

The physiological correlates of variable gradient cycling performance

Bradley Clark¹✉, Carl Paton² and Brendan O'Brien³

Abstract

This study investigates the physiological correlates of computer simulated rolling terrain time-trial performance in a group of competitive cyclists. Twenty eight trained cyclists (age 33 ± 10 years, body mass 74.4 ± 7.3 kg, and peak oxygen uptake 64 ± 7 mL·kg⁻¹·min⁻¹) participated in this study. Cyclists initially completed a graded exercise test (GXT) to establish measures of peak power output (PPO), peak oxygen uptake ($\dot{V}O_{2peak}$), onset blood lactate accumulation (OBLA), ventilatory threshold (VT) and gross efficiency (GE). On a further occasion cyclists then completed a 20-km time-trial over a computer simulated rolling terrain course from which performance time and mean power output were determined. Pearson's correlation (r) was used to examine the magnitude of the relationship between measures in the GXT and time-trial. There were large to very large ($r = 0.51-0.9$) correlations between performance time and mean power output in the time-trial and measures of absolute $\dot{V}O_{2peak}$ and PPO from the GXT. Correlations between time-trial performance time and physiological measures were further increased when physiological measures were expressed relative to body mass. The smallest correlations ($r < 0.3$) were reported between time-trial performance time and mean power output when anaerobic threshold parameters were reported as fractional utilisations of peak power. These findings support the use of body mass corrected variables for predicting performance in rolling terrain time-trials. Cyclists preparing for rolling terrain races are recommended to optimise their power to weight ratio to gain a performance advantage.

Keywords: cyclist, maximal oxygen uptake, time-trial, onset blood lactate accumulation, self-paced exercise, cycle ergometer.

✉ Contact email: bradclark1987@gmail.com (B. Clark)

¹ University of Canberra Research Institute for Sport and Exercise, Australia

² Eastern Institute of Technology, New Zealand

³ Federation University Australia

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Introduction

The performance outcome from competitive cyclists during road cycling events is largely mediated by the type of event, interaction with other competitors and the environmental conditions. Competitive road cycling events have previously been well described, and it is clear that different events have specific performance demands and are therefore suited to cyclists of different physiological characteristics (Fernandez-Garcia et al. 2000; Padilla et al. 2001; Ebert et al. 2006; Vogt et al. 2006). Whilst all competitive road cyclists require a highly developed aerobic capacity, descriptive studies indicate cyclists within professional male cycling teams have different physiological and anthropometrical profiles dependent upon their areas of speciality (Padilla et al. 1999; Lucia et al. 2000; Mujika and Padilla 2001). For example Padilla et al. (1999) reported that time-trial specialists generally have lower frontal areas and body surface area to mass ratios, as well as higher power outputs when compared to uphill, all terrain or flat specialists.

In addition to studies describing the physiological characteristics of different specialists, further investigations have examined the physiological predictors of performance via comparison between graded exercise tests (GXT) and laboratory and field based cycling time-trials (Hawley and Noakes 1992; Balmer et al. 2000; Stickland et al. 2000; Bentley et al. 2001; Kenefick et al. 2002; Amann et al. 2004a; Amann et al. 2004b; Bentley et al. 2005; Tan and Aziz 2005; Amann et al. 2006; Dumke et al. 2006; McNaughton et al. 2006; Anton et al. 2007; Morris and Shafer 2010; Costa et al. 2011; Storen et al. 2013). In the majority of these investigations, a constant flat gradient (i.e. flat), self-paced time-trial has been used as the performance measure. Results reported in several of these studies indicate there is a strong to very strong relationship ($r = 0.69-0.72$) between flat time-trial performance and absolute maximal oxygen uptake ($\dot{V}O_{2peak}$) (Stickland et al. 2000; Bentley et al. 2001). However, these studies generally report weaker correlation ($r = 0.11-0.59$) between relative $\dot{V}O_{2peak}$ and time-trial performance. Strong to nearly perfect correlations have been reported between lactate threshold ($r = 0.67-0.97$) (Bentley et al. 2001; McNaughton et al. 2006; Anton et al. 2007; Morris and Shafer 2010; Storen et al. 2013) or ventilatory threshold (VT) ($r = 0.61-0.90$) (Amann et al. 2004a; Amann et al. 2004b; Amann et al. 2006) reported as absolute power output and flat time-trial performance of various distances. Several studies (Tan and Aziz 2005; Anton et al. 2007; Costa et al. 2011) in which a



constant uphill gradient was used as the performance test, report stronger correlations between cycling performance physiological variables when values are scaled relative to a proponent of body mass. However, as all previous studies have used a performance test with a constant gradient profile, the physiological correlates of rolling terrain cycling performance remain unknown.

Interestingly, differences in the strength of correlations between flat and uphill cycling suggest there may be a shift in the relative importance of physiological variables to cycling performance when the terrain changes. However, to our knowledge, there are no studies examining the physiological correlates of rolling terrain cycling performance during which cyclists must respond to frequent variations in gradient. Given the growing prevalence of rolling terrain time-trials in cycling Grand Tours (for example stage nine of the 2016 Giro d'Italia) it seems pertinent that research examine the physiological predictors of performance in such events. Fortunately, recent advances in ergometer technology allow for test protocols that better mimic changes in resistance that cyclists face when cycling over rolling terrain. Therefore, whilst the physiological profile best suited to constant gradient self-paced and experimenter paced time-trials is well established, it is unclear whether rolling terrain time-trial performance requires specific development of a similar physiological profile development. Consequently, the principal aim of this investigation was to establish the physiological correlates of rolling terrain time-trial performance.

Materials and methods

Participants

Twenty-eight competitive male cyclists (Mean \pm SD, age: 33 \pm 10 years, body mass 74 \pm 7 kg, height 178 \pm 5 cm) gave their written informed consent to participate in this study. All cyclists had a minimum of two years

Table 1. Physiological and performance characteristics of cyclists (mean \pm SD).

Variable	Mean \pm SD
Time-trial time (mm:ss)	37:39 \pm 2:28
Time-trial power output (W)	288 \pm 29
Time-trial power output ($W \cdot kg^{-1}$)	3.9 \pm 0.6
Peak power output (W)	352 \pm 29
Peak power output ($W \cdot kg^{-1}$)	4.8 \pm 0.6
Maximal oxygen uptake ($L \cdot min^{-1}$)	4.8 \pm 0.4
Maximal oxygen uptake ($mL \cdot kg^{-1} \cdot min^{-1}$)	64 \pm 7
OBLA (W)	289 \pm 35
OBLA ($W \cdot kg^{-1}$)	3.9 \pm 0.6
OBLA (%PPO)	82 \pm 6
VT (W)	288 \pm 29
VT ($W \cdot kg^{-1}$)	3.9 \pm 0.6
VT (%PPO)	82 \pm 4
Gross Efficiency (%)	21.8 \pm 1.2

of racing experience and were competitive at A and B grade Oceania National level. The study was completed in the cyclist's competitive phase and was carried out in accordance with the ethical and procedural requirements of the journal (Harriss and Atkinson 2013) and approved by the institutional human research ethics committees.

Study design and general procedures

The study was a repeated measures experimental trial where each cyclist completed a GXT and two computer-simulated 20-km variable gradient time-trials. In accordance with the recommendations of Currell and Jeukendrup (2008), the first trial served as a habituation trial to familiarise participants with the test procedure and the second as the experimental trial. All tests were completed on an electro-magnetically braked cycle ergometer (Velotron Dynafit Pro, RacerMate Inc, Seattle, USA) using the company's associated 3D Race and Coaching Software packages. Prior to the first trial, the Velotron factory calibration was confirmed according to manufacturer instructions using the "Accuwatt" function. During the first testing session each participant was fitted to the ergometer in a position to replicate their own racing bicycle; the fit measurements were recorded and repeated for each subsequent session. In the 24 hours before any testing session, participants were instructed to prepare as if it was a competition, and to avoid strenuous physical activity and any performance altering supplements. Participants reported to the laboratory approximately 30 minutes prior to each test having slept a minimum of seven hours and in a well fed and hydrated state. Throughout all tests, cooling was provided via two 30 cm pedestal fans and the ambient temperature of the laboratory was controlled at $\sim 20^{\circ}C$ with a relative humidity of $\sim 50-60\%$.

Graded Exercise Test

Cyclists completed a GXT to volitional exhaustion, from which measures of peak power output (PPO), $\dot{V}O_{2peak}$, power at the 4 mmol/L lactate point (OBLA), VT and gross efficiency (GE) were assessed. During the GXT respiratory gases were continuously measured breath-by-breath with a metabolic cart (Metalyser 3B, Cortex, Leipzig, Germany) calibrated in accordance with the manufacturer instruction using Alpha gas standards. Cyclists initially began exercising at 100 W increasing by 40 W every four minutes thereafter until reaching volitional exhaustion. The ergometer was set to isokinetic mode during the GXT so that power output remained constant regardless of changes in pedal cadence. Cyclists were allowed to freely vary their cadence during the test though were encouraged to maintain a cadence of ~ 90 revolutions per minute. During the final 30 seconds of each stage, 25 μL of blood was collected from the participant's fingertip and immediately analysed for whole blood lactate concentration using an automated system (YSI 1500, Yellow Springs, OH, USA) calibrated to the manufacturer's specifications. Peak power output in the

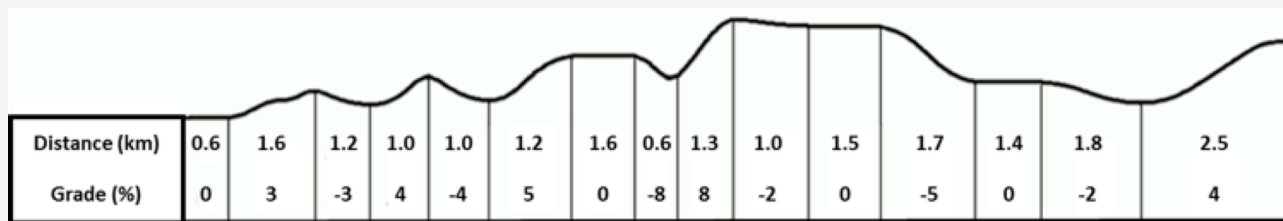


Figure 1

test was determined as the final completed stage plus the proportion of any uncompleted stage reached during the GXT in accordance with Kuipers et al. (1985). Maximal oxygen uptake was determined as the highest 30-second oxygen uptake value recorded during the test. The onset of blood lactate accumulation (OBLA) was determined as the power at which blood lactate reached a fixed concentration of 4 mmol/L using the Lactate-E software (Newell et al. 2007) and expressed as absolute power output (OBLA), power output relative to body mass ($OBLA_{W \cdot kg^{-1}}$) and as a percentage of PPO ($OBLA_{\%PPO}$). Ventilatory threshold was determined as the breakpoint in $VE/\dot{V}O_2$ without a concomitant rise in $VE/\dot{V}CO_2$ in accordance with the methods of (Amann et al. 2004b) and expressed as absolute power output (VT), power output relative to body mass ($VT_{W \cdot kg^{-1}}$) and as a percentage of PPO ($VT_{\%PPO}$). Gross efficiency (GE) was determined from $\dot{V}O_2$ and RER data collected during the last minute of the 220 W stage of the GXT in accordance with the method described by de Koning et al. (2012) and is expressed as the ratio of mechanical power output to metabolic power input (%).

Time-trial

The time-trial was completed on a computer simulated course using the same ergometer as previously described and a novel test protocol that has been shown to be a reliable measure of cycling performance time and power output (Clark et al. 2014). During the time-trial there was a total elevation gain of 352 m and an elevation of loss of 265 m, leading to a difference in meters above sea-level from start to finish of 87 m at a mean gradient of 0.44%. The developed course was based upon topography of a local racing circuit and consisted of numerous changes in gradient represented by both ascents and descents as shown in figure 1. Participants were able to view the course profile and their progress over the course on a computer monitor and were provided with information on distance completed and gear selected; all other information was blinded. Participants were requested to complete each time-trial as quickly as possible with no restriction on gear selection, cadence or cycling posture (seated or standing). Participants were not restricted to a set pacing strategy and were not coached on how to best ride the course. Throughout the trial participants were able to consume water *ad libitum*.

Statistical analysis

All descriptive statistics are reported as means ± standard deviation. The relationship between physiological variables measured during the GXT and performance time, mean power output and mean power output relative to body mass in the variable gradient time-trial were examined using Pearson’s product-moment correlation coefficient and are reported ± 90% confidence limits. Magnitudes of the correlation between variables were interpreted and reported using the thresholds of 0.1, 0.3, 0.5, 0.7 and 0.9 for small, moderate, large, very large and nearly perfect correlations, respectively, according to the recommendations of Hopkins (2010). Correlation coefficients below 0.1 were considered trivial. Given the study sample size, any correlation above $r = 0.45$ was considered significant at $\alpha = 0.05$. The difference in mean power output for flat, uphill and downhill segments was estimated using a spreadsheet via the unequal-variances t statistic computed for difference between the mean power outputs for each of the three segment types (Hopkins 2006). Magnitudes of the standardised differences were interpreted and reported using the effect size thresholds of 0.2, 0.5, and 0.8 for small, moderate, and large differences, respectively, in accordance with the recommendations of Cohen (1986). Effect size values <0.2 were considered trivial differences.

Results

Cyclist time-trial performance and physiological characteristics are shown in table 1. There were a moderate to large differences (4.6-10.9%, $ES = 0.50-1.22$) between overall mean power output and mean power output for each segment category (table 2). Similarly, there were moderate to large differences (6.6-12.1%, $ES = 0.72-1.36$) in mean power output between flat and both uphill and downhill segments, and there was a large difference (17.9%, $ES = 2.09$) in mean power output between uphill and

Table 2. Characteristics and mean power output for overall time-trial and flat, uphill and downhill segments (mean ± SD)

	Overall (mean ± SD)	Flat (mean ± SD)	Uphill (mean ± SD)	Downhill (mean ± SD)
Distance (km)	20	5.1	7.6	7.3
Grade (%)	0.5	0	4.8 ± 1.9	-4.0 ± 2.3
Power (W)	294 ± 28.9	281 ± 36.7	318 ± 28.6	263 ± 33.0

	TT _{TIME}			
TT _w	-0.94 (-0.89, 0.97)	TT _w		
TT _{w.kg⁻¹}	-0.88 (-0.78, -0.94)	0.83 (0.70, 0.91)	TT _{w.kg⁻¹}	
PPO	-0.73 (-0.54, -0.85)	0.82 (0.68, 0.90)	0.46 (0.17, 0.68)	
PPO _{w.kg⁻¹}	-0.89 (-0.80, -0.94)	0.83 (0.70, 0.91)	0.95 (0.91, 0.97)	Nearly Perfect
VO ₂ max (L.min ⁻¹)	-0.50 (-0.22, -0.71)	0.63 (0.39, 0.79)	0.22 (-0.11, 0.50)	Very Large
VO ₂ max (mL.kg ⁻¹ .min ⁻¹)	-0.83 (-0.70, -0.91)	0.81 (0.66, 0.90)	0.87 (0.76, 0.93)	Large
OBLA _w	-0.56 (-0.29, -0.75)	0.65 (0.42, 0.80)	0.35 (0.04, 0.60)	Moderate
OBLA _{w.kg⁻¹}	-0.80 (-0.65, -0.89)	0.78 (0.61, 0.88)	0.83 (0.70, 0.91)	Small
OBLA _{%PPO}	-0.07 (0.25, -0.38)	0.11 (-0.22, 0.41)	-0.07 (-0.44, 0.19)	Trivial
VT _w	-0.74 (-0.55, -0.86)	0.84 (0.71, 0.91)	0.59 (0.34, 0.76)	
VT _{w.kg⁻¹}	-0.84 (-0.71, -0.91)	0.82 (0.68, 0.90)	0.94 (0.89, 0.97)	
VT _{%PPO}	-0.27 (0.05, -0.54)	0.32 (0.00, 0.58)	0.39 (0.08, 0.63)	
GE (%)	-0.70 (-0.49, -0.83)	0.67 (0.45, 0.81)	0.65 (0.42, 0.80)	

Abbreviations: TT_{TIME} = time-trial performance time; TT_w = time-trial mean power output; TT_{w.kg⁻¹} = time-trial mean power output relative to body mass; PPO = peak power output; PPO_{w.kg⁻¹} = peak power output relative to body mass; VO₂max (L.min⁻¹) = absolute maximal oxygen uptake; VO₂max (mL.kg⁻¹.min⁻¹) = relative maximal oxygen uptake; OBLA_w = power output at onset blood lactate; OBLA_{w.kg⁻¹} = power output at onset blood lactate relative to body mass; OBLA_{%PPO} = power output at onset blood lactate relative to peak power output; VT_w = absolute ventilatory threshold; VT_{w.kg⁻¹} = power output at ventilatory threshold relative to body mass; VT_{%PPO} = power output at ventilatory threshold relative to peak power output; GE (%) = cycling gross efficiency.

downhill segments.

The strength of correlations between time-trial performance and physiological variables was dependent on the manner in which performance and physiological parameters were expressed (Figure 2). Time-trial time was strongly to very strongly correlated (r = -0.50 to -0.84) to all physiological variables with the exception of OBLA_{%PPO} and there were very large to nearly perfect correlations between time-trial time and other performance measures (r = -0.73 to -0.94). Similarly there were large to very large correlations (r = 0.65 to 0.84) between time-trial mean power output and all measures (physiological and performance) with the exception of OBLA and VT when expressed as fractional utilisation of PPO (r = 0.11-.32). Relative time-trial mean power output was very strongly to nearly perfectly correlated with all physiological variables and performance measures expressed relative to body mass (r = 0.83 to 0.95) however the strength of correlations reduced when the same variables were expressed as an absolute value (r = 0.22-0.59). There was a large to very large correlation between time-trial time and relative time-trial mean power output and

body mass (r = 0.55 & -0.81 respectively). However the correlation between time-trial mean power output and body mass was only moderate (r = -0.37).

Discussion

The aim of the present study was to establish the correlations between physiological and performance measures during a novel variable gradient individual cycling time-trial. Results from this study show that rolling terrain time-trial performance time is most strongly related to physiological and performance variables assessed during a GXT when measured variables are expressed relative to body mass. Further, results indicate physiological variables expressed as a fractional utilisation of PPO correlate poorly with rolling terrain time-trial performance time and mean power output and are therefore poor predictors of performance.

Similar to previous studies that have used flat profile performance tests, the measure from a GXT that was most strongly related to variable gradient time-trial performance was PPO (Balmer et al. 2000; Bentley et al. 2001; McNaughton et al. 2006; Levin et al. 2014). However, the strength of the relationship between PPO and time-trial performance increased when PPO was expressed relative to body mass. Previous investigations also report stronger correlations with uphill time-trial performance when PPO is expressed relative to body mass (Heil et al. 2001; Tan and Aziz 2005; Anton et al. 2007; Costa et al. 2011). In contrast to these studies in which the time-trial was exclusively uphill, the uphill segments of the protocol used in this study only comprised

little more than one-third of the total course distance (7.6 km), the rest being either flat (5.1 km) or downhill (7.3 km). Therefore, even with the inclusion of segments where greater mass may yield higher speeds, and subsequently better performance time (Nevill et al. 2006), PPO scaled to body mass is an important determinant of variable gradient cycling performance. Subsequently, it is important that cyclists who are targeting rolling or variable gradient events optimise their power to mass ratio to improve performance. In line with previous research, there were moderate to strong correlations between cycling performance and $\dot{V}O_2$ peak (Stickland et al. 2000; Bentley et al. 2001; Bentley et al. 2005; Storen et al. 2013), OBLA (Bentley et al. 2001; McNaughton et al. 2006; Morris and Shafer 2010; Storen et al. 2013) and VT (Amann et al. 2004a; Amann et al. 2004b; Amann et al. 2006). However, similar to PPO, when variables were expressed relative to body mass, the strength of relationships was increased. Gregory et al. (2007) reported similar correlations between physiological variables expressed relative to mass and mountain bike performance which included multiple changes in gradient. Therefore, it

appears the inclusion of uphill segments in self-paced performance tests increases the importance of expressing physiological variables relative to body mass.

In contrast to earlier research (Bentley et al. 2005) there was a very strong correlation between cycling gross efficiency and time-trial performance time. These results suggest comparison of physiology and performance from constant grade tests underestimate the importance of GE to field cycling performance. Importantly, muscle fibre type recruitment and substrate utilisation are different for variable intensity cycling (Palmer et al. 1997) and GE decreases when cycling up steep hills (> 4%) (Arkesteijn et al. 2013), a similar grade to the uphill segments included in the performance test of the current study. Additionally, GE is trainable (Hopker et al. 2010), improves throughout a competitive cycling season (Hopker et al. 2009) and is considered an important determinant of endurance performance (Joyner and Coyle 2008). Therefore, testing protocols for competitive cyclists should include some measure of GE to present an analysis of physiology relevant to field cycling performance.

In agreement with previous research (Bentley et al. 2005; Storen et al. 2013), the physiological measures that did not, at least, share a moderate correlation with time-trial performance were OBLA and VT expressed as a fractional utilisation of PPO. Previous studies indicate fractional utilisation is a stable measure and is generally not as responsive to training as other physiological variables (Rønnestad et al. 2012). In a group of well-trained competitive cyclists, it is likely other physiological variables are more important determinants of overall cycling performance and should therefore be the main focus of training programs.

A limitation of the current study is that the ergometer used does not actively drive the pedals or actively speed up the flywheel during downhill segments somewhat limiting its ecological validity to simulate downhill cycling. However, the ergometer takes cyclists body mass into account to determine flywheel resistance and the power output-speed relationship, suggesting heavier cyclists would achieve higher speed for lower power output during downhill segments. A further limitation was the lack of a set cadence during the GXT. While participants were encouraged to maintain a cadence of ~90 revolutions per minute, they were allowed to freely select cadence which may have artificially altered their GE value.

Conclusion

Performance in rolling terrain time-trials is more closely related to physiological variables when they are expressed relative to body mass as opposed to their absolute values. Overall results suggest the strongest determinants of rolling terrain time-trial performance are PPO and $\dot{V}O_{2peak}$ scaled to body mass. Conversely, the correlation between fractional utilisation and performance was poor. Therefore, cyclists targeting rolling terrain events require a highly developed, efficient aerobic energy system and the

ability to generate high power output relative to body mass.

Practical applications

These data highlight the physiological variables that underpin rolling terrain cycling performance and indicate cyclists targeting rolling terrain events need to produce high power relative to body mass and have a high relative $\dot{V}O_{2peak}$. When assessing performance and physiology, sport scientists should evaluate and report results as absolute and relative values to better predict performance potential in rolling terrain events. Additionally, gross efficiency should be measured and reported during routine physiological assessment of cyclists as it is likely an important determinant of competitive performance particularly when the course is over rolling terrain. However, VT and OBLA expressed as a percentage of PPO (fractional utilisation) were poorly correlated with performance and were largely homogenous between cyclists of different ability. As such cyclists should focus on training strategies that target maximal aerobic power and gross efficiency as opposed to fractional utilisation to improve performance in rolling terrain events.

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References

1. Amann M, Subudhi A, Foster C (2004a) Influence of testing protocol on ventilatory thresholds and cycling performance. *Med Sci Sports Exerc* 36 (4): 613-622
2. Amann M, Subudhi AW, Foster C (2006) Predictive validity of ventilatory and lactate thresholds for cycling time trial performance. *Scand J Med Sci Sports* 16 (1): 27-34
3. Amann M, Subudhi AW, Walker J, Eisenman P, Shultz B, Foster C (2004b) An evaluation of the predictive validity and reliability of ventilatory threshold. *Med Sci Sports Exerc* 36 (10): 1716-1722
4. Anton MM, Izquierdo M, Ibanez J, Asiain X, Mendiguchia J, Gorostiaga EM (2007) Flat and uphill climb time trial performance prediction in elite amateur cyclists. *Int J Sports Med* 28 (4): 306-313
5. Arkesteijn M, Jobson SA, Hopker J, Passfield L (2013) Effect of gradient on cycling gross efficiency and technique. *Med Sci Sports Exerc* 45 (5): 920-926
6. Balmer J, Davison RC, Bird SR (2000) Peak power predicts performance power during an outdoor 16.1-km cycling time trial. *Med Sci Sports Exerc* 32 (8): 1485-1490
7. Bentley DJ, McNaughton LR, Thompson D, Vleck VE, Batterham AM (2001) Peak power output, the lactate threshold, and time trial performance in cyclists. *Med Sci Sports Exerc* 33 (12): 2077-2081
8. Bentley DJ, Vleck VE, Millet GP (2005) The isocapnic buffering phase and mechanical efficiency: relationship to cycle time trial performance of short and long duration. *Can J Appl Physiol* 30 (1): 46-60
9. Clark B, Paton CD, O'Brien BJ (2014) The Reliability of Performance During Computer-Simulated Varying Gradient Cycling Time Trials. *Journal of Science in Cycling* 3 (3)
10. Cohen J (1988) *Statistical power analysis for the behavioral sciences* Lawrence Erlbaum, New Jersey
11. Costa VP, Pertence LC, Paton CD, De Matos DG, Martins JAN, De Lima JRP (2011) Physiological Correlates of 10-Km Up-hill Cycling Performance in Competitive Cyclists. *Journal of Exercise Physiology Online* 14 (3): 26-33

12. Currell K, Jeukendrup AE (2008) Validity, reliability and sensitivity of measures of sporting performance. *Sports Med* 38 (4): 297-316
13. de Koning JJ, Noordhof DA, Lucia A, Foster C (2012) Factors affecting gross efficiency in cycling. *Int J Sports Med* 33 (11): 880-885
14. Dumke CL, Brock DW, Helms BH, Haff GG (2006) Heart rate at lactate threshold and cycling time trials. *The Journal of Strength & Conditioning Research* 20 (3): 601-607
15. Ebert TR, Martin DT, Stephens B, Withers RT (2006) Power output during a professional men's road-cycling tour. *Int J Sports Physiol Perform* 1 (4): 324-335
16. Fernandez-Garcia B, Perez-Landaluce J, Rodriguez-Alonso M, Terrados N (2000) Intensity of exercise during road race pro-cycling competition. *Med Sci Sports Exerc* 32 (5): 1002-1006
17. Gregory J, Johns DP, Walls JT (2007) Relative vs. Absolute Physiological Measures as Predictors of Mountain Bike Cross-Country Race Performance. *The Journal of Strength & Conditioning Research* 21 (1): 17-22
18. Harriss DJ, Atkinson G (2013) Ethical standards in sport and exercise science research: 2014 update. *Int J Sports Med* 34 (12): 1025-1028
19. Hawley JA, Noakes TD (1992) Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. *Eur J Appl Physiol Occup Physiol* 65 (1): 79-83
20. Heil DP, Murphy OF, Mattingly AR, Higginson BK (2001) Prediction of uphill time-trial bicycling performance in humans with a scaling-derived protocol. *Eur J Appl Physiol* 85 (3-4): 374-382
21. Hopker J, Coleman D, Passfield L (2009) Changes in cycling efficiency during a competitive season. *Med Sci Sports Exerc* 41 (4): 912-919
22. Hopker J, Coleman D, Passfield L, Wiles J (2010) The effect of training volume and intensity on competitive cyclists' efficiency. *Appl Physiol Nutr Metab* 35 (1): 17-22
23. Hopkins WG (2006) Spreadsheets for analysis of controlled trials with adjustment for a predictor. *SportScience* 10: 46-50
24. Hopkins WG (2010) Linear Models and Effect Magnitudes for Research, Clinical and Practical Applications. *SportScience* 14: 49-58
25. Joyner MJ, Coyle EF (2008) Endurance exercise performance: the physiology of champions. *J Physiol* 586 (1): 35-44
26. Kenefick RW, Mattern CO, Mahood NV, Quinn TJ (2002) Physiological variables at lactate threshold under-represent cycling time-trial intensity. *J Sports Med Phys Fitness* 42 (4): 396-402
27. Kuipers H, Verstappen FT, Keizer HA, Geurten P, van Kranenburg G (1985) Variability of aerobic performance in the laboratory and its physiologic correlates. *Int J Sports Med* 6 (4): 197-201
28. Levin GT, Laursen PB, Abbiss CR (2014) Reliability of physiological attributes and their association with stochastic cycling performance. *Int J Sports Physiol Perform* 9 (2): 309-315
29. Lucia A, Joyos H, Chicharro JL (2000) Physiological response to professional road cycling: climbers vs. time trialists. *Int J Sports Med* 21 (7): 505-512
30. McNaughton LR, Roberts S, Bentley DJ (2006) The relationship among peak power output, lactate threshold, and short-distance cycling performance: effects of incremental exercise test design. *The Journal of Strength & Conditioning Research* 20 (1): 157-161
31. Morris DM, Shafer RS (2010) Comparison of Power Outputs During Time Trialing and Power Outputs Eliciting Metabolic Variables in Cycle Ergometry. *International Journal of Sport Nutrition & Exercise Metabolism* 20 (2): 115-121
32. Mujika I, Padilla S (2001) Physiological and performance characteristics of male professional road cyclists. *Sports Med* 31 (7): 479-487
33. Nevill AM, Jobson SA, Davison RC, Jeukendrup AE (2006) Optimal power-to-mass ratios when predicting flat and hill-climbing time-trial cycling. *Eur J Appl Physiol* 97 (4): 424-431
34. Newell J, Higgins D, Madden N, Cruickshank J, Einbeck J, McMillan K, McDonald R (2007) Software for calculating blood lactate endurance markers. *Journal of Sports Sciences* 25 (12): 1403-1409
35. Padilla S, Mujika I, Cuesta G, Goiriena JJ (1999) Level ground and uphill cycling ability in professional road cycling. *Med Sci Sports Exerc* 31 (6): 878-885
36. Padilla S, Mujika I, Orbananos J, Santisteban J, Angulo F, Jose Goiriena J (2001) Exercise intensity and load during mass-start stage races in professional road cycling. *Med Sci Sports Exerc* 33 (5): 796-802
37. Palmer GS, Noakes TD, Hawley JA (1997) Effects of steady-state versus stochastic exercise on subsequent cycling performance. *Med Sci Sports Exerc* 29 (5): 684-687
38. Ronnestad BR, Hansen J, Ellefsen S (2012) Block periodization of high-intensity aerobic intervals provides superior training effects in trained cyclists. *Scand J Med Sci Sports*
39. Stickland MK, Petersen SR, Dressendorfer RH (2000) Critical aerobic power during simulated 20 km bicycle racing. *Sports Medicine, Training and Rehabilitation* 9 (4): 289-301
40. Storen O, Ulevag K, Larsen MH, Stoa EM, Helgerud J (2013) Physiological determinants of the cycling time trial. *The Journal of Strength & Conditioning Research* 27 (9): 2366-2373
41. Tan FH, Aziz AR (2005) Reproducibility of outdoor flat and uphill cycling time trials and their performance correlates with peak power output in moderately trained cyclists. *J Sports Sci Med* 4 (3): 278-284
42. Vogt S, Heinrich L, Schumacher YO, Blum A, Roecker K, Dickhuth HH, Schmid A (2006) Power output during stage racing in professional road cycling. *Med Sci Sports Exerc* 38 (1): 147-151