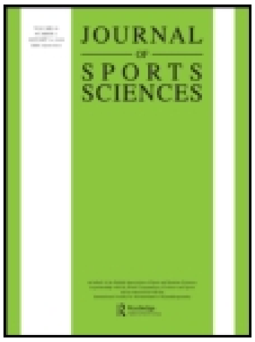

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G. Atkinson , O. Peacock & L. Passfield

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Variable versus constant power strategies during cycling time-trials: Prediction of time savings using an up-to-date mathematical model

G. ATKINSON[1], O. PEACOCK[2], & L. PASSFIELD[3]

[1]*Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool,* [2]*School of Sport and Exercise Sciences, Loughborough University, Loughborough, and* [3]*School of Applied Sciences, University of Glamorgan, Pontypridd, UK*

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Abstract

Swain (1997) employed the mathematical model of Di Prampero *et al.* (1979) to predict that, for cycling time-trials, the optimal pacing strategy is to vary power *in parallel* with the changes experienced in gradient and wind speed. We used a more up-to-date mathematical model with validated coefficients (Martin *et al.*, 1998) to quantify the time savings that would result from such optimization of pacing strategy. A hypothetical cyclist (mass = 70 kg) and bicycle (mass = 10 kg) were studied under varying hypothetical wind velocities (-10 to 10 $m \cdot s^{-1}$), gradients (-10 to 10%), and pacing strategies. Mean rider power outputs of 164, 289, and 394 W were chosen to mirror baseline performances studied previously. The three race scenarios were: (i) a 10-km time-trial with alternating 1-km sections of 10% and -10% gradient; (ii) a 40-km time-trial with alternating 5-km sections of 4.4 and -4.4 $m \cdot s^{-1}$ wind (Swain, 1997); and (iii) the 40-km time-trial delimited by Jeukendrup and Martin (2001). Varying a mean power of 289 W by $\pm$ 10% during Swain's (1997) hilly and windy courses resulted in time savings of 126 and 51 s, respectively. Time savings for most race scenarios were greater than those suggested by Swain (1997). For a mean power of 289 W over the "standard" 40-km time-trial, a time saving of 26 s was observed with a power variability of 10%. The largest time savings were found for the hypothetical riders with the lowest mean power output who could vary power to the greatest extent. Our findings confirm that time savings are possible in cycling time-trials if the rider varies power in parallel with hill gradient and wind direction. With a more recent mathematical model, we found slightly greater time savings than those reported by Swain (1997). These time savings compared favourably with the predicted benefits of interventions such as altitude training or ingestion of carbohydrate-electrolyte drinks. Nevertheless, the extent to which such power output variations can be tolerated by a cyclist during a time-trial is still unclear.

Keywords: *Mathematical model, pacing strategy, power output, cycling velocity*

Introduction

Various human and environmental factors have been found to influence cycling power output and speed (Atkinson, 2003). Of these factors, the rider's self-selected pacing strategy has been relatively under-researched. This lack of research is surprising, since an appropriate distribution of energetic resources has been considered vital to athletic performance (Foster, Schrager, Snyder, & Thompson, 1994; Foster *et al.*, 2003). An appropriate pacing strategy, which has been defined by Atkinson and Brunskill (2000, p. 1450) as "the within-race distribution of work-rate (power output)", is important for the many athletic events in which athletes are required to complete a given distance in the shortest possible time (Foster *et al.*, 2003). In cycling time-trials, the performance of the rider is less clouded by factors such as team tactics, social facilitation, and the "drafting" of other riders, since each rider races alone. Therefore, the selection of the best pacing strategy for cycling time-trials is especially relevant.

Road cycling time-trials in World Championships, Olympic Games, and the major "Tours" are typically of a long duration (20–60 km). Since the contribution of the standing start to overall time is negligible for these events, the adoption of an "even" pace (constant power) has been advised from a physiological standpoint (Palmer, Hawley, Dennis, & Noakes, 1994). This advice is especially relevant for cyclists who tend to select too high a power early in the time-trial (Atkinson & Brunskill, 2000). Identification of the optimal pacing strategy for road time-trials, is complicated by the fact that gradient and wind direction almost always vary

Correspondence: G. Atkinson, Research Institute for Sport and Exercise Sciences, Liverpool John moores University, 15–21 Webster Street, Liverpool L3 2ET, UK. E-mail: g.atkinson@ljmu.ac.uk

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within a race. Even if the course is completely flat, it would be very unlikely for there to be either no wind at all or a consistent 90/180° side wind during a time-trial. In only these conditions would there be no variation in the major retarding forces on bicycle speed.

Variability in gradient and wind direction alters the relationship between rider power output and cycling speed (Atkinson *et al.*, 2003). Generally, time-trials with variations in terrain and wind take more time to complete than races held on flat courses and in calm conditions because the more time spent on the slower sections is not compensated for on the faster sections when using a constant power strategy (Martin, Milliken, Cobb, McFadden, & Coggan, 1998; White, 1994). This prediction is valid, even if there is no net change in wind velocity or gradient. Yet, there has been little evaluation of how different pacing strategies might ameliorate the slower performance times during time-trials with variable conditions of hills and wind.

Swain (1997) used the equation of motion of a cyclist presented by Di Prampero, Cortili, Mognoni, and Saibene (1979) to model performance on undulating and windy time-trial courses. Faster times were predicted when a cyclist increased power in slower uphill or headwind sections even if this higher power was compensated for by reducing power in faster downhill or tailwind sections so that total work done was unchanged. A more recent and accurate model of cycling performance than that of Di Prampero *et al.* (1979) has been proposed by Martin *et al.* (1998). These researchers were the first to validate a mathematical model against actual power measured during outdoor road cycling. A modern bicycle was ridden by a cyclist, who adopted a contemporary aerodynamic position. Data from modern racing tyres were incorporated into the model, which also allowed the effects of bicycle "yaw angle" (the effective angle of cycling direction relative to wind direction) to be examined. The model was later used by Jeukendrup and Martin (2001) to predict the effects of various determinants of cycling performance. Although Jeukendrup and Martin (2001) incorporated variable conditions of hills and wind direction into the "typical" 40-km time-trial course that they examined, they did not consider the implications of different pacing strategies on performance.

Like Swain (1997), we aimed to quantify the possible time savings that would result from a variable power pacing strategy, but we selected the more up-to-date and empirically validated mathematical model of cycling speed (Martin *et al.*, 1998) for our calculations. We also aimed to appraise the practical impact of such time savings through comparisons with those associated with other typical performance-enhancing interventions (Jeukendrup & Martin, 2001).

Methods

The mathematical model

Cycling speed was calculated using the mathematical model recently derived by Martin *et al.* (1998), which incorporates validated terms for the mechanical power generated by the cyclist and for all the external factors that impede the motion of the rider. These factors included aerodynamic drag, rolling resistance, wind conditions, wheel bearing friction, potential and kinetic energy, and mechanical efficiency (Martin *et al.*, 1998). The final expression of power delivery was:

$$
\begin{aligned}
\mathrm{P_{TOT}} = \\
&\{V_a^2 V_G \tfrac{1}{2}\, \rho(C_D A + F_W) && \text{– air resistance}\\
&+ V_G C_{RR} m_T g \cos\left[\tan^{-1}(G_R)\right] && \text{– rolling resistance}\\
&+ V_G(91 + 8.7V_G)10^{-3} && \text{– frictional losses in wheel bearings}\\
&+ V_G G_R m_T g \sin\left[\tan^{-1}(G_R)\right] && \text{– changes in potential energy}\\
&+ \tfrac{1}{2}(m_T + I/r^2)({V_{Gf}}^2 - {V_{Gi}}^2)/(t_i - t_f)\}/E_C && \text{– changes in kinetic energy}
\end{aligned}
$$

where V_a is air velocity tangent to the direction of travel of the cyclist and is dependent on both the ground speed of the bicycle and rider and wind velocity; V_G is the ground speed of the bicycle and rider; ρ is air density; C_D is the coefficient of drag; A is the frontal area of bicycle and rider; F_W is a factor associated with wheel rotation that equates to the incremental drag area of the spokes (C_DA); C_{RR} is the coefficient of rolling resistance (including tyre and ground surface characteristics); m_T is the combined mass of bicycle and rider; g is the acceleration due to gravity; G_R is the road surface gradient; $V_G\ (91 + 8.7V_G)10^{-3}$ accounts for wheel bearing friction; I is the moment of inertia of the wheels; r is the radius of the bike wheel; V_{Gi} is the initial ground speed; V_{Gf} is the final ground speed; t_i is the initial time; t_f is the final time; and E_C accounts for chain efficiency factors.

The above mathematical model was entered into a Microsoft Excel spreadsheet. To calculate a given cycling speed, power output was entered into the model as the target variable to achieve. The "solver" function (Frontline Systems, Incline Village, USA) in Excel was used to calculate the cycling velocity that corresponded to the stipulated power output. The solver function employs an iterative procedure to interpolate the value of ground speed that is related to the specified value for power.

Relationships between wind velocity, gradient, and cycling speed

The possible time savings using hypothetical riders and race scenarios were explored using exact data inputted into the above model. The various relationships between the model inputs of power, wind velocity, and gradient and the model output of cycling speed were also examined. Such relationships were described by Martin *et al.* (1998) using a hypothetical "average" participant who could sustain 255 W during a time-trial. For example, Martin *et al.* (1998) found that their model predicted that a 1% increase in gradient led to an approximate 11% decrease in cycling speed. In the present study, a range of hypothetical riders and power outputs (100 – 600 W) were examined with respect to cycling speed and either wind velocity (-10 to $10\ \text{m} \cdot \text{s}^{-1}$) or gradient ($-6$ to 6%). We delimited the relatively high upper hypothetical power output of 600 W, since it is possible for cyclists to maintain such a power output for short periods of time, such as when travelling uphill. Here, we were interested in whether the use of the above rather complicated model would lead to simpler relationships between terms so that a coach could estimate the effects of varying power in different race conditions.

Hypothetical rider characteristics

A hypothetical cyclist (mass = 70 kg) and bicycle (mass = 10 kg) with a drag area of $0.258\ \text{m}^2$ (Martin *et al.*, 1998) were studied in three main race scenarios. Mean power outputs of 164, 289, and 394 W were chosen to mirror the baseline performance times proposed by Jeukendrup and Martin (2001). These power outputs were deemed typical of a novice cyclist ($\dot{V}O_{2max} = 48\ \text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), a well-trained cyclist ($\dot{V}O_{2max} = 66\ \text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), and an elite road cyclist ($\dot{V}O_{2max} = 80\ \text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), respectively (Jeukendrup & Martin, 2001). Furthermore, the mean power of 289 W was equivalent to the $4\ \text{l} \cdot \text{min}^{-1}$ category of rider studied by Swain (1997), and those of 164 and 394 W were similar to the 3 and $5\ \text{l} \cdot \text{min}^{-1}$ rider categories of Swain (1997).

Race scenarios

For each segment of a particular time-trial course, power output, hill gradient, and wind velocity were entered into the model as independent variables. This enabled calculation of bicycle speed, from which time to complete a given segment (and therefore overall course time) could be calculated. The model did not account for time taken to accelerate the bike at the beginning of each time-trial, or for the time taken to change speed between segments of the hypothetical courses. These times are negligible relative to the overall time taken to complete a comparatively long time-trial (Swain, 1997).

The race conditions examined by Swain (1997) and Jeukendrup and Martin (2001) were modelled using the results of Martin *et al.* (1998). The initial course (Course 1) examined by Swain (1997) was a 10-km time-trial with alternating 1-km segments of uphill and downhill. For each trial, gradient was alternated by 0, 5, or 10%, while net elevation remained constant. The second course (Course 2) considered by Swain (1997) was a 40-km time-trial with alternating 5-km segments of headwind and tailwind. Wind velocities were set at 0, 2.2, 4.4, and $6.6\ \text{m} \cdot \text{s}^{-1}$ both for tailwinds and headwinds so that there was no net change in wind velocity. The final race condition (Course 3) was the "standard" 40-km time-trial delimited by Jeukendrup and Martin (2001). The hypothetical cyclist travelled 5 km up a 1% grade into a $2\ \text{m} \cdot \text{s}^{-1}$ headwind, 5 km down a 1% grade into a $2\ \text{m} \cdot \text{s}^{-1}$ headwind, 5 km up a 1% grade with a $2\ \text{m} \cdot \text{s}^{-1}$ tailwind, 5 km down a 1% grade with a $2\ \text{m} \cdot \text{s}^{-1}$ tailwind, 10 km along a flat section into a $2\ \text{m} \cdot \text{s}^{-1}$ headwind, and 10 km along a flat section with a $2\ \text{m} \cdot \text{s}^{-1}$ tailwind (Figure 1). This combination of varied gradient and wind velocity resulted in no net change in either variable across the trial.

Results

Approximate relationships between wind velocity, gradient, and cycling speed

Following application of the mathematical model, the generalized impact of tailwinds and headwinds of -10 to $10\ \text{m} \cdot \text{s}^{-1}$ on the cyclist is illustrated in Figure 2a. The linear relationship between wind velocity and cycling speed was found to be strong ($r^2 > 0.99$) across the range of power outputs and

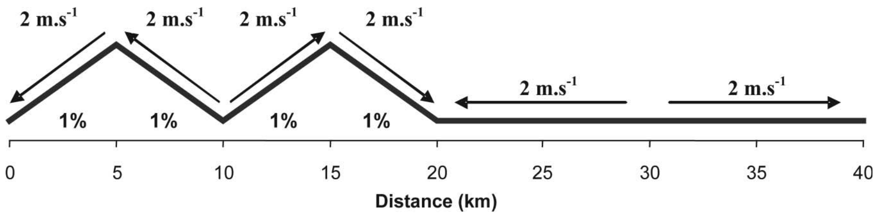


Figure 1. Race conditions for the "standard" 40-km time-trial delimited by Jeukendrup and Martin (2001). The hypothetical rider travels from left to right. The black arrows indicate wind direction.

wind velocities studied. The slopes of the fitted least squares regression lines relating wind velocity to cycling speed were found to be -0.58 to -0.64 for power outputs of 100–600 W. The model was also used to describe the general effects of downhill and uphill gradients of -6 to 6%, across the same range of power outputs (Figure 2b). Similar strong linear relationships ($r^2 > 0.99$) were observed between gradient and cycling speed for power outputs >100 W. For the power output 100 W, the relationship between gradient and cycling speed deviated more from a linear model ($r^2 = 0.97$). It was apparent that cycling speeds were slightly higher than those predicted by a linear model when travelling up steep gradients (6%) at a power output of 100 W. The slope of the least squares regression lines relating gradient to cycling speed were found to be -1.5 to -1.1 for power outputs of 100–600 W. It is stressed that these general relationships were examined to appraise their usefulness for estimating the effects of gradient and wind velocity. The predictions below are not based on these relationships but on the direct application of the mathematical model.

Courses 1 and 2

Under the same conditions that were modelled by Swain (1997), Figure 3 shows the times for completion of course 1 (10 km) and course 2 (40 km), where gradient (-15 to 15%) and wind velocity (-6.6 to 6.6 $m \cdot s^{-1}$) were varied for a hypothetical cyclist riding at 289 W. When power was varied from 0 to 15%, while gradient or wind velocity were kept constant, finish times increased. For example, time to complete Course 2 was 3448 s when power remained constant and 3468 s when power was varied by 15% (Figure 3b). Similar, albeit smaller differences in performance times were found for course 1 (Figure 3a). Therefore, a constant-paced time-trial was superior when gradient and wind conditions were constant.

By referring to the left-hand column (power variability of 0%) of each of the separate groups of columns in Figure 3, one can see that variation in gradient and wind led to longer finish times in general. For example, time to complete course 1 when gradient varied by 10% was 817 s longer than the same time-trial but over a flat course with no wind (Figure 3a). Time to completion was reduced as power variations increased from 0 to 15% and wind velocity or gradient increased. When power was varied by as little as 5% with a variable wind velocity of -4.4 to 4.4 $m \cdot s^{-1}$, a time saving of 30 s was achieved compared with a constant power of 289 W (Figure 3b).

Figure 4 illustrates the time savings for the three cyclists with different abilities (mean power of 164, 289, and 394 W, respectively) and when power was varied by $\pm 10\%$ over courses 1 and 2, respectively. Varying a mean power of 289 W by $\pm 10\%$ resulted in time savings of 126 s for the hilly course 1 (Figure 4a) and 51 s for the windy course 2 (Figure 4b). It was also apparent that as cycling ability increased, the potential time savings decreased.

Course 3

Jeukendrup and Martin (2001) presented a "standard" 40-km time-trial course split into 5- or 10-km sections of varying gradient (-1 to 1%) and wind velocity (-2 to 2 $m \cdot s^{-1}$). For the same conditions that were modelled by Jeukendrup and Martin (2001), the time to complete their 40-km time trial at a mean power of 289 W was 1501, 1486, 1478 s, and 1470 s when power was varied by 0, ± 5, ± 10, and $\pm 15\%$, respectively, using the most effective strategy for power variability (i.e. increasing power on hills and into the 10-km headwind section, and vice versa). Therefore, when pacing strategy changed from a constant power to a $\pm 15\%$ variable power, time to complete the "standard" course decreased. Greater time savings were predicted for lower mean power outputs (Figure 5).

Discussion

The main findings of this study, which employed a recently validated mathematical model (Martin *et al.*, 1998), are that time savings can be obtained when power output is varied in parallel with variable conditions of hills and wind. It was also found that these time savings are practically significant and

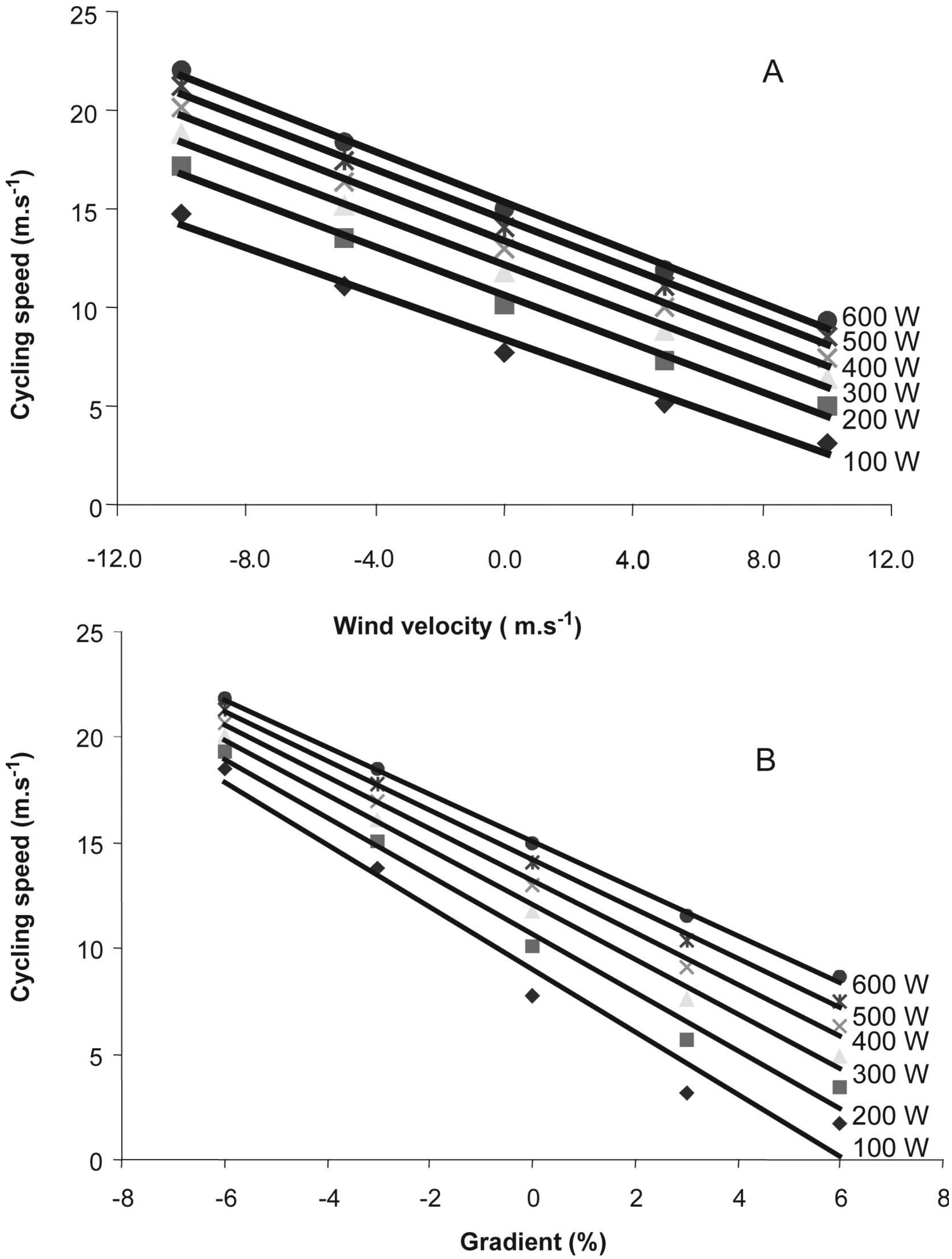
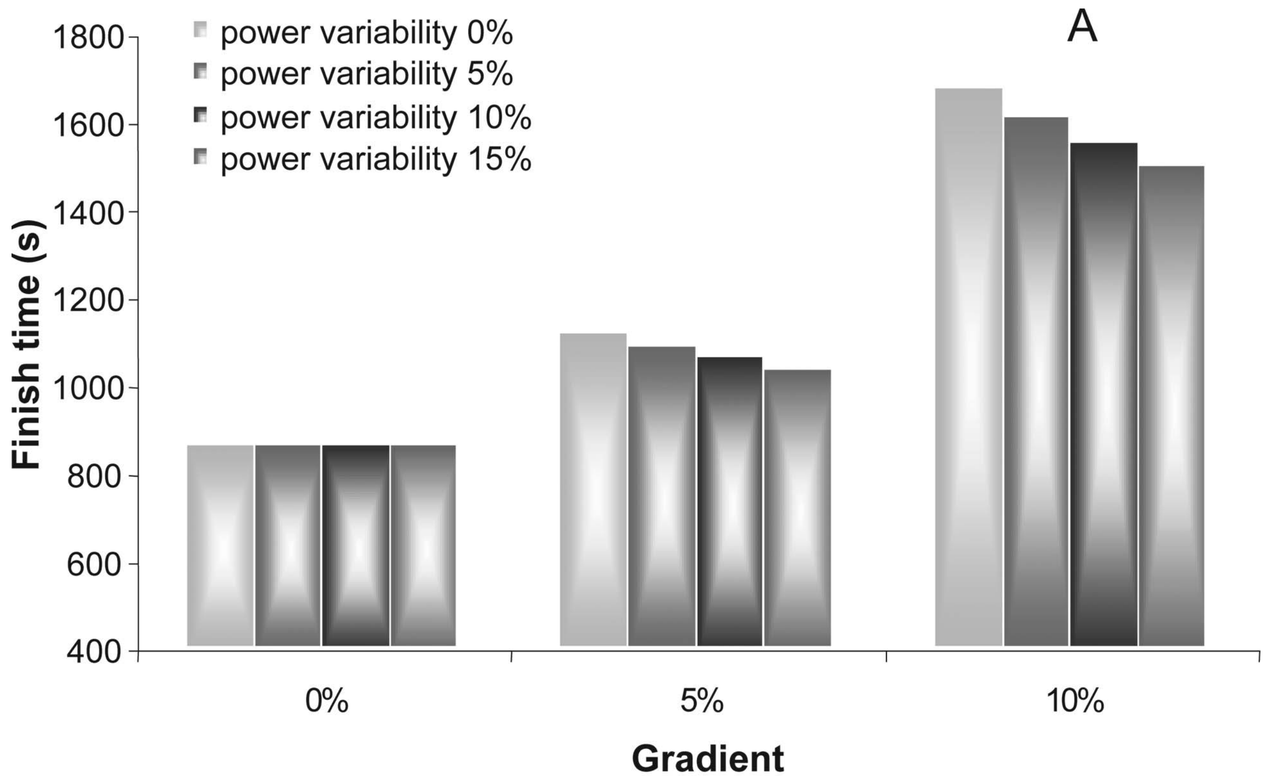


Figure 2. (A) Wind velocity (-10 to $10\ m \cdot s^{-1}$) effects on cycling speed for a range of power outputs (100–600 W) calculated using the mathematical model proposed by Martin *et al.* (1998). (B) The predicted effects of gradient (-6 to 6%) on cycling speed for a range of power outputs (100 – 600 W).

could be greater than with some more expensive or time-consuming interventions designed to improve time-trial performance.

The mathematical model developed by Martin *et al.* (1998) was used to describe the general effects of different wind velocities and road gradients for a hypothetical cyclist who could sustain 255 W during a time-trial. The present study extended this research to consider a range of theoretical power outputs (100 – 600 W). The linear relationship between wind velocity and cycling speed was strong ($r^2 > 0.99$) and with a similar regression slope across the range of different power outputs and wind velocities studied. This finding suggests that the prediction of Martin



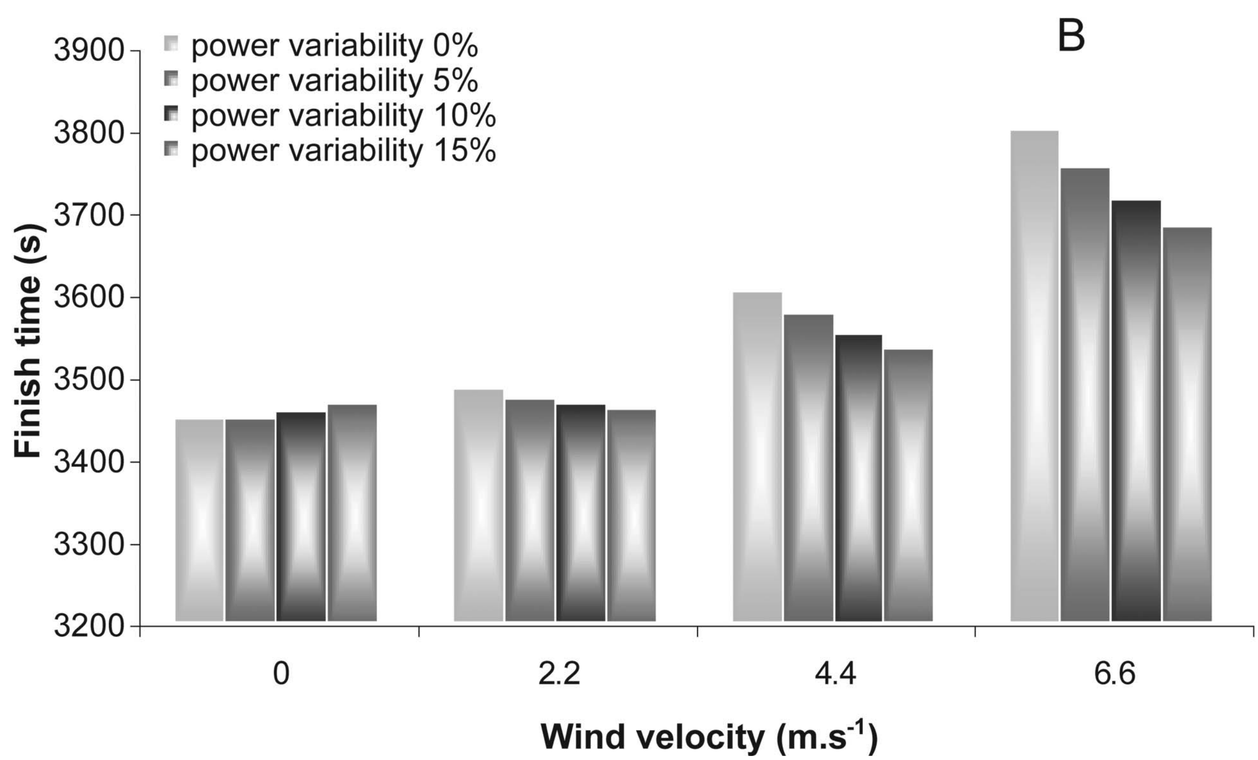


Figure 3. Times for completion of Swain's (1997) 10-km time-trial at 289 W calculated using the equation of Martin *et al.* (1998), and when gradient and power are varied (A) and when wind velocity and power are varied (B). Bars from left to right represent power variability of 0%, 5%, 10%, and 15%, respectively.

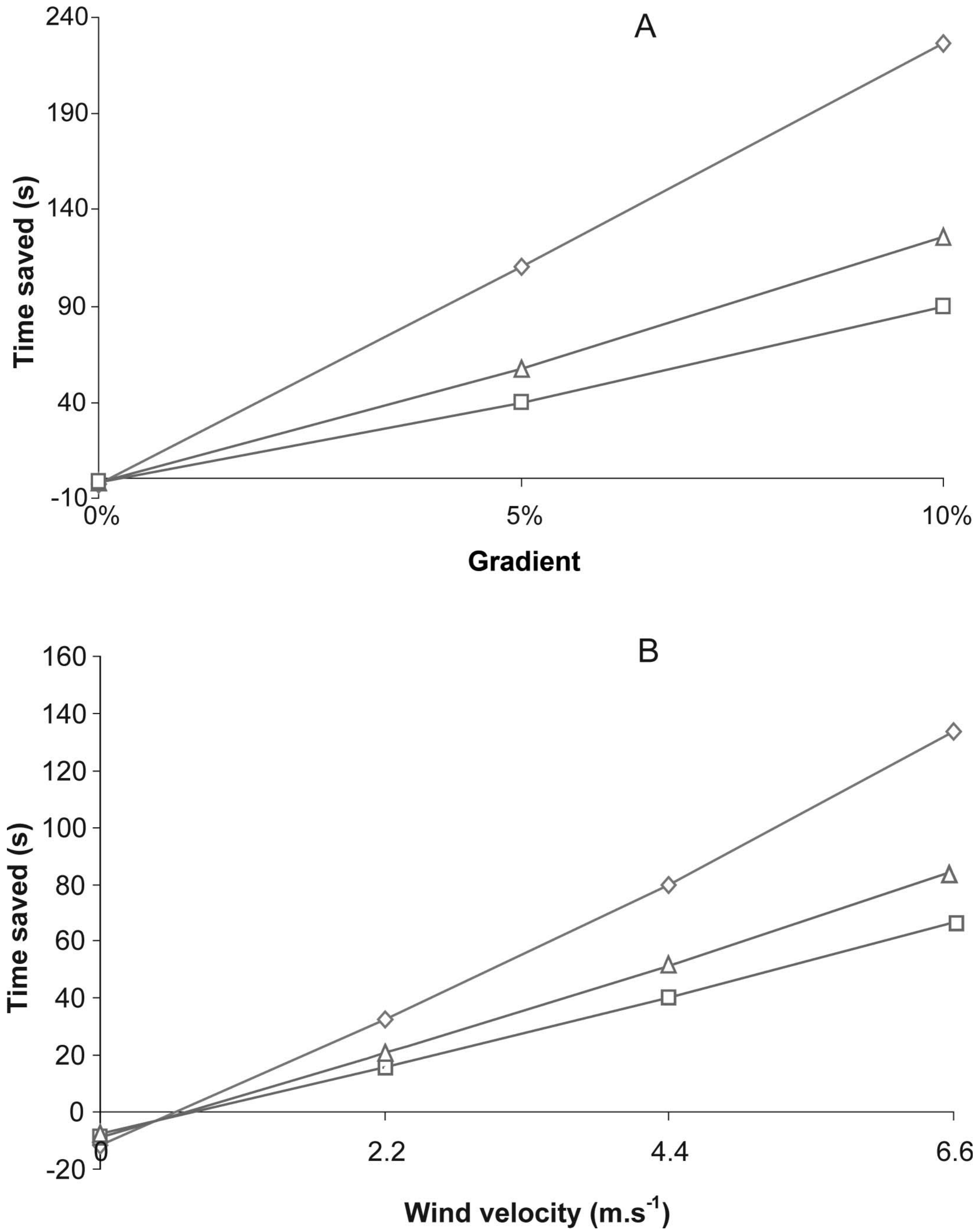


Figure 4. Predicted time savings for the 10-km time-trial modelled by Swain (1997) calculated using the equation of Martin *et al.* (1998), when power was varied by 10% for cyclists of three abilities (◇, 164 W; Δ, 289 W; □, 394 W) and when gradient varied (A) and when wind velocity was varied (B).

et al. (1998) that wind influences cycling speed by approximately two-thirds of a given wind velocity is acceptably consistent across a larger range of rider power outputs. Similar strong linear relationships ($r^2 > 0.99$) with equal regression slopes were observed between hill gradient and cycling speed for power outputs > 200 W, which corroborates the claim by Martin *et al.* (1998) that, for every 1% change in road gradient, cycling speed is affected by approximately 11%. Nevertheless, we found that the relationship between hill gradient and cycling speed was not linear for power outputs < 200 W. A combination of low power outputs (164 W) and steep gradients (5–10%) generated marginally higher cycling speeds than those predicted by a linear model. Despite this non-linearity in quite extreme and uncommon circumstances of very low power and very steep gradient, the original simplified guidelines provided by Martin *et al.* (1998) might still be applicable to coaches and athletes in

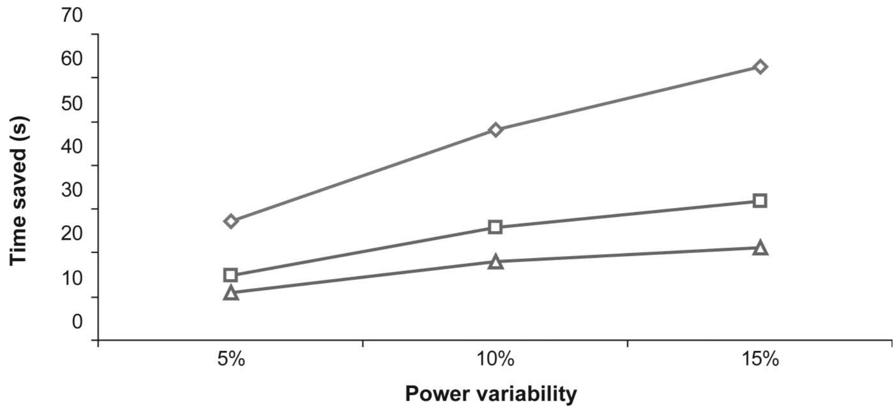


Figure 5. Time savings for the "standard" 40-km time-trial delimited by Jeukendrup and Martin (2001) using the equation of Martin *et al.* (1998), when power was varied by 5–10% for cyclists of three abilities (◇, 164 W; Δ, 289 W; □, 394 W).

providing a practical expectation of how environmental circumstances, aerodynamics, and body mass affect subsequent performance. Nevertheless, we stress that the correlation of power calculations using Martin and co-workers' (1998) model with actual power measurements using a bicycle-mounted device (e.g. SRM power meter) has yet to be fully examined at such extreme gradients and wind velocities.

We replicated the conditions modelled by Swain (1997) to confirm his three main findings that: (i) any variation in power and therefore speed on a course with no hills or wind adds to overall performance time; (ii) if a cyclist maintains a constant power output over a time-trial course that has variable conditions of hills and wind, then finish times will be longer compared with a flat course with no variation in wind direction all other factors being equal; and (iii) if a cyclist alters power to compensate for the hilly and windy conditions, variations in speed are reduced and times to complete are shorter compared with a constant power pacing strategy.

The use of a recently validated model (Martin *et al.*, 1998) led to some disagreement between our results and those of Swain (1997) in terms of the magnitude of predicted time differences. With respect to finding (i), Swain (1997) predicted that a 15% variation in power by a cyclist who was able to maintain a mean $\dot{V}O_2$ of $4.0\ \mathrm{l \cdot min^{-1}}$ on a course with no hills or wind leads to an increased 40-km race time of 9 s compared with a constant power strategy. We predicted an additional 11 s increase in race time for a 15% variation in power under the same modelled conditions, which adds weight to the negative consequences of such a strategy. With respect to finding (ii), we demonstrated that, for a cyclist who is able to sustain 289 W, 40-km time increased from 3448 s on a flat course with no wind to 3602 s with variable conditions of wind. This increase in time was just 3 s longer than the equivalent predictions of Swain (1997). With respect to finding (iii), our results suggested that varying an average power of 289 W by 10%, the 10-km (course 1) and 40-km time-trials (course 2) were completed 126 s and 51 s faster, respectively, compared with a constant power strategy. These time savings are larger than those originally considered by Swain (1997), which were approximately 90 s and 30 s for the respective courses. The reason for these better time savings could be that Martin *et al.* (1998) derived the values of the various terms using a modern aerodynamic bicycle and a rider in a contemporary aerodynamic position compared with the model employed by Swain (1998). The outcome of such a difference is that, for a given change in power output, a greater change in speed could result with a more modern bicycle and rider position than in 1979. The disagreement may also be due to the way in which the models of Di Prampero *et al.* (1979) and Martin *et al.* (1998) were validated. Di Prampero *et al.* (1979) towed the bicycle and rider behind a car and measured the changes in resistive force as various conditions were changed. Martin *et al.* (1998) validated their model against a modern and extremely accurate power measuring device on the bicycle itself.

An additional aim of the present investigation was to relate these time savings to other typical performance-enhancing interventions, and thus asses the practical significance of the variable pacing strategies. We adopted the "standard" 40-km time-trial course developed by Jeukendrup and Martin (2001) and examined the most effective strategy for power variability. As power variability was increased from 0 to 15%, to compensate for the conditions of hills and wind during the race, time savings became greater. For example, despite only minor fluctuations in external conditions, and for a rider who is able to vary a mean power of 289 W by 10%, performance time would decrease by 26 s compared with an even paced strategy. This time saving is comparable to those of other performance-enhancing interventions calculated by Jeukendrup and Martin (2001), including the use of carbohydrate-electrolyte drinks (36 s), altitude training (26 s), reducing body mass (21 s), and reducing bicycle mass (7 s). As considered by Jeukendrup and Moseley (2002), athletes must decide which variable should be manipulated to give the optimal effect for a given investment of time and money. On this basis, athletes might decide to spend more time training to deal with variable pacing strategies as well to determine whether a variable strategy can be adopted during competitive races.

The adoption of a variable power pacing strategy has physiological constraints. Liedl *et al.* (1999) maintained that the power variations required to completely eliminate speed fluctuations during a time-trial over a hilly course would be physiologically impossible. Furthermore, since elite cyclists can maintain exercise intensities above 90% $\dot{V}O_{2max}$ for up to 60 min (Lucia *et al.*, 1999), a 15% increase in power should not be sustainable for extended periods of time. However, our findings confirm those of Swain (1997), that just a 5% variation in power could derive meaningful time savings. Liedl *et al.* (1999) examined the physiological and subjective strain associated with a constant versus variable power distribution during endurance cycling. Mean power output was calculated from an initial 1-h time-trial (equivalent to 78% $\dot{V}O_{2max}$). Participants then rode for 1 h at this intensity (constant trial) or performed the same duration in 5-min blocks, alternating 5% above and below the mean work rate (variable trial). No differences in physiological stress were observed between the different pacing strategies. Nevertheless, Liedl *et al.* (1999) varied power output in relation to time elapsed while maintaining a constant external resistance, as opposed to varying power output and external conditions with reference to distance travelled. This latter scenario is analogous to actual time-trial conditions, which were simulated in a 16.1-km time-trial by Atkinson and Brunskill (2000). These authors showed that a variable versus constant power strategy reduced overall perceived exertion and produced small but important time savings.

We conclude that time savings are possible in cycling time-trials if the rider varies power in parallel with hill gradient and wind direction. With a more recent mathematical model that employs modern terms for aerodynamic position and bicycle, we found slightly larger time savings than those reported by Swain (1997). These time savings compared favourably with the predicted benefits of interventions such as altitude training, or ingestion of carbohydrate-electrolyte drinks. Nevertheless, the extent to which such power output variations can be tolerated by a cyclist during an actual time-trial is still unclear.

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