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M. S. Wells & S. Marwood *Simulated hilly time-trial performance*

ORIGINAL ARTICLE

Effects of power variation on cycle performance during simulated hilly time-trials

Abstract Word Count: 250

Article Word Count: 3584

Number of figures: 3

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Note. This is an Authors Accepted Manuscript of an article whose final and definitive form, the Version of Record, has been published in European Journal of Sport Science http://www.tandfonline.com/10.1080/17461391.2016.1156162

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Abstract

It has previously been shown that cyclists are unable to maintain a constant power output during cycle time-trials on hilly courses. The purpose of the present study is therefore to quantify these effects of power variation using a mathematical model of cycling performance. A hypothetical cyclist (body mass: 70 kg, bicycle mass: 10 kg) was studied using a mathematical model of cycling, which included the effects of acceleration. Performance was modelled over three hypothetical 40-km courses, comprising repeated 2.5-km sections of uphill and downhill with gradients of 1, 3, & 6% respectively. Amplitude (5-15%) and distance (0.31-20.00 km) of variation were modeled over a range of mean power outputs (200-600 W) and compared to sustaining a constant power. Power variation was typically detrimental to performance; these effects were augmented as the amplitude of variation and severity of gradient increased. Varying power every 1.25 km was most detrimental to performance; at a mean power of 200 W, performance was impaired by 43.90 s (± 15% variation, 6% gradient). However at the steepest gradients, the effect of power variation was relatively independent of the distance of variation. In contrast, varying power in parallel with changes in gradient improved performance by 188.89 s (± 15% variation, 6% gradient) at 200 W. The present data demonstrate that during hilly time-trials, power variation that does not occur in parallel with changes in gradient is detrimental to performance, especially at steeper gradients. These adverse effects are substantially larger than those previously observed during flat, windless time-trials.

Keywords: Pacing, cycling, hilly, mathematical model, modelling.

Introduction

Mathematical modelling of cycling performance has demonstrated that varying external power output during a flat, windless, 40-km time-trial can be detrimental to performance (Atkinson, Peacock, & Passfield, 2007; Swain, 1997; Wells, Atkinson, & Marwood, 2013). In contrast, varying power output in parallel with changes in gradient can improve time-trial performance (Atkinson, Peacock, & Passfield, 2007; Boswell, 2012; Swain, 1997). The greatest improvements to performance time occur when the magnitude of power and gradient variation is maximised (Atkinson, Peacock, & Passfield, 2007; Boswell, 2012; Swain, 1997).

The studies of Swain (1997), Atkinson, Peacock, and Passfield (2007) and Boswell (2012) demonstrated that the performance benefits due to adopting a variable pacing strategy were based upon the increases and decreases in power output being maintained for the complete duration of the uphill and downhill, respectively. However, cyclists appear to have difficulty maintaining such pacing strategies due to both mechanical and / or skill limitations (Cangley, Passfield, Carter, & Bailey, 2011) and being physiologically unable to sustain the required power output (Atkinson, Peacock, & Passfield, 2007). Consequently it is important to evaluate the potentially detrimental effects on time-trial performance when power is varied more frequently than changes in course gradient dictate.

The modelling approach adopted by Swain (1997) and Atkinson, Peacock, and Passfield (2007) assumed instantaneous changes in speed at the point of power variation, thereby not taking into account the lag between change in power and change in bicycle speed. Although this approach does not greatly influence simulated performance during longer time-trials with a low frequency of variation (Boswell, 2012), the difference between performances assuming instantaneous changes in speed and those accounting for acceleration widen as the frequency of variation increases and the time trial distance decreases (Boswell, 2012). The assumption that changes in speed are instantaneous also appears to exaggerate the time saving associated with varying power in parallel with changes in course gradient (Atkinson, Peacock, & Passfield, 2007; Boswell, 2012; Swain, 1997). Therefore, when utilizing mathematical models of cycling performance to accurately quantify performance time when power is varied, it is important to account for the impact of acceleration.

Therefore, the aim of the current study was to quantify the effects of variations in external power output during simulated hilly time-trials, when the distance of power variation does not match the changes in course gradient, while also accounting for the effects of acceleration.

Methods

A hypothetical rider (body mass 70 kg, bicycle mass 10 kg) was studied over 3 separate undulating 40-km courses comprising 8 hills starting with 2.5 km of uphill and followed by 2.5 km downhill, with course gradients of 1%, 3%, and 6%, resulting in no net elevation change. A range of mean power outputs 200-600 W (**in** 100 W increments) were considered and power output was systematically varied by ± 5%, ± 10%, ± 15% from this mean baseline; a "fast start" strategy was employed whereby each trial started with power output greater than the trial mean. For each combination of power output and gradient, there was a frequency of variation in power output of 2, 4, 8, 16, 32, 64, and 128 per time-trial; distance of variation (in km) were thus calculated as event distance divided by the frequency of variation (20, 10, 5, 2.5, 1.25, 0.625, and 0.3125 km respectively). A total of 3 (gradients) x 5 (mean power outputs) x 3 (amplitudes of variation) x 7 (distances of variation) were examined, therefore a total of 315 simulations were undertaken. The length of course, range of values for gradient, mean power output and distance of variation were based upon previous studies utilising the model of Martin, Milliken, Cobb, McFadden, and Coggan (1998) (Atkinson, Peacock, & Passfield, 2007; Wells et al.,

2013) and to encompass the range of values that might reasonably be expected during a hilly cycle time-trial of a range of physical capabilities (Nimmerichter, Eston, Bachl, & Williams, 2012; Padilla, Mujika, Orbananos, & Angulo, 2000; Vogt et al., 2008). The frequency, and thus duration, of each hill was chosen to maximise the number of changes in gradient, whilst providing sufficient distance for the effects of power variation on changes in speed to be demonstrated. The study was approved by an institutional research ethic committee.

Model assumptions

It was assumed that the time-trial would be completed in windless conditions with an air density of 1.2234 kg·m^3*,* road surface would remain constant with a rolling coefficient of 0.0032 a·M^{-1}·g^{-1} (reflecting typical values for tyre construction, pressure, and smooth asphalt; Martin et al., 1998). It was also assumed that the cyclist would maintain the same position throughout the time-trial, with a drag area (drag coefficient * frontal area (Martin et al., 1998) of 3,070 cm^2, reflecting riding using the handlebar drops (Martin & Cobb, 2002). Although it is acknowledged that it is likely this position would, in reality, change to a more aerodynamic 'tuck' position on shallower gradients, the 'drops' position allows control of the bike to be maintained at all times while also allowing direct comparisons to be made across gradients without the need to account for differing rider positions. Rider mass (70 kg) is similar to that reported for elite cyclists, 68.8 kg (Padilla et al., 2000) and 69.6 kg (Vogt et al., 2008); bike mass was in line with other applications of the model of Martin *et al* (1998), (Atkinson, Peacock, & Passfield, 2007; Jeukendrup & Martin, 2001; Wells et al., 2013).

Power output was defined as the external power output at the crank. Power is the rate of doing work; external work was defined as torque * Θ (where torque is equal to force * crank length (Nm) and Θ is the displacement of the crank in radians). Therefore power output was defined as external work divided by Δ time (seconds) taken to displace the crank (Broker & Gregor, 1994; Winter, 1990). Performance was defined as the time required to complete the time-trial (Tucker et al., 2007).

Cycling speed was calculated using a previously validated equation of motion (Martin et al., 1998) and forward integration (2 Hz) was used to account for the effects of acceleration (Martin, Gardner, Barras, & Martin, 2006). The model validated by Martin et al. (1998) expresses power output as a function of the mechanical influences normally experienced during cycling i.e. air resistance, rolling resistance, wheel bearing resistance, kinetic and potential energy. A given speed is therefore associated with an exact power output in the steady state. Martin et al. (2006) validated the modelling of acceleration components during cycle performance using forward integration; this process requires initial conditions of both power output (P1) and speed (S1) for data point 1. The power required to maintain S1 in the steady state (Pss) is then calculated using the equation given by Martin et al. (1998). Acceleration (a, in either direction) occurs when $Pss \neq P1$: $a = (P1 - Pss) / (mass * S1)$. Speed at the next time point (S2) is then a function of the initial speed, acceleration and the sampling frequency (f); $S2 = S1 + a/f$. From point 2 forward, speed is predicted using power data only. The above equation of motion (Martin et al., 2006; Martin et al., 1998) was applied using customised software written to match the pacing strategies described above (Matlab, 2009a, Mathworks, U.S.A). Each trial assumed a starting speed of 1 $m \cdot s^{-1}$ and all trials started with the higher power of the imposed pacing strategy ("fast start"). In time-trial 1, the baseline power (200-600 W) was used to define the imposed constant power strategy. The baseline power from time-trial 1 was multiplied by the amplitude of variation (± 5%, ± 10%, ± 15%) to identify the peak to peak amplitude of power variation, which was maintained for the variation distance. These data formed the variable pacing strategy and were used to define the variable power strategy, time-trial 2. Time-trial 3 was defined as a constant power output trial with a mean power output equivalent to that of time-trial 2; a slight difference in mean power exists between time-trial 1 and time-trial 2 because the harmonic mean is different to the arithmetic mean. The use of a harmonic mean is appropriate when the average rate (i.e power output) is required, determining a distance based mean rather than a time based mean. For example, cycling at 40 $km \cdot h^{-1}$ for 20 km and 20 km at 35 $km \cdot h^{-1}$ gives an average speed of 37.333 $km \cdot h^{-1}$ rather than 37.5 $km \cdot h^{-1}$ which is the arithmetic mean. The effect of the power variations was then determined as the difference in the time to complete time-trial 2 vs. time-trial 3.

Results

Distance of variation ≤ 1.25 km

When power was varied with a distance of variation of ≤ 1.25 km (i.e. more rapidly, and thus not in parallel, with changes in gradient), time trial performance was typically impaired as compared to a constant power. These detrimental effects of power variation were augmented as course gradient and / or amplitude of variation increased, but were mitigated by increasing baseline power or reducing the distance of variation (figure 1). Performance was most adversely affected by a distance of variation of 1.25 km. However, at the steepest gradient (6%), performance impairment was similar for a given power output regardless of the distance of variation. At this gradient, performance impairment due to power variation was up to 43.90 s, (200 W, 15% amplitude of variation).

2.5 km distance of variation

Performance was improved for all strategies that maintained an increase in external power for the entire 2.5 km uphill sections of the course, i.e. power being varied in parallel with changes in gradient. Increasing the gradient, amplitude of variation, and reducing baseline power augmented this effect (figure 2). For example, with a baseline power of 200 W and 5% amplitude of variation, performance was improved by 16.36 and 78.42 s for a 1% and 6% gradient respectively. Moreover, increasing the amplitude of variation to 15% led to performance being improved by 43.38 and 188.89 s respectively.

Distance of variation ≥ 5 km

When power was varied with a distance of variation of ≥ 5 km (i.e. not in parallel, with changes in gradient), time trial performance was typically impaired as compared to a constant power (figure 3). When the amplitude of variation was 5%, the detrimental effects on performance were small (≤ 6.92 s) (figure 3). However, increasing the amplitude of variation and / or increasing course gradient increased the magnitude of performance impairment by up to 27.20 s at 200 W (figure 3, panel c), though these effects were mitigated by higher power outputs. For a given mean power output and amplitude of variation, increasing the distance of variation above 5 km had little additional effect (0.45-3.45 s) on performance. Taken together therefore, the adverse effects of power variation on hilly time-trial performance were smaller when the distance of variation was ≥ 5 km (i.e. greater than the length of each hill) as compared to ≤ 1.25 km (i.e. less than the length of each hill).

Discussion

The purpose of the present study was to quantify, by use of a mathematical model of cycling performance, the effect of power variation during a hilly time-trial. The design of the current study allowed the effects of frequent, controlled, systematic changes in power output to be examined while travelling uphill and downhill, taking into account the effect of acceleration. Previous studies have assessed the impact of power variation on cycling performance when power was varied in parallel with changes in gradient (Atkinson, Peacock, & Passfield, 2007; Boswell, 2012; Swain, 1997). However, Cangley et al. (2011) showed that a prescribed pacing strategy was difficult for cyclists to maintain, with variable and constant power strategies characterised by oscillations around prescribed power outputs. By considering distances of variation both shorter and longer than the length of each hill, the present study therefore extends and improves upon previous studies (Atkinson, Peacock, & Passfield, 2007; Swain, 1997; Wells et al., 2013) by quantifying the effect of power variation upon cycling performance during hilly cycling time trials.

With the exception of pacing strategies with a 2.5 km distance of variation, varying power output during a hilly time-trial was typically detrimental to performance when compared to maintaining a constant power. The few exceptions to this rule were restricted to the lowest amplitude of variation and either the lowest distance of variation (1% gradient) or for distance of variations ≥ 5 km (6% gradient). These effects are likely to be an artifact of the "fast start" assumed in the present study which minimizes the time taken to overcome the inertia of the bike and rider from the initial starting speed. A "fast start" strategy mirrors the self-selected strategy during flat time-trials (Atkinson & Brunskill, 2000; Thomas, Stone, Thompson, Gibson, & Ansley, 2012) and has previously been shown to minimise the effects of power variation on simulated cycle time-trial performance, at least during flat, windless time-trials (Wells et al., 2013). These exceptions aside, the present data are qualitatively similar to the previously reported effect of varying power output on flat, windless time-trial courses (Atkinson, Peacock, & Passfield, 2007; Swain, 1997; Wells et al., 2013). However, in our previous study investigating the effects of power variation during flat, windless cycle time-trials, when power was varied every 1.25 km during a 40-km time-trial, performance was impaired by 7.97 s at 200 W with 15% amplitude of variation. Comparison of these same criteria during a hilly time-trial show that performance was impaired by 10.76 s and 43.90 s at 1% and 6% gradient respectively. The adverse effect of power variation on cycle time-trial performance is therefore quantitatively much more important during steep, hilly time-trials than in flat, windless conditions. The present data therefore demonstrate that for time-trials that include frequent and severe changes in gradient, competitive cyclists should be encouraged to minimise the frequency and amplitude of power variation, especially on uphill sections, as the adverse effects of power variation are much greater than for flat, windless time-trials.

In the present study, at the most severe gradients the greatest detrimental effect of power variation on performance was when the distance of variation was 1.25 km (figures 1 & 3). This is in contrast to previous simulations of flat, windless course**s** where progressively increasing the distance of variation was shown to augment the detrimental effect on performance (Wells et al., 2013). These effects are however both likely due to the pacing profiled resulting in the poorest adherence to a constant speed. Hence in the present study, a distance of variation of 1.25 km results in a complete cycle of power variation above and below the baseline power being undertaken between the top and bottom of each hill. This provides sufficient distance to approach the steady state speed associated with the power output during each variation, thus resulting in poorest adherence to a constant speed.

Since the combination of a single variation in power while riding uphill (when also combined with a single variation on the downhill) was most detrimental to performance, it could therefore be argued that the typically rapid alterations in power output that cyclists carry out (Cangley et al., 2011; Jobson, Passfield, Atkinson, Barton, & Scarf, 2009) mean that power variation are of little consequence to hilly time-trial performance. However, underlying these rapid power variations, or “noise”, regular variations in power output remain (Tucker et al., 2006). Furthermore at the most severe gradient in the present study, the detrimental effects of power variation on performance were relatively independent of the distance and thus frequency of variation. This demonstrates that even rapid variations in power output result in a considerable impairment to performance (up to 43.90 s in the present simulation) during hilly time-trials with more severe gradients.

In agreement with previous research (Atkinson, Peacock, & Passfield, 2007; Cangley et al., 2011; Swain, 1997), the present data also demonstrate that on a hilly time-trial course, it is beneficial for a cyclist to vary power output in parallel with changes in gradient (2.5 km distance of variation). These improvements in performance were augmented with increases in the amplitude of variation and severity of gradient (figure 2), but mitigated by higher power outputs. However, in the field such pacing strategies are likely to result in additional physiological stress being placed upon a cyclist who is already working at or close to their sustainable limit. The effect of power variation on indicators of fatigue such as ratings of perceived exertion (RPE), lactate, and maximal voluntary contraction has, though, proved equivocal. There is a similarity in the physiological responses to constant exercise (~75% $\dot{V}O_{2\,\text{max}}$) when the power variation is modest (≤± 15%) (Lepers, Theurel, Hausswirth, & Bernard, 2008; Liedl, Swain, & Branch, 1999). However, brief periods of large variation (≥± 30%) when combined with brief recovery periods (≤ 60 s) augment the physiological response to variable intensity exercise when compared to constant intensity exercise-(Theurel & Lepers, 2008; Thomas et al., 2012). These increased physiological perturbations can however be mitigated by increasing the recovery periods (~2 minutes) (Brickley et al., 2007).

However, the regular periods of variation adopted by some of these previous studies are not representative of hilly cycle time-trials where more time is spent ascending than descending. Consequently, Atkinson, Peacock, and Law (2007) have shown that cyclists were not always able to maintain an imposed variable power strategy designed to enhance hilly cycle time-trial performance, when power was varied by 5% relative to the mean power recorded during a self-paced flat time-trial. The participants recruited by Atkinson, Peacock, and Law (2007) were trained cyclists exercising at a mean power output that approximates critical power in this population (Black, Durant, Jones, & Vanhatalo, 2013; Burnley, Doust, & Vanhatalo, 2006). It is therefore likely that the participants recruited by Atkinson, Peacock, and Law (2007) were exercising above critical power during the uphill sections, with the inability to maintain the required pacing strategy indicating that they exhausted their W' (the volume of work available above critical power) at some point on an uphill section. In such cases, a cyclist may be advised to reduce their power output to the highest constant power that they can maintain for the remainder of the uphill. Indeed, Atkinson, Peacock, and Law (2007) showed that even when it is not possible to maintain an increase in power output when travelling uphill, performance will be improved so long as the pacing strategy had been maintained for at least half of the event distance. Further research is warranted to determine the physiological limits of variable power pacing strategies during hilly cycle time-trials.

Conclusion

The present data demonstrate that varying power during hilly time-trials is detrimental to performance unless power is varied in parallel with the change in gradient, in which case performance is improved. Performance was most adversely affected when the distance of power variation was half that of the hill length (1.25 km). However, at the most severe gradient examined in the present study (6%), the effect of power variation was relatively independent of the distance (and thus frequency) of power variation. Therefore at severe gradients, even frequent variations in power output are severely detrimental to performance compared to maintaining a constant power output. These effects on performance are markedly greater than previously demonstrated during flat, windless time-trials.

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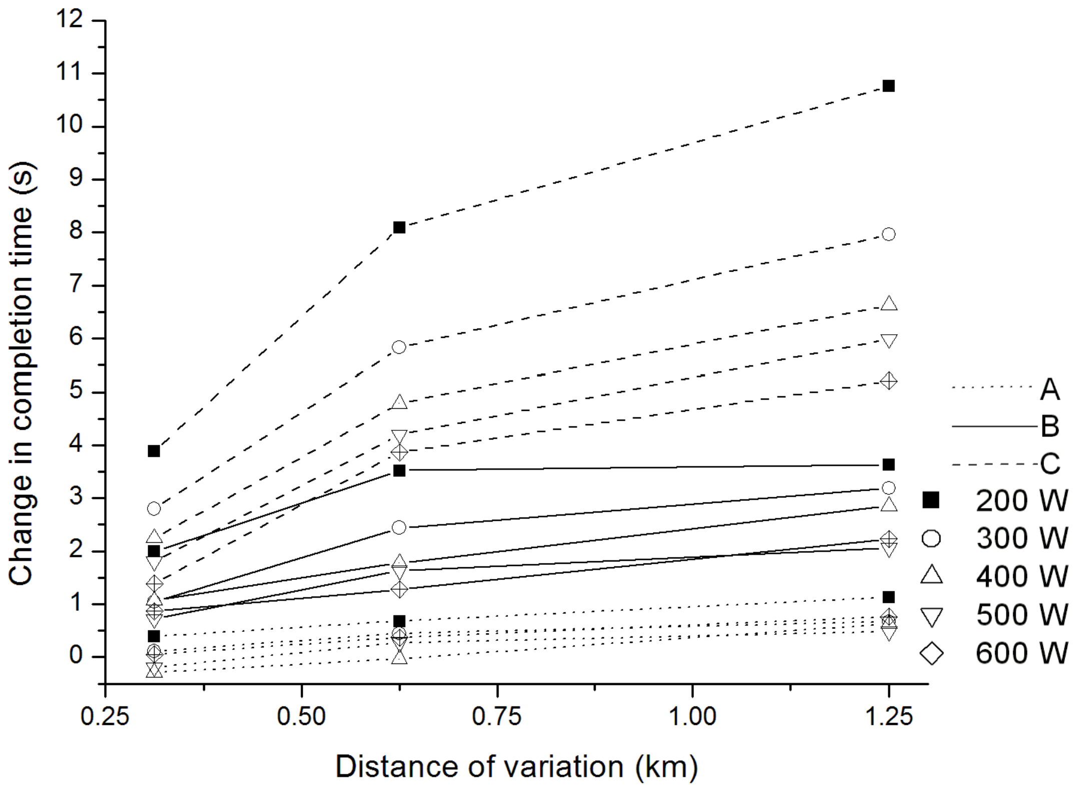

12
11
10
9
8
7
6
5
4
3
2
1
0
Change in completion time (s)
0.25
0.50
0.75
1.00
1.25
Distance of variation (km)
A
B
C
200 W
300 W
400 W
500 W
600 W

Figure 1A

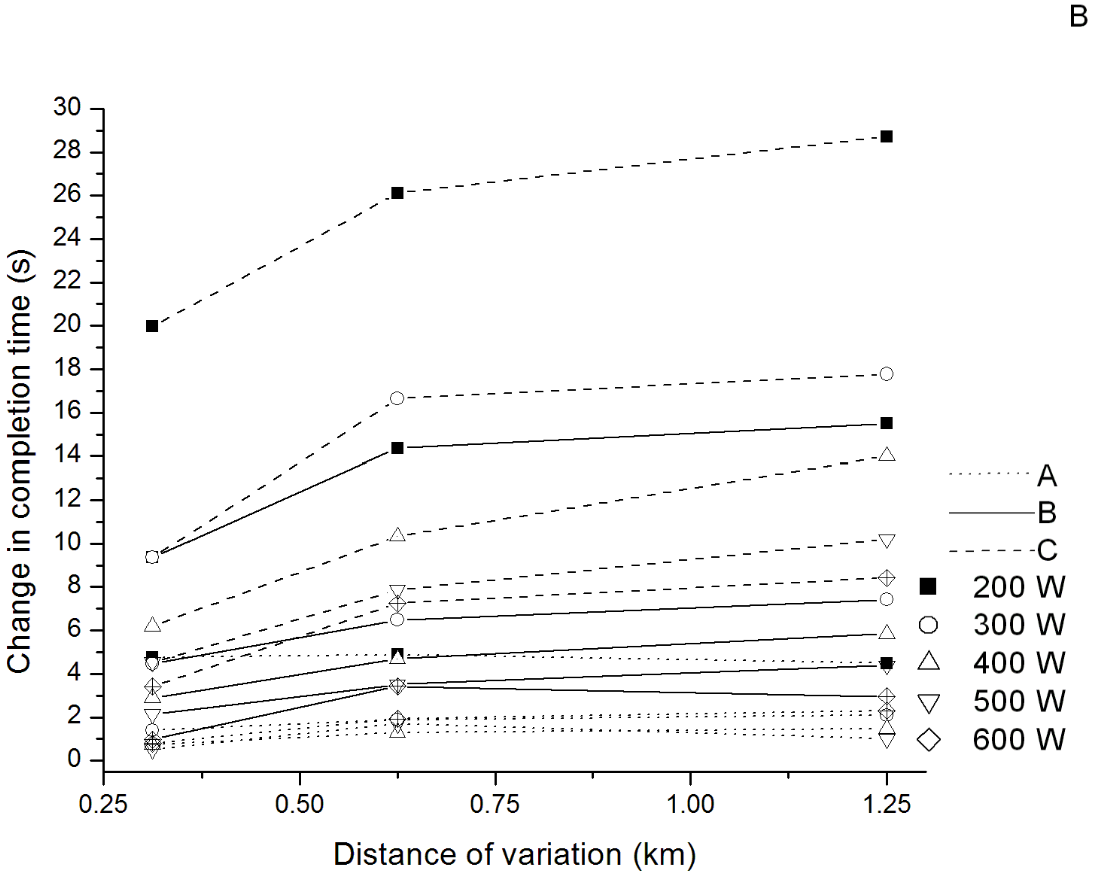
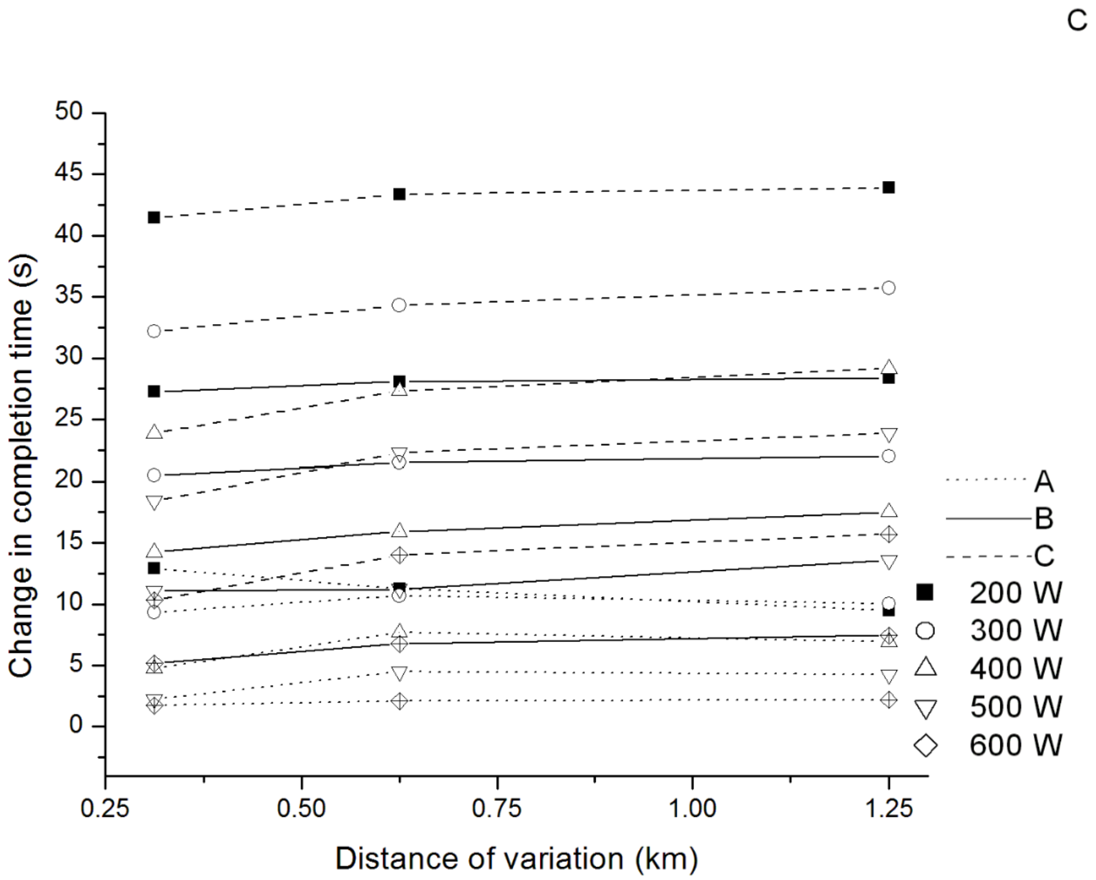

B
Change in completion time (s)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Distance of variation (km)
0.25
0.50
0.75
1.00
1.25
A
B
C
200 W
300 W
400 W
500 W
600 W

Figure 1B


C
Change in completion time (s)
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5
10
15
20
25
30
35
40
45
50
Distance of variation (km)
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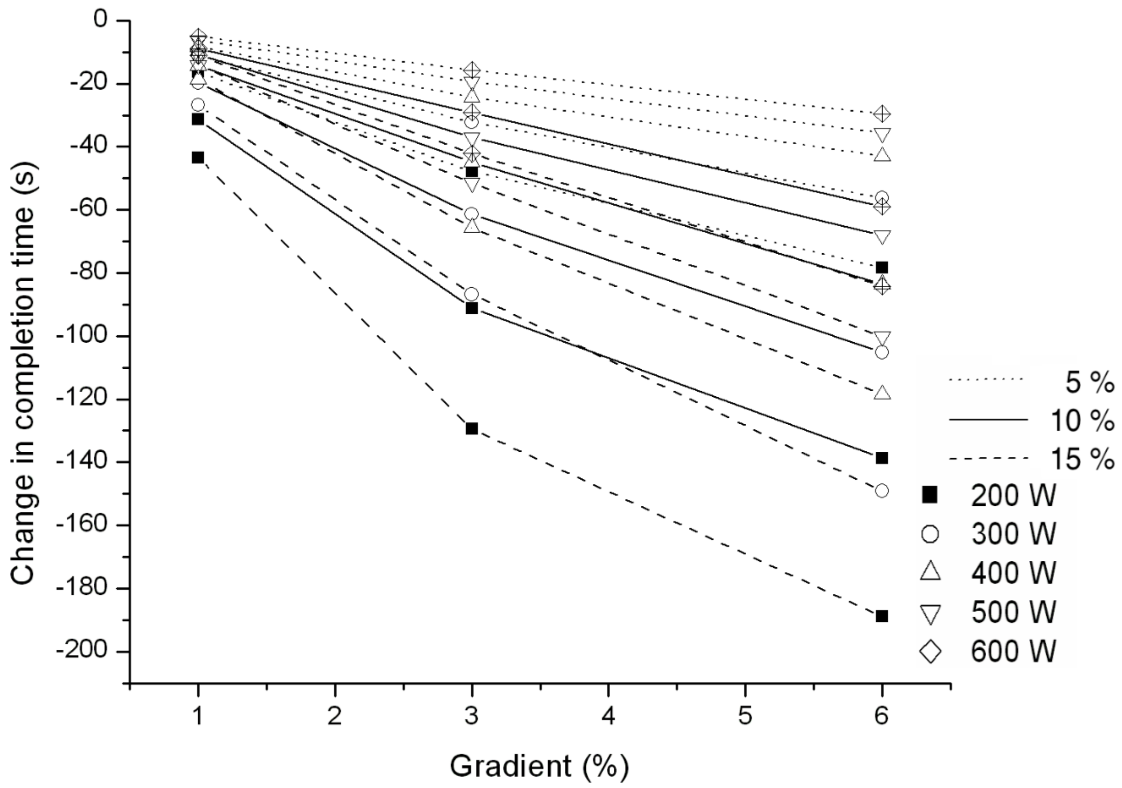
1.25
A
B
C
200 W
300 W
400 W
500 W
600 W

Figure 1C


Change in completion time (s)
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-40
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-80
-100
-120
-140
-160
-180
-200
Gradient (%)
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2
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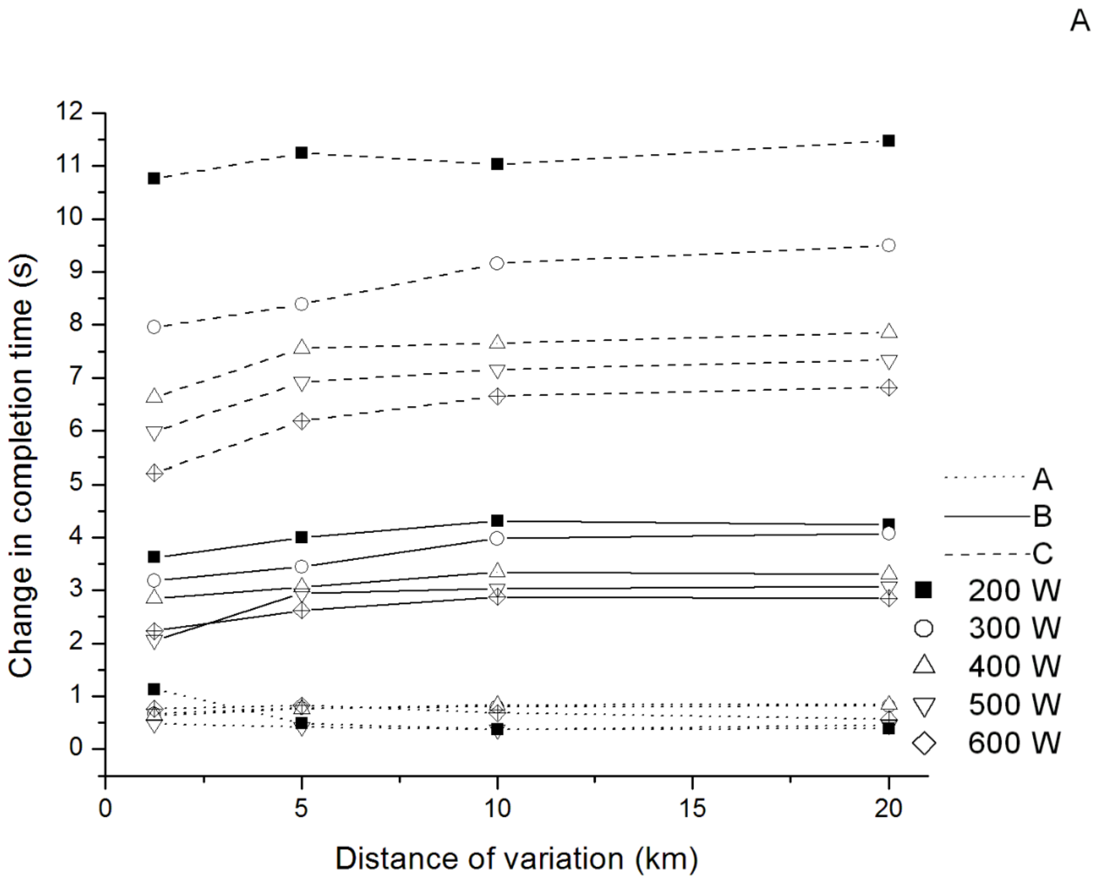
4
5
6
5 %
10 %
15 %
200 W
300 W
400 W
500 W
600 W

Figure 2


A
12
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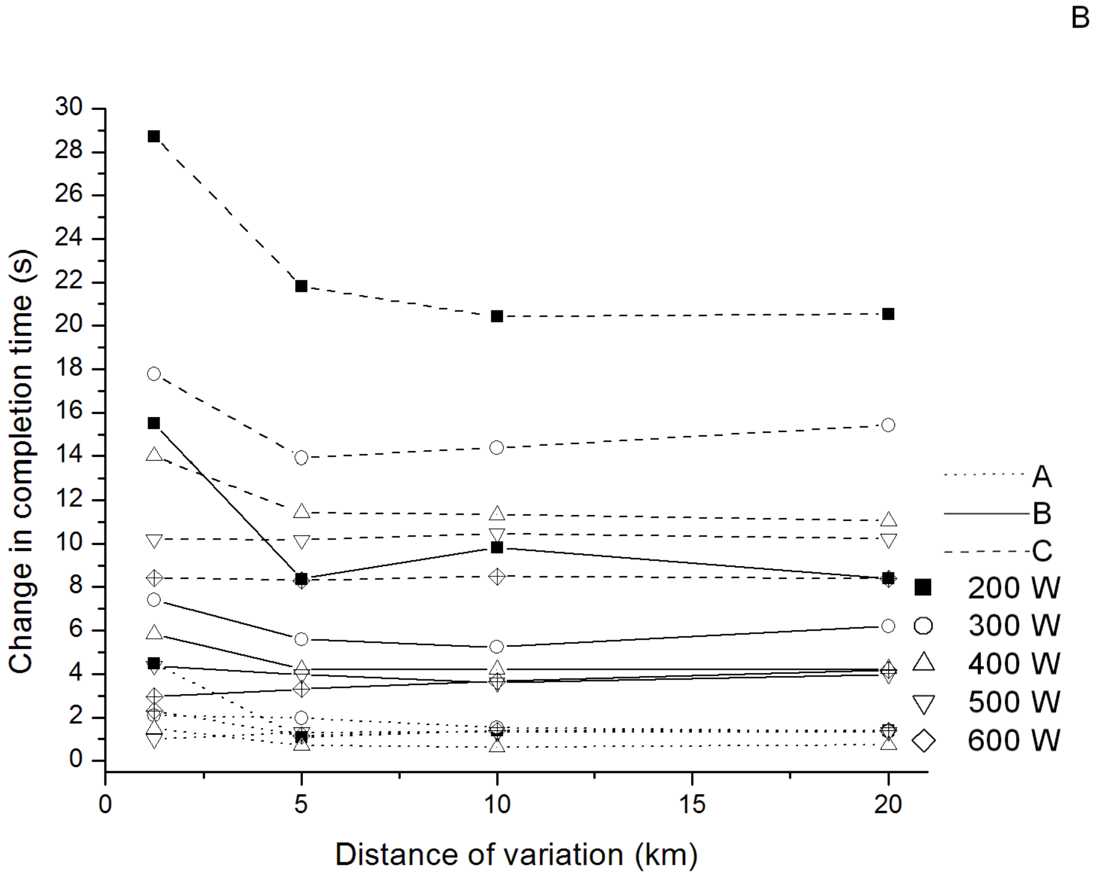
0
Change in completion time (s)
0
5
10
15
20
Distance of variation (km)
A
B
C
200 W
300 W
400 W
500 W
600 W

Figure 3A


B
Change in completion time (s)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
Distance of variation (km)
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5
10
15
20
A
B
C
200 W
300 W
400 W
500 W
600 W

Figure 3B

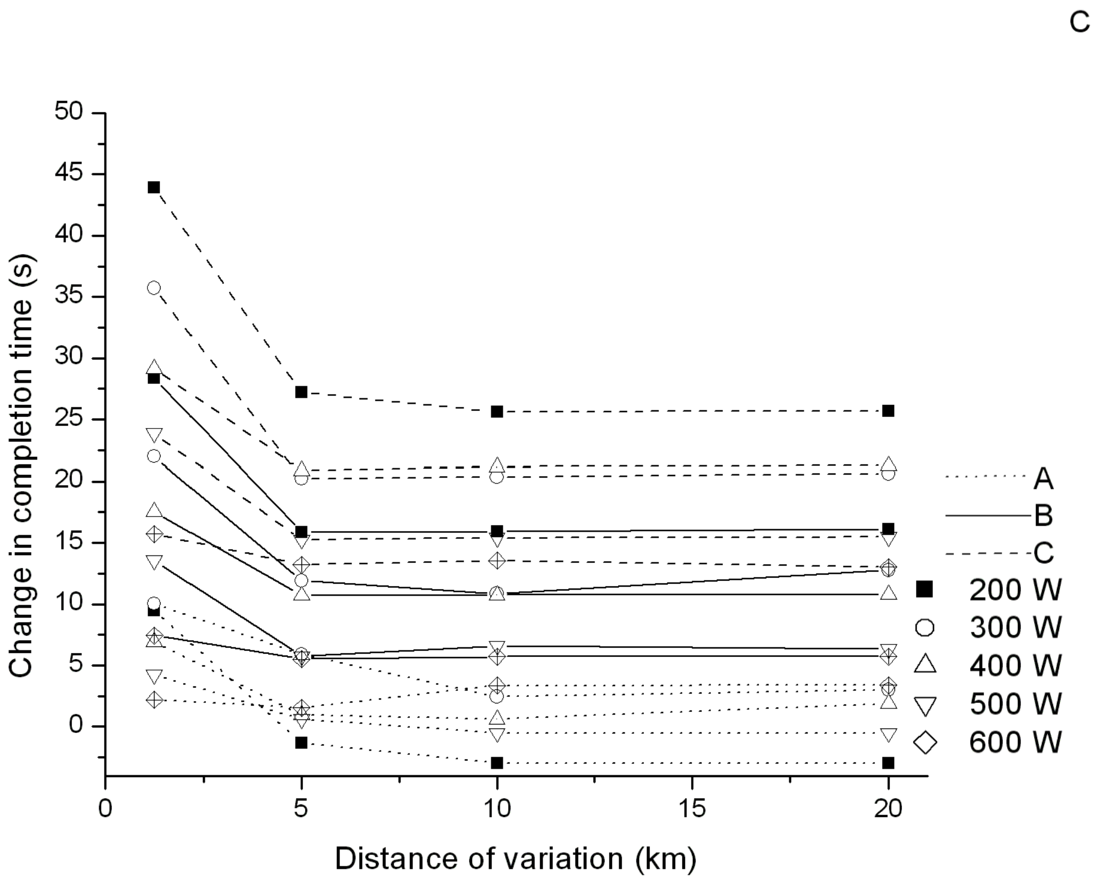
C
Change in completion time (s)
0
5
10
15
20
25
30
35
40
45
50
Distance of variation (km)
0
5
10
15
20
A
B
C
200 W
300 W
400 W
500 W
600 W

Figure 3C

Figure captions

Figure 1 (A, B, C)

Increase in completion time (s) for a 40-km time-trial using variable-power pacing strategies. Distance of variation < 1.25 km, gradient 1% (A), 3% (B), 6% (C), amplitude of variation 5% (A), 10% (B), 15% (C).

Figure 2

Decrease in completion time (s) for a 40-km time-trial using variable-power pacing strategies for the entire uphill / downhill, 2.5 km distance of variation.

Figure 3 (A, B, C)

Increase in completion time (s) for a 40-km time-trial using variable-power pacing strategies. Distance of variation $\geq 5\ \mathrm{km}$, although 1.25 km included to allow ease of comparison, gradient 1% (A), 3% (B), 6% (C), amplitude of variation 5% (A), 10% (B), 15% (C).