Kent Academic Repository

Full text document (pdf)

Citation for published version

Cangley, P. and Passfield, Louis and Carter, Helen and Bailey, M. (2011) The effect of variable gradients on pacing in cycling time-trials. International journal of sports medicine, 32 (2). pp. 132-6. ISSN 1439-3964.

DOI

https://doi.org/10.1055/s-0030-1268440

Link to record in KAR

https://kar.kent.ac.uk/27846/

Document Version

UNSPECIFIED

Copyright & reuse
Content in the Kent Academic Repository is made available for research purposes. Unless otherwise stated all content is protected by copyright and in the absence of an open licence (eg Creative Commons), permissions for further reuse of content should be sought from the publisher, author or other copyright holder.

Versions of research
The version in the Kent Academic Repository may differ from the final published version.
Users are advised to check **http://kar.kent.ac.uk** for the status of the paper. **Users should always cite the published version of record.**

Enquiries
For any further enquiries regarding the licence status of this document, please contact:
researchsupport@kent.ac.uk

If you believe this document infringes copyright then please contact the KAR admin team with the take-down information provided at **http://kar.kent.ac.uk/contact.html**

The Effect of Variable Gradients on Pacing in Cycling Time-Trials

Authors P. Cangley[1], L. Passfield[2], H. Carter[1], M. Bailey[1]

Affiliations [1] University of Brighton, Chelsea School, Eastbourne, United Kingdom
[2] University of Kent, Centre for Sports Studies, Chatham Maritime, United Kingdom

Key words
- pacing
- modeling
- time-trial
- cycling

Abstract

It has been reported that performance in cycling time-trials is enhanced when power is varied in response to gradient although such a mechanical pacing strategy has never been confirmed experimentally in the field. The aim of this study was, therefore, to assess the efficacy of mechanical pacing by comparing a constant power strategy of 255 W with a variable power strategy that averaged to 255 W over an undulating time-trial course. 20 experienced cyclists completed 4 trials over a 4 km course with 2 trials at an average constant power of 253 W and 2 trials where power was varied in response to gradient and averaged 260 W. Time normalised to 255 W was 411 ± 31.1 s for the constant power output trials and 399 ± 29.5 s for the variable power output trials. The variable power output strategy therefore reduced completion time by 12 ± 8 s (2.9 %) which was significant ($p < 0.001$). Participants experienced difficulty in applying a constant power strategy over an undulating course which acted to reduce their time gain. It is concluded that a variable power strategy can improve cycling performance in a field time-trial where the gradient is not constant.

Introduction

Changes in human and environmental variables are known to influence cycling speed [2]. In races where the environmental conditions are variable, it has been calculated that a pacing strategy that attempts to maintain a constant speed, rather than a constant effort or power output strategy should prove fastest [1, 3, 12]. The time advantage of a variable power output strategy has been proposed to be proportional to the magnitude and frequency of changes in environmental resistive forces [2]. Consequently, changes in gradient have been predicted to have the most frequent implications for pacing strategy [7] and are therefore the focus of this study.

The principle behind a constant speed pacing strategy is that the fastest time between two points is achieved by varying power output in response to changes in the course gradient [7, 15]. For example, on an undulating time-trial course, a constant power output strategy results in more time spent on the ascents compared to the descents. Whilst physiological and technical constraints may prevent a constant speed being achieved over an undulating course [4], an advantage could still be gained if the variance from a constant speed is minimised [3].

Swain [15] was one of the first investigators to draw attention to the mechanical performance advantage that could be obtained by varying power output (expressed as VO_2) in response to variances in wind and gradient. Over a theoretical 10 km course with 10 symmetrical climbs and descents of 5–15 % gradient, Swain [15] calculated time savings of 4–8 % were possible. Subsequently, Atkinson *et al.* [3] re-calculated the results of Swain [15] using a more complete model of cycling power output demands [12]. These researchers calculated that a variable power output strategy would reduce race time by 8 %. Gordon [7] modelled a 40 km course with 20 symmetrical climb/descents of 2.5 % and obtained a time saving of 1.6 % compared to an equivalent constant power output strategy. The lesser time saving of Gordon [7] reflects the reduced gradient profile and emphasises the importance of a large gradient variance if the advantage of a variable power output strategy is to be realised.

Thus, whilst performance improvement has been calculated in previous studies by adopting a variable power output strategy on an undulating

accepted after revision
October 08, 2010

Bibliography
DOI http://dx.doi.org/10.1055/s-0030-1268440
Published online: December 16, 2010
Int J Sports Med 2011; 32: 132–136 © Georg Thieme Verlag KG Stuttgart · New York
ISSN 0172-4622

Correspondence
Patrick Cangley
University of Brighton
Chelsea School
Hillbrow
BN20 7SR Eastbourne
United Kingdom
Tel.: +44/1372/273 163
Fax: +44/1372/273 163
p.cangley@brighton.ac.uk

This is a copy of the author's personal reprint

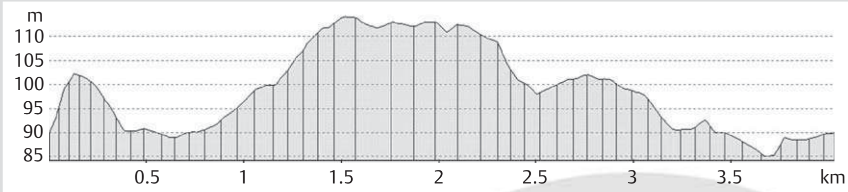

Fig. 1 Height profile of G10/42 course from TQ16677 46828 to TQ17817 43047.

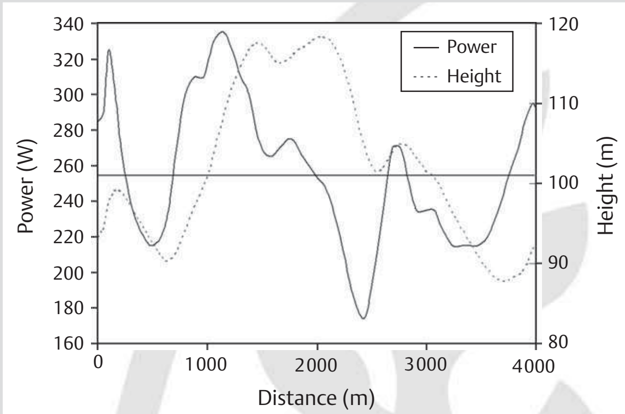

Fig. 2 Optimum power profile and course height profile.

course, this has not been experimentally validated in the field. The aim of this study was, therefore, to experimentally assess the effect of adopting a variable power output strategy over an undulating field time-trial course. It was hypothesised that a variable power output strategy, in contrast to a constant power output strategy, would reduce speed variation and result in a time saving.

Methods

General outline

The investigation compared the time taken to cover a 4 km undulating time-trial course at an average power output of 255 W utilising either constant or variable power output strategies.

Participants

21 competitive male time trial cyclists gave informed consent to take part in this study [(mean ± SD), age 34 ± 8 y, mass 76 ± 8 kg, competitive experience 8 ± 4 y]. Selected participants were representative of club level competitors with a current time of 21–25 min for a 10 mile time-trial (2010 UK national championship times ranged from 18:37 to 23:27 min). The study was approved by the university Ethics Committee and performed in accordance with the ethical standards specified by Harriss and Atkinson [8].

Time-trial course

Trials were conducted on the first 4 km of a regularly used cycling time-trial course in the UK. The selected course track and height profile (TQ16677 46828 to TQ17817 43047) was modelled using Ordinance Survey digital data (Memory Map Europe, Aldermaston, UK). The course is a straight dual-carriageway with a mean gradient of 3 %, a peak of 9 % and no appreciable flat sections. The start and finish were at the same height (**Fig. 1**). The gradient of the selected course was considered representative of the 'sporting' time trial that is necessary to identify a mechanical advantage. Limiting the distance minimised physiological fatigue which could also have distorted the mechanical findings which are the focus of this study.

The cycling model

A 3D model was developed using Matlab (Version 7.5, The Mathworks Inc, Natick, MA) that combines bicycle mechanics, rider biomechanics and environmental factors into a single dynamic system. The aim of the model is to identify mechanical mechanisms that influence speed in a road cycling time trial. The model is constructed using two Matlab toolboxes, SimMechanics to model physical entities and Simulink to model control structures. In SimMechanics, a 'machine' is built using blocks to represent rigid bodies linked by joints (including closed loops). The system is actuated by force or motion actuators applied to joints or bodies with sensors measuring the resulting forces and motion. A range of constraint blocks allow limits to be placed on forces/motions and provide functions such as gears and rolling wheels. Rigid bodies and joints are linked with lines that essentially represent 2-way 'action-reaction' physical connections providing implicit inertial effects in a complete system. Initial conditions are specified in respect of bicycle/rider mass, aerodynamic drag, wind conditions and tyre characteristics. The developed system operates in forward dynamics mode where forces applied to the model result in motion subject to constraints. This modelling system has been widely employed in industry including development of the F-18 fighter by Lockheed Martin and a Mars orbiter by NASA.

Variable power profile

For this study, the model calculated a variable power output strategy which minimised speed variance while constraining mean power output to 255 W and power output variance to ± 27 % (**Fig. 2**). These constraints were based on pilot work to ensure that all participants could complete all trials and maintain a near-competitive intensity. The variable power output strategy was derived as follows: The model initially calculated speed for a mean participant on a completely flat, straight, smooth, windless course at 255 W. The course track and gradients were then introduced resulting in a calculated change in speed as the participant proceeded. The participants' power output was then recalculated to minimise this change in speed but without increasing the power output above 325 W or decreasing power output below 186 W whilst maintaining an overall mean of 255 W. Changes in aerodynamic resistance with speed were included in the calculations but environmental wind and rolling resistance were modelled as constant between trials for a participant.

Equipment

Participants rode their own bicycles. The aerodynamic characteristics of bicycle, clothing and accessories together with tyre pressures were not specified but were required to remain con-

This is a copy of the author's personal reprint

Table 1 Constant -v- Variable power results.

	Constant Power			Variable Power		
	Mean	±SD	Range	Mean	±SD	Range
actual time (s)	412	31.9	360–480	397	30.1	352–465
time normalised to 255 W mean power (s)	411	31.1	359–475	399*	29.5	354–467
mean power (W)	253	13.0	204–266	260	14.5	204–272
power RMSE (W)	39	10.4	22–69	64	10.5	46–93
speed RMSE (m.s^{-1})	3	0.2	2–3	2	0.3	1–2

* = significantly different from Constant Power mean (P<0.001)

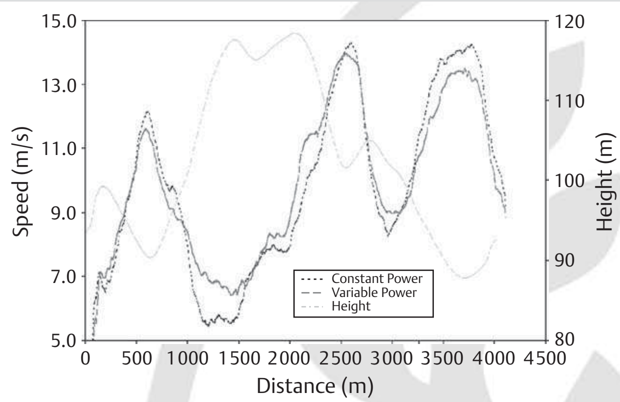

Fig. 3 Comparison of speed at constant and variable power (relative to gradient profile).

stant for each participant. The performance of 16 participants was measured utilising a power measuring rear hub (PowerTap SL, Saris Cycling Group, Madison, WI). The performance of the remaining 5 participants was measured from a power measuring crank system (Schoberer Rad Messtechnik GmbH, Julich, DE). Both systems were calibrated before each trial in accordance with the manufacturer's instructions.

The variable power output profile was downloaded as sound files to a small personal digital assistant combined with a global positioning system (PDA/GPS, Mio P560, Mio Technology Ltd, Gatwick, UK) which was secured to the participant's arm. As the participant progressed along the course, the required power output was conveyed via an earpiece at ~80 m intervals. During pilot testing, intervals of any greater frequency were found to be impractical for participant implementation.

Experimental trials

All the experimental field trials were conducted over a 5 h period which started with a warm-up and equipment familiarisation. Participants completed 4 separate trials, 2 adopting a constant power output and 2 using the variable power output strategy. Rolling starts were implemented so that participants crossed the starting line at the target power output. Testing was conducted in dry weather with winds of less than 5 m·s^{-1}. The wind strength and direction was measured with an anemometer (WindWorks, USA, www.bythebeachsoftware.com). If the wind speed changed by more than 1 m·s^{-1} or by 20 degrees in direction, a trial was rejected and repeated after a delay. This occurred on 4 occasions.

Trials 1 and 2 ('constant power output') required a constant power of 255 W to be maintained over the course. Trial 3 and 4 ('variable power output') required the participants to vary power output with the objective of minimising speed variation over the course while maintaining a 255 W average. Participants were instructed to maintain the same riding position within and between trials to minimise variance due to aerodynamics. The results for one participant were excluded as a constant aerodynamic position was not maintained within trials.

Data collection

Time, power, speed and distance data for each trial were recorded using the power meter at ≈1 s intervals. The root mean squared error (RMSE) between targeted and actual values for both power and speed were calculated for each trial. Where mean power output differed from the 255 W target power, completion time was normalised to the estimated speed that would have resulted if the target power had been maintained. The data for this normalisation was derived by running multiple simulations of the model over the complete course using a range of power values and obtaining an exponential power-to-speed relationship. The relationship was essentially linear within the range of experimentally observed power variances.

Statistical analysis

Data sets were checked for normality with a Shapiro-Wilkes test and for equal/unequal residual variance with an F-Test. Data were analysed with an SPSS linear mixed model (Version 15.1, SPSS Inc, Chicago, IL) to identify any significant difference between completion time at constant and variable power [9]. Trial order was not randomised since a pilot study had shown that the selected sequence aided a learning effect and thus improved accuracy in achieving the required power profile. Due to changes in wind conditions, 2 participants failed to complete one trial each and the trials could not be repeated due to time constraints.

Results

▼

The required assumptions for a mixed model were confirmed with data normally distributed (P>0.248) and F-Tests showing unequal variances between all data sets except the first and second variable power trial (F>1.194, P>0.288). A Toeplitz covariance matrix best reflected the variance and correlation between data sets as indicated by the lowest −2 Log Likelihood value. Results for both strategies are presented in ▸ **Table 1**. The achieved mean power for the constant strategy was 253 W and 260 W for the variable strategy. The mean time normalised to 255 W for the constant power output trials was 411 ± 31.1 s and 399 ± 29.5 s for the variable power output trials. The difference of 12 ± 8 s was significant (P<0.001). The 95 % confidence interval (CI) time for the variable power output trial was 391–413 s and 401–428 s for the constant power output trial. An example of the constant and variable power output strategies is shown in ▸ **Fig. 3**. RMSE for the constant power strategy was 39 ± 10 W which, because it was not zero, indicated that participants had

This is a copy of the author's personal reprint

difficulty following the constant power output strategy. As expected, the variable power output strategy RMSE was higher at 64 ± 11 W indicating that participants implemented the increase in power phasing required by this strategy. Speed RMSE exhibited the reverse pattern with the constant strategy at $3 \pm 0.2\,m \cdot s^{-1}$ and the variable strategy at $2 \pm 0.3\,m \cdot s^{-1}$. This confirmed that the variable power output strategy more closely approximated to a constant speed as required by mechanical pacing theory.

Discussion

The main finding of this study was that a variable power output strategy saved 12 s over a 4 km undulating time-trial course. This 2.9 % time saving would have promoted the 10th placed rider to 3rd in the 2008 UK National 10 time trial championship [16]. The underlying concept of the constant -v- variable power strategy is apparent from **Fig. 3**. As the cyclist negotiates the steepest gradient changes, the speed variance increases more for the constant power strategy than for the variable power strategy. This is due to the cyclist frequently adjusting power levels during a variable power trial and thus reducing variance from the optimal constant speed.

This study sought to confirm the concept of mechanical pacing by adopting a protocol that minimised the effects associated with individual variability in physiology. Studies examining physiological pacing in a road time-trial context have found reduced performance when power change is greater than ± 5 % at near threshold intensity for approximately one hour [6, 10, 11, 13]. The ± 27 % power variance employed in the present study could therefore confound the mechanical pacing findings if a maximal intensity was specified. It should be noted that investigation of physiological versus mechanical pacing necessitates deployment of different instrumentation and protocols. The reductionist approach adopted in the present study prevents the confounding influence of physiological factors over mechanical in the attribution of any time saving.

The model predicted a time saving of 4 % with a variable power output strategy which was greater than that actually achieved (2.9 %). This may be explained by the inability of participants to perfectly follow either the constant or variable power strategies. This was highlighted in the constant power output strategy where the RMSE should have been 0 W but was actually 39 W (**Table 1**). This error acted to reduce the time saving. The practical difficulty of following a defined power output profile is at least partly a consequence of instantaneous changes in gradient requiring rapid changes in power output. The result is a tendency for the rider to oscillate around the target power output. This issue is likely to constrain accuracy in all cycling strategies that attempt to specify work rates.

Comparison with the theoretical predictions of previous studies is problematic as there has been no standardisation of power output strategies or gradient profiles on which the effectiveness is dependent. For example, variable power output levels have been fixed at ± 5 % of 224 W [3] and ± 20 % of 435 W [7] while mean power output variance in this study was ± 27 % of 255 W. The average climbing/descending gradient is the second parameter critical to the amount of time saved. Fixed gradients have been specified in previous studies, e.g. Atkinson *et al.* [3] ± 5 % and Gordon [7] ± 2.5 % while the mean gradient change in the present study was ± 3 % but included gradients of up to 9 % for short intervals. It is noted that in time-trials on the road constant gradient is extremely unlikely, even over short distances [2, 12]. Despite the above limitations, comparisons with previous studies show comparable time savings. Atkinson *et al.* [3] calculated a 2.3 % time saving while Gordon [7] calculated a 1.6 % time saving. Interestingly, a trend is apparent where the larger the gradient variance the greater the time saved which is consistent with the theory of a variable power output strategy. Cyclists who can maintain a substantially higher power output than 255 W may be less able to vary their power by the 27 % used in this study. If this was the case, then the ability to maintain constant speed and obtain the associated time saving would be reduced.

A potential limitation of the study is the reliability of the power meters employed. The PowerTap typically gives a 1.2 % lower power reading compared to the 'gold standard' SRM with power coefficients of variation (CV) of 1.8 % and 1.5 % respectively [5]. Paton & Hopkins [14] reported similar power CVs of 1.5 % for the PowerTap and 1.6 % for the SRM but more importantly for this study, identified the mechanical component of the CVs as 0.9 % and 1.1 % respectively (equivalent to a ~0.4 % speed error). Speed error is the quantity of interest when evaluating the within-subject measurement error of the power meter which is applicable to this study.

It could be argued that work-done should be the same in the constant and variable power output trials as implemented by others [4]. In the present study, power output and distance were held constant while work-done was allowed to vary in order to calculate elapsed time. The alternative protocol of keeping work-done constant would result in the variable power output strategy covering a different distance, but time-trials in the UK are not generally decided in this manner.

Environmental wind changes and aerodynamic effects from passing vehicles were not measured within a trial. However, it is unlikely that these factors contributed substantially to the identified time difference considering that measured wind speed varied by $\leq 1\,m \cdot s^{-1}$ at the start of successive trials for a participant. Although not measured, traffic volume did not change noticeably over the duration of any participants' trials. Nevertheless, an important objective for a future study is to quantify the aerodynamic effects of any changes in wind and traffic during a trial.

In conclusion, this study has found with an experimental field trial that a variable power output strategy saves time over an undulating time-trial course compared to an equivalent constant power output strategy. Competitive cyclists may find it advantageous to explore their capacity to adopt a variable power output strategy where resistive forces vary during a race.

References

1 *Atkinson G, Brunskill A.* Pacing strategies during a cycling time trial with simulated headwinds and tailwinds. Ergonomics 2000; 43: 1449–1460
2 *Atkinson G, Davison R, Jeukendrup A, Passfield L.* Science and cycling: current knowledge and future directions for research. J Sports Sci 2003; 21: 767–787
3 *Atkinson G, Peacock O, Passfield L.* Variable versus constant power strategies during cycling time-trials: prediction of time savings using an up-to-date mathematical model. J Sports Sci 2007; 25: 1001–1009
4 *Atkinson G, Peacock O, Law M.* Acceptability of power variation during a simulated hilly time trial. Int J Sports Med 2007; 28: 157–163
5 *Bertucci W, Duc S, Villerius V, Pernin JN, Grappe F.* Validity and reliability of the PowerTap mobile cycling powermeter when compared with the SRM Device. Int J Sports Med 2005; 26: 868–873

This is a copy of the author's personal reprint

6 *Chaffin ME*, *Berg K*, *Zuniga J*, *Hanumanthu VS*. Pacing pattern in a 30-minute maximal cycling test. J Strength Cond Res 2008; 22: 2011–2017
7 *Gordon S*. Optimising distribution of power during a cycling time trial. Sports Eng 2005; 8: 81–90
8 *Harriss DJ*, *Atkinson G*. International Journal of Sports Medicine – Ethical Standards in Sport and Exercise Science Research. Int J Sports Med 2009; 30: 701–702
9 *Landau S*, *Everitt B*. A Handbook of Statistical Analysis Using SPSS. London: Chapman & Hall; 2004
10 *Lander PJ*, *Butterley RJ*, *Edwards AM*. Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. Br J Sports Med 2009; 43: 789–795
11 *Liedl MA*, *Swain DP*, *Branch JD*. Physiological effects of constant versus variable power during endurance cycling. Med Sci Sports Exerc 1999; 31: 1472–1477
12 *Martin JC*, *Milliken DL*, *Cobb JE*, *McFadden KL*, *Coggan AR*. Validation of a mathematical model for road cycling power. J Appl Biomech 1998; 14: 276–291
13 *Palmer GS*, *Noakes TD*, *Hawley JA*. Effects of steady-state versus stochastic exercise on subsequent cycling performance. Med Sci Sports Exerc 1997; 29: 684–687
14 *Paton CD*, *Hopkins WG*. Ergometer error and biological variation in power output in a performance test with three cycle ergometers. Int J Sports Med 2006; 27: 444–447
15 *Swain DP*. A model for optimizing cycling performance by varying power on hills and in wind. Med Sci Sports Exerc 1997; 29: 1104–1108
16 *UK National 10 Time Trial Results*. Available at http://www.rttc.org.uk [Accessed 21st December 2009].

This is a copy of the author's personal reprint