Title: Effects of magnitude and frequency of variations in external power output on simulated cycling time-trial performance

Running title: Simulated variable pacing strategies

Keywords: Mathematical model, pacing strategy, variable, constant, cycling speed.

Abstract

Mechanical models of cycling time-trial performance have indicated adverse effects of variations in external power output on overall performance times. Nevertheless, the precise influences of the magnitude and number of these variations over different distances of time trial are unclear. 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 times were modelled over distances of 4–40 km, mean power outputs of 200–600 W, power variation amplitudes of 5-15% and variation frequencies of 2-32 per time-trial. Effects of a “fast-start” strategy were compared with those of a constant-power strategy. Varying power improved 4-km performance at all power outputs, with the greatest improvement being 0.90 s for ±15% power variation. For distances of 16.1-, 20- and 40-km, varying power by ±15% increased times by 3.29, 4.46 and 10.43 s respectively, suggesting that in long-duration cycling in constant environmental conditions, cyclists should strive to reduce power variation to maximise performance. The novel finding of the present study is that these effects are augmented with increasing event distance, amplitude and period of variation. These two latter factors reflect a poor adherence to a constant speed.

Introduction

Performance during a cycling time-trial is determined by the interaction of environmental conditions, physiological characteristics of the cyclist and the distribution of external power output, otherwise known as pacing strategy (Atkinson & Brunskill, 2000). The optimum pacing strategy is influenced by event distance (Foster et al., 2004a; Nikolopoulos, Arkinstall, & Hawley, 2001) and environmental conditions such as wind speed and direction as well as the gradient of the road (Atkinson, Peacock, & Passfield, 2007; Swain, 1997).

Mathematical models of cycle time-trial performance that incorporate only mechanical factors have demonstrated that, for any given mean power output and when environmental conditions (i.e. wind and gradient) vary, it is beneficial to increase external power output when pedalling uphill or into a headwind and reduce power output in downhill and wind-assisted sections. (Atkinson et al., 2007; Boswell, 2012; Swain, 1997). In contrast, when environmental conditions are constant, time-trial performance is worse over 10- and 40-km when external power output varies (Atkinson et al., 2007; Swain, 1997). During a simulated 40-km trial in constant gradient and wind conditions, varying power output by 15% increased completion time by 9 s (Swain, 1997) and 11 s (Atkinson et al., 2007).

Importantly, Swain (1997) and Atkinson et al. (2007) did not take into account the effects of acceleration at the point of power variation in their previous studies. Such an approach does not allow investigation of the effects of altering the power variation frequency since, for a given amplitude of variation, removing the effects of acceleration will yield the same performance regardless of the frequency by which the variation is applied. Furthermore, the long periods of variation (≥10% of event distance) that have been studied are unlikely to represent typical time-trial pacing strategy (Tucker et al., 2006). It is therefore important to investigate whether the effect on performance (i.e. completion time) is mitigated or exacerbated with more frequent variations in power, or with shorter time-trial distances, when effects of acceleration are accounted for.

It is also important to note that disparities in the magnitude of the variable power effect reported by Swain (1997) and Atkinson et al. (2007) could have been attributable to the use of different equations of motion. The disparities could have also been because mean power output of the constant trial was not matched to the harmonic mean of the variable-power trial. A harmonic mean is a more appropriate statistic for quantifying the central tendency of data that is the form of a rate (Ferger, 1931). Therefore the aim of the current study was to use validated equations of motion (Martin, Gardner, Barras, & Martin, 2006; Martin, Milliken, Cobb, McFadden, & Coggan, 1998), to investigate effects of variations in power output during simulated time-trials in constant conditions, using greater frequencies of variation and ranges of distances than previously examined while accounting for effects of acceleration.

Methods

A hypothetical rider (body mass 70 kg, bicycle mass 10 kg) was studied over a flat, windless, time-trial of 4-, 16.1-, 20-, and 40-km. A range of mean power outputs 200–600 W (100 W increments) were considered and for each distance mean power was systematically varied by ±5, ±10, ±15%. For each combination of power output and event distance, there was a frequency of variation in power output of 2, 4, 8, 16 and 32 per time-trial. Periods of variation (in km) are therefore calculated as event distance divided by frequency of variation.

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) accounted for effects of acceleration (Martin et al., 2006). The model validated by Martin et al. (1998) expressed 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. For a given set of values, any given speed is therefore associated with an external power output (Broker & Gregor, 1994). Forward integration requires initial conditions both of 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 ≠ P1 (thus producing a net impulse): 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 (Martin et al., 2006). From point 2 forward, speed is predicted using power data only. Forward integration (Martin et al., 2006) of the equation of motion (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 each case, the baseline power (200–600 W) was used to define the constant-power strategy time-trial 1. The amplitude of variation (±5, ±10, ±15%) was multiplied by the baseline power to identify the peak-to-peak amplitude of power variation. The additional power required above the baseline power was maintained for the period of variation as determined by the frequency of variation and event distance. This formed the variable pacing strategy and was used to define the variable power strategy, time-trial 2. The mean power from time-trial 2 was recorded and used as the baseline power for a second constant-power trial (time-trial 3) that differed slightly from the mean power for time-trial 1. The effect of the power variations was then determined as the difference in the time to complete time-trial 2 vs. time-trial 3.

Model assumptions

It was 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 2,914 cm^2, reflecting a "tuck" time-trial position (Martin & Cobb, 2002). Differences in the modelled variables exist between the 4-km (track) and those ≥ 16.1-km (road). Since track and road time-trials are undertaken on different surfaces the rolling coefficient was adjusted to match the surface, track: 0.0021 a•M^{-1}•g^{-1} (di Prampero, 2000), road: 0.0032 a•M^{-1}•g^{-1} (Martin et al., 1998). To replicate typical conditions encountered during track cycling, additional rolling resistance was calculated to account for both banking angle on the straight (12.6°) and around the bend (42.0°) (Lukes, Carre, & Haake, 2006; Underwood & Jermy, 2010). Furthermore, changes in speed attributable to centripetal acceleration were also modelled entering and exiting the bend (Lukes et al., 2006; Underwood & Jermy, 2010) assuming a bend radius of 25 m.

Results

For all modelled strategies, 4-km performance was improved with a variable-power strategy (figure 1). This effect was augmented as the period of variation increased (frequency of variation decreased) until a nadir of 0.5–1 km, after which this effect waned as the period of variation increased. These effects of a variable pacing strategy were also augmented as the amplitude of power variation was increased from ±5% through to ±15%. For example, at a baseline power of 200 W and a period of variation of 0.5 km, performance was improved by 0.42 s with ±5% power variation compared with 0.84 s at ±15% variation. Furthermore, the difference in performance at 0.5 km versus 2.0 km period of variation was 0.02 s at ±5% amplitude of variation as compared with 0.40 s at ±15% (baseline power of 200 W). Changing baseline power did not bring about consistent effects on performance; effects depended both on the amplitude and period of variation.

For 16.1-, 20- and 40-km time-trials, use of a 10 or 15% variation in mean external power output across the range of periods of variation and baseline power impaired performance compared with constant-power output (figures 2a, 2b, 2c). These effects were greater at ±15% than ±10% variation and augmented by increases in the period of variation. For example, during the 40-km time-trial with a period of variation of 1.25 km and baseline power output of 200 W, performance was impaired by 3.19 s and 7.97 s for ±10% and ±15% amplitude of variation, respectively. However, with a period of variation of 20 km, performance was impaired by 4.26 s and 10.43 s respectively. Increases in baseline power output consistently reduced performance impairments across all combinations of amplitude and frequency of variation at simulated distances of 16.1-, 20- and 40-km. However, the effect of baseline power output was smaller than the effects of changes in amplitude or periods of power variation. When power output was varied by just ±5% for time-trials of 16.1- and 20-km, performance was improved at the shortest periods of variation (figures 2a, 2b). However, performance was impaired as either time-trial distance or the period of variation increased.

Figure 3 shows the effect of simulated time-trial distance (≥ 16.1 km) for each baseline power output and period of variation for amplitude of variation of ±10%. Generally, adoption of a variable pacing strategy over simulated distances ≥ 16.1-km impaired performance; this effect was augmented primarily by increases in the amplitude and period of variation, and to a lesser extent by decreasing the baseline external power output. Figure 3 also indicates that the effect of power variation is augmented by increases in time-trial distance. While the proportion of the time-trial completed at each frequency of variation remained the same between trials of differing total distance, by design the absolute distance completed per frequency of variation (i.e. the period of variation) differed by time-trial distance. However figure 3 demonstrates that whether variation is compared by period or frequency the qualitative effect is the same: performance is impaired when power is varied and effects are accentuated by increases in the amplitude and duration of variation. Figure 4 shows speed profiles for a 40-km trial at 300 W with a 15% amplitude of variation and periods of variation of 5 km (panel A) and 1.25 km (panel B) each versus constant-power. Taken together with figure 3, the data show that impaired performance was exacerbated by those factors associated with a poor adherence to a constant speed.

Discussion

The present data demonstrate that, as in previous studies (Atkinson et al., 2007; Swain, 1997) when environmental conditions are constant, increasing the magnitude of power variation about the event mean will impair performance (figures 2a, 2b, 2c, 3). However, the novel findings of the present study are that these effects are exacerbated by increases in event distance, period of variation (whether considered as an absolute distance or relative frequency) and, to a lesser extent, reductions in mean power output (see figure 3). In contrast, figures 1, 2a and 2b suggest that for some combinations of event distance, amplitude and period of variation, performance is improved when a variable pacing strategy was adopted. Such outcomes likely relate to the beneficial effect (in mechanical terms) of the “fast-start” strategy used in the present study.

Using mechanical models of cycling performance, it has been shown that when varying power by as little as 5% about an event mean during flat windless conditions, performance is impaired (Atkinson et al., 2007; Swain, 1997). However, in both of these studies, the effects of acceleration at the point of power variation were not modelled. Rather, it was assumed that one could change instantly between the steady-state speeds associated with the new power output. Furthermore these studies examined a limited range of event distances and frequencies of variation. Whether the effect on completion time would be mitigated or exacerbated with more frequent variations in power, or with shorter time-trial distance, is unclear. By including these factors, the present study therefore extends and improves previous studies on quantifying effects of power variation on cycling time-trial performance when environmental conditions are constant.

During a simulated 40-km flat, windless time-trial, Swain (1997) showed that, at a mean power of 289 W, varying power by 15% in 5-km sections increased completion time by 9 s. However, using the validated model in the present study (Martin et al., 1998), Atkinson et al. (2007) showed that for the same conditions, completion time was extended by 11 s. The use of different models could explain part of the discrepancy between these two studies. However, the latter study calculated completion time for the constant-power trial utilising the arithmetic mean of the variable-power trial, rather than the harmonic mean, which was lower at 286.65 W. Recalculation of completion time in the constant-power trial on this basis results in completion time in the variable-power trial to be extended by 9.8 s, similar to the finding of Swain (1997). Examination of this condition in the present study, which considered the effects of acceleration and where comparisons were made between effects of constant and variable-power using the harmonic mean of the variable-power trial, the extension to completion time at a baseline of 300 W was 8.28 s. Since the effects of the “fast-start” are less important for the 40-km trial (see discussion below and figure 3), modelling the effects of acceleration seem to mitigate slightly the overall adverse effects of power variation during a cycling time-trial. Furthermore, the present data also show that if the period of variation is reduced (power varied more frequently), the effects of power variation would also reduce. For example, completion time would be extended by only 7.72 s and 6.61 s if power varied every 2.5 km and, 1.25 km, respectively. Figure 4 suggests that these effects are because of a closer adherence to constant speed when power is varied more frequently. Long periods of variation result in more time being spent at the steady state speed associated with the upper and, most importantly, lower power output. Hence, not only is there a metabolic limit on the ability to make up for lost time during periods of low power output (Fukuba and Whipp (1999), but there is also a mechanical constraint. However, with an amplitude of variation of ±5% the mechanical constraints on performance are modest at best (figure 2c).

The adverse effects of power variation are reduced as time-trial distance reduces. Indeed at 20- and 16.1-km, there are combinations of baseline power, amplitude and period of variation that improved performance, with performance for the 4-km trial being improved for all variable power strategies. These effects occur because of the adoption of a “fast-start” to all simulated time-trials. While the aim of the present study was not to examine the effects of different starting strategies, inclusion of acceleration in the model necessitates defining a starting strategy for the variable-power trials. The adopted pacing strategy of starting with the positive (relative to baseline) power variation ("fast-start") was based on previously optimised simulations (de Koning, Bobbert, & Foster, 1999; van Ingen Schenau, de Koning, & de Groot, 1992) and self-adopted strategies (Atkinson & Brunskill, 2000; Foster et al., 2004b; Thomas, Stone, Thompson, St Clair Gibson, & Ansley, 2012); such an approach reduces the time spent at low speeds, (Hettinga, De Koning, Broersen, Van Geffen, & Foster, 2006) and maximally activates the metabolic machinery of oxidative metabolism (Jones, Wilkerson, Vanhatalo, & Burnley, 2008).

The resultant effect of a fast-start over the 4-km time-trial was that performance was improved for all modelled conditions (figure 1). However, the precise effects with respect to baseline power, period and amplitude of variation were inconsistent. These varied effects over the 4-km time-trial probably reflect the interaction of the beneficial fast-start and otherwise adverse effects of power variation during the remainder of the time-trial and the location on the simulated track (i.e. straight or bend) where the change in power occurs. Unlike previous simulations (van Ingen Schenau et al., 1992), the present model included the influence of centripetal force on entering and exiting the bends of a cycling track that results in a change in speed (Lukes et al., 2006; Underwood & Jermy, 2010).

As time-trial distance increases to 16.1- and 20-km, the number of period/amplitude of variation combinations where an improvement in performance is shown reduces, and is restricted to low periods of variation and 5% amplitude of variation. These data suggest that while augmenting the “fast-start” by increasing the period and / or magnitude of power variation improves performance, this is off-set by the adverse effects on mean speed for the remainder of the simulation. When power variation (period or magnitude) is low the cyclist is benefitted with the fast start, but adversely affected least by the imposed variable strategy (speed kept nearest to constant). As the period of variation increases, the beneficial effect of the fast-start is progressively outweighed by the adverse effects of the power variation, and performance is impaired. It is also noteworthy that the adverse effect of increasing the period of variation becomes proportionally less important as time-trial distance increases (figure 3). This is probably because of the importance of the fast-start strategy reduces as time-trial distance increases (Atkinson & Brunskill, 2000). Indeed, at a time-trial distance of 40-km, all variable power strategies impair performance. Furthermore, figure 5 shows that the relative difference in performance between fast- and slow-start strategies is unaffected by the period of variation at 40-km.

The present data demonstrate that long-distance cycling performance is optimised, in terms of external mechanics, by maintaining a constant power output, and thus pace. However, since exercise above the lactate threshold engenders a “slow component” of oxygen uptake (Burnley & Jones, 2007), which causes increased relative exercise intensity, sustaining pace above lactate threshold increases effort. Moreover, oxygen uptake responses to exercise reflect external power, but also include influences of internal power, the power required by the legs to overcome gravitational and inertial forces (Foss & Hallen, 2004). Large fluctuations in power output are likely to result in a change in cadence, which although minimized by selection of appropriate gearing, can cause exponential changes in internal work. For example, it can be calculated that an increase in cadence from 80 – 100 rev•min^{-1} can double internal power from 50–100 W for a 70 kg cyclist (Minetti, 2010; Tokui & Hirakoba, 2007). Therefore variation in external power might also increase internal power and therefore inhibit performance either by compromising available external power or causing a disproportionate increase in the relative exercise intensity that might not be sustainable (Jones, Vanhatalo, Burnley, Morton, & Poole, 2010). The effects of power variation on cycling time-trial performance are not restricted to external mechanical influences.

The purpose of the present study was to investigate mechanical effects of a variable-pacing strategy. It was also possible to compare data with others (Atkinson et al., 2007; Swain, 1997). To simplify the examination of pacing strategy on performance, the present and other studies compared effects of highly regular, alternately high and low power profiles with those from equivalent, but constant, mean external power outputs. A similar approach has occurred in investigations of physiological response (Lepers, Theurel, Hausswirth, & Bernard, 2008; Theurel & Lepers, 2008; Thomas, Stone, Thompson, Gibson, & Ansley, 2012) and performance consequences of variable-power strategies (Bernard et al., 2007; Suriano, Vercruyssen, Bishop, & Brisswalter, 2007) and results have been equivocal. However, the highly regular periods and amplitudes of variation presented in the present and other studies are unlikely to represent the periods and amplitudes of variation that occur during self-paced trials (Jobson, Passfield, Atkinson, Barton, & Scarf, 2009). While techniques such as discrete Fourier transform can identify changes in power distributions (Tucker et al., 2006), they do not indicate how changes in period and amplitude of variation occur throughout a trial (Abbiss et al., 2006). Exposure variation analysis (EVA) has been proposed to quantify variations in amplitude, frequency of variation and time (Abbiss et al., 2006) and has identified tri-dimensional differences in the variability of power distribution between time-trial, criterium, and road race events (Abbiss, Straker, Quod, Martin, & Laursen, 2008). Whether the typical variations in power output seen in time-trials in constant environmental conditions would be sufficient to result in adverse physiological and performance effects compared to constant power output remains to be tested.

By incorporating components of acceleration across a range of periods and amplitudes of variation, the present study extends and improves previous studies that have investigated mechanical effects of power variation on cycling time-trial performance (Atkinson et al., 2007; Swain, 1997). The present study demonstrates that time-trial duration depends on event distance, mean power, amplitude of variation, period/frequency of variation, and starting strategy. The present data show that during 4-km time-trials, it is advantageous to start the time-trial with a power output greater than the anticipated mean power for the time-trial; hence a variable-power strategy is beneficial. However, at distances > 4-km, varying power output can be detrimental to performance and effects are exacerbated by increases in event distance along with amplitudes and periods of variation (reductions in the frequency of variation) and, at event distances ≥ 20-km, irrespective of starting strategy. High frequencies of power variation detract less from performance, these effects probably relate to stability of speed. During long-distance cycling time-trials, if high power outputs cannot be maintained, reducing the amplitudes and periods of power variation allow consistency of speed and so optimise performance.

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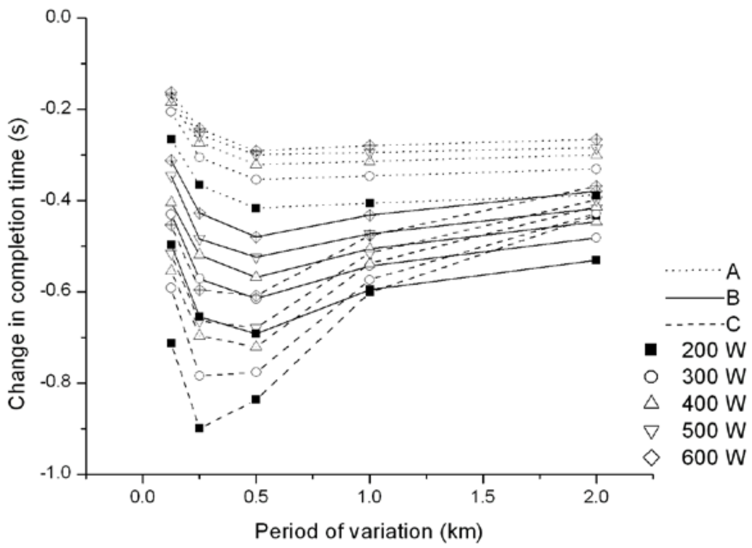

Fig. 1 Changes in completion time (s) for a 4-km time-trial using variable-power pacing strategies. Amplitude of variation 5%(A), 10%(B), 15%(C).

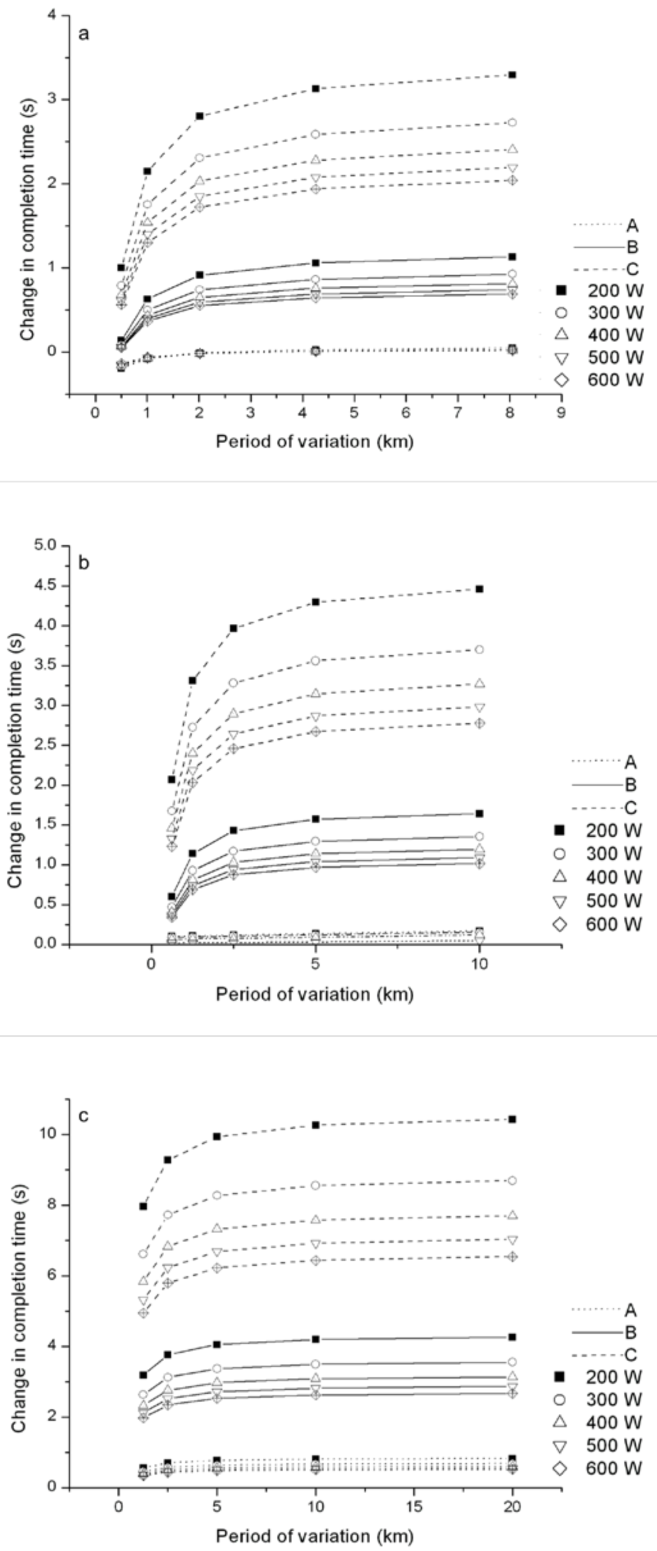

Fig. 2 Changes in completion time (s) for 16.1-km (a), 20-km (b), 40-km (c) time-trials using variable-power pacing strategies. Amplitude of variation 5%(A), 10%(B), 15%(C).

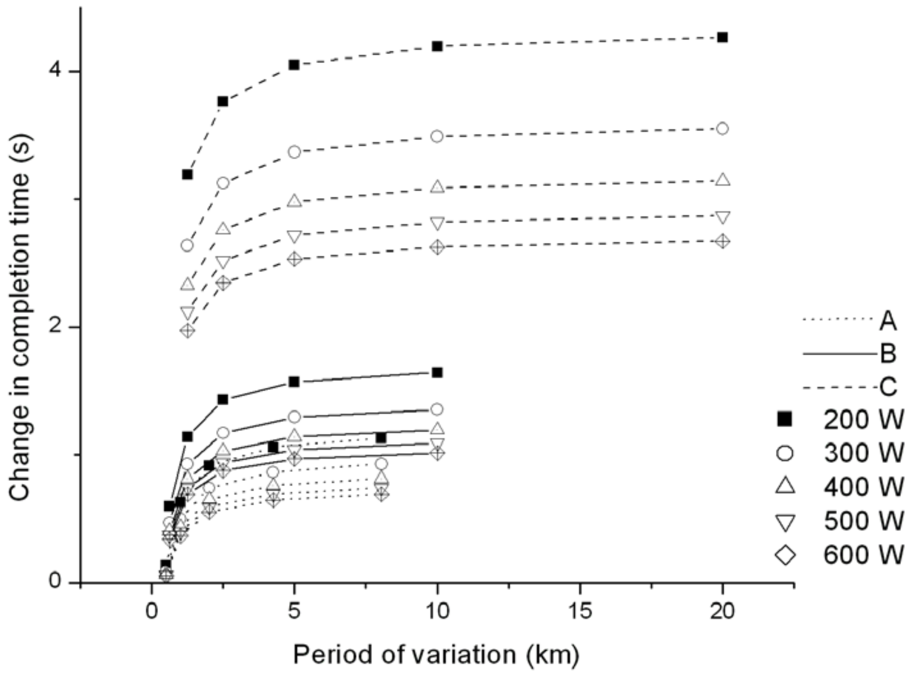

Fig. 3 A 10% amplitude of variation combined with 2, 4, 8, 16, and 32 frequencies of variation examined over 16.1- (A), 20- (B), and 40-km (C).

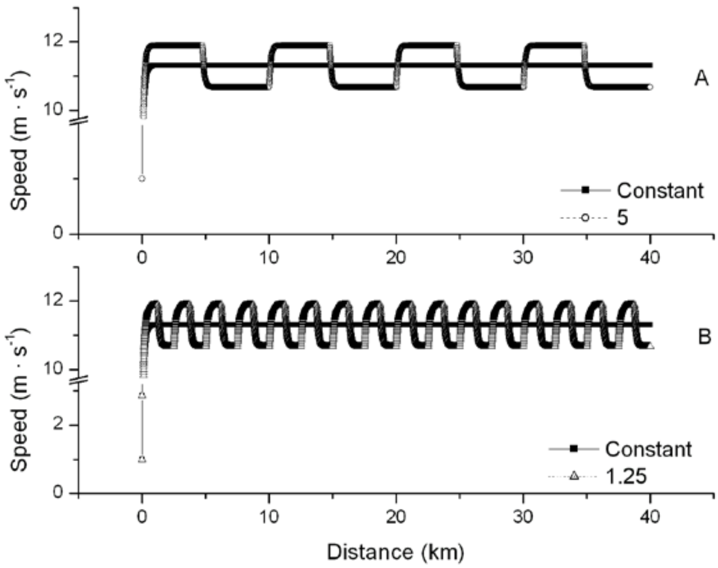

Fig. 4 Speed during 40-km time-trial at 300 W, 15% amplitude of variation, periods of variation of 5 km (A), 1.25 km (B).

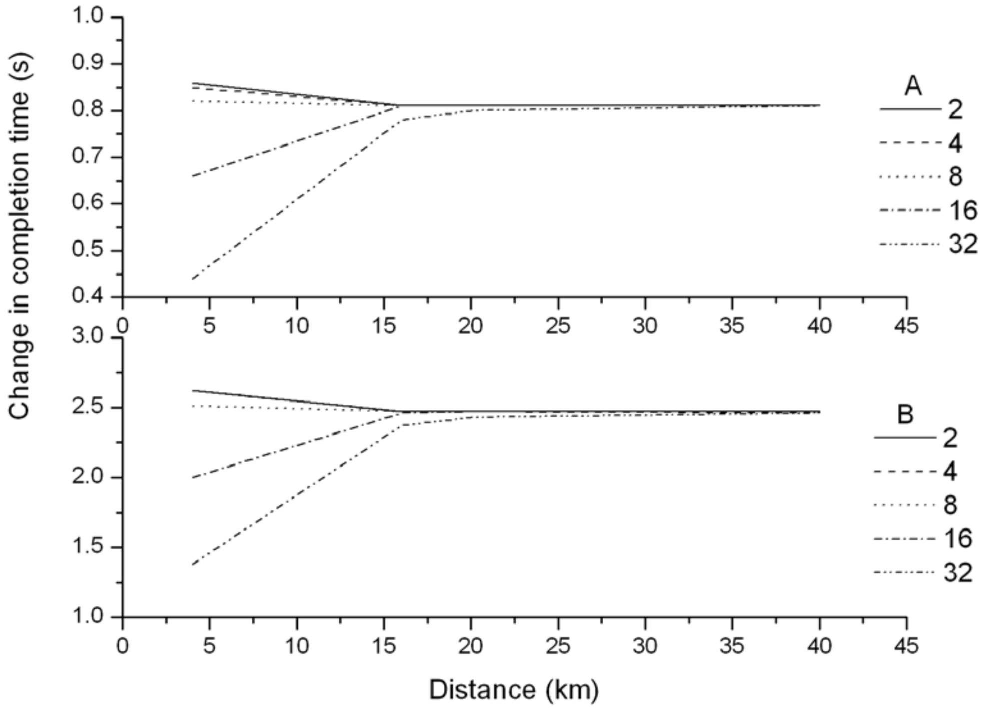

Fig. 5 Effect of starting strategy (low/high – high/low) on time-trial duration (s) at all distances. Mean 300 W 5%(A) & 15%(B) amplitude of variation combined with 2, 4, 8, 16, and 32 frequencies of variation.