secondly by showing how speed regulation on hills covaries 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. 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 $m \cdot s^{-1}$ for every 1% change in gradient (20), whereas in our study, this figure was substantially higher at 0.082 $m \cdot s^{-1}$. This substantially greater influence 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 $mL \cdot kg^{-1} \cdot min^{-1}$) and could therefore run approximately 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. Although the runners in the study by Mastroianni 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, whereas the runners in the study of Mastroianni et al's (20) had some more abrupt transitions (including one steep ascent of 90 m in between two downhill sections), which will have attenuated some of the speed changes.

A similar explanation may underlie the fact that, although Mastroianni 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 are 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 the conclusion of Mastroianni et al. (20) 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—although relatively short-lived—lags in speed changes at these transitions.

Modified gradient, transition effects, and lags. 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 before 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 (Fig. 2). Although Staab et al. (26) have 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 820 m (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 s. As suggested by Staab et al. (26), this lag in returning to the prior level of speed is likely to be a result of runners being forced to recover from the high anaerobic cost of uphill running.

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 s or approximately 95 m) for these runners. Although 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.

O_2 not a limitation downhill. The ventilatory threshold (V_T) 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 to prevent exceeding this threshold. Runners in this study seemed to regulate their efforts in line with their threshold on uphill sections. After a faster uphill on lap 1 where $\dot{V}O_2$ averaged ≈ 105% of V_T, runners subsequently reduced speeds such that $\dot{V}O_2$ was just under V_T on the uphill sections of laps 2 and 3.

Although 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 with a 23% reduction uphill. Despite this increase, downhill speeds were not limited by physiological cost because oxygen consumption was substantially less than V_T (Table 1). This suggests that other factors limited runners' downhill speeds, confirming findings from earlier laboratory studies. Minetti et al. (24) have previously shown that speed estimates on the basis of energy cost compare favorably 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 HR (11,29). In this study, it was evident that speeds on downhill sections were not limited by the capacity to use oxygen.

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 V_T) showing that whereas 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. 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 an accelerometer to detect steps now allows the collection and analysis of data during longer periods and in more natural settings (19). Using this method, we found that the mean stride frequency was not significantly different among 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.

Despite this small contribution from stride frequency to speed changes in these sections, speed was still primarily regulated by stride length. Whereas improving speed on downhill sections offers a potential opportunity for improving performance in hilly races, other factors may limit the full utilization of these strategies. It has previously been suggested that individuals with musculoskeletal injuries may choose to forsake minimizing energy cost in order to select gait parameters, which maximize shock attenuation and 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 $m{\cdot}s^{-1}$ on a -9% grade compared with the level, substantially increasing the likelihood of overuse injury (13). Shock attenuation has been shown to be altered primarily by 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. As shown in Figure 3 (right panel), runners in our study fell into two clear groups, with half slowing continuously across the three laps, whereas the other half were able to accelerate from lap 2 to lap 3. A "positive split" pacing strategy (first half faster than the second half) has been shown to be effective in events lasting less than 2 min where the accompanying anaerobiosis can be tolerated for the duration of the event; however, there is no clear consensus as to the optimal strategy for more prolonged durations (1).

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

Conversely, from the few studies of running, there is evidence that variable pacing may be more optimal. Billat et al. (4) have demonstrated that runners constrained to a constant pace (on the level) incur a higher physiological cost (↑ $\dot{V}O_2$, 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 5-km race 3%–5% faster than the mean speed resulted in faster times during a treadmill trial when compared with even pacing (12). Although all of these studies took place on level ground, many athletes engage in road races that 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 so as to optimize performance.

Pacing strategies—gradient effects. Our results show large individual variations in pacing with respect to gradient (Fig. 3, left panel). 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.

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 (minimizing lap-to-lap energy expenditure fluctuations by keeping average speed consistent) did not necessarily do so over hills (minimizing uphill vs downhill energy expenditure fluctuations by *increasing* speed differences on these sections; Fig. 3, right and left panels). If confirmed in larger studies, this would suggest that different factors can influence pacing at the macro (whole distance) and micro (component section) levels.

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 hill. This study has shown that runners tended to limit uphill running to a speed that resulted in oxygen consumption values in line with their ventilatory threshold. Conversely, there was a large potential to improve time on downhill sections because runners were not limited by physiological cost. Despite this, runners may be unable or unwilling to greatly increase speeds on these sections because of the 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 s.

Conversely, although speeds were elevated for a short time on levels after a downhill, the $\dot{V}O_2$ on these sections was still well below their ventilatory threshold. One possible suggestion for minimizing time 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 $\dot{V}O_2$ just below their ventilatory threshold.

SUMMARY

This study is the first to characterize how runners regulate their speeds during a time trial on a hilly course through the recording 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 s. This research has suggested that these level sections following hills represent the most likely source of potential improvements for runners wishing to minimize 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 on hills also warrant further investigation, not only to enhance performance but also to understand, more broadly, the optimization principles that account for the spontaneous choice of running speed in humans.

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