The Physiology of Road Cycling: New Testing and Training Methodologies for Competitive Cyclists

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Submitted in fulfilment of the requirements of the degree

Doctor of Philosophy

August 2014

ABSTRACT

Objective: The objective of this project is to describe and test the efficacy of new testing and training techniques for competitive cyclists. **Methods:** Physiological variables and cycling performance were measured during a graded exercise test (GXT) and a novel, computer-simulated, variable gradient 20-km cycling time-trial. Initially, data collected from the time-trial and GXT were used to establish the reliability of the time-trial, determine the laboratory correlates of hilly cycling performance and examine the pacing pattern during hilly cycling performance. Then, results from a series of GXT's and time-trials were used to establish the effects of a brief period of overload training on the physiology and performance of competitive cyclists. Results: Power output and performance time measured during a computer simulated 20-km variable gradient cycling test were reliable, however reliability diminished with increasing time between trials. Performance in variable gradient time-trial correlated strongly with absolute measures of physiological variables; however the strength of correlations increased when variables were measured relative to body mass. Power output was highest during the first four and last two kilometres of a variable gradient time-trial. Additionally, there were large differences in power output between consecutive one kilometre segments throughout the trial, particularly when the difference in gradient between segments was greater. Performance in the variable gradient time-trial improved substantially following a brief period of overload training. Performance improvement corresponded with adaptation in important physiological determinants of cycling performance, namely maximal oxygen uptake, lactate threshold and gross efficiency. **Conclusions:** Variable gradient, cycling time-trial tests can be used to detect meaningful changes in performance, evoke dynamic distribution of power output and are best suited to cyclists who produce high power outputs relative to body mass. The current project also determined that a brief period of overload training induces physiological adaptation and substantial improvement in cycling performance in competitive cyclists. Sport scientists, coaches and cyclists can use this information to determine the testing and training techniques used in preparation for competition.

ACKNOWLEDGEMENTS

Firstly I would like to acknowledge and thank my principle supervisor Dr. Brendan O'Brien for his encouragement, patience and direction throughout this project. During my seven years of tertiary education at the University of Ballarat, the examples he set as a lecturer and researcher were something for me to aspire to and challenge myself to achieve. The academic skills and life knowledge he imparted on me were imperative to my development as a researcher and preparation of this thesis. Most importantly, his friendship was invaluable and is something I will cherish into the future.

Secondly, I would like to thank my associate supervisor Dr. Carl Paton for his wisdom and guidance throughout this project. His ability to constantly get me to question the status quo allowed me to develop essential skills and new ideas on which to base my research. Carl's example as a researcher and passion for the science of competitive cycling encouraged me to extend myself throughout this project. I will be forever grateful for his friendship and particularly for inviting me to spend time with him in his home to write up studies one and four.

I would also like to thank the cyclists whose participation in this series of investigations made this project possible. The enthusiasm and vigour the participants brought to this project were invaluable. The commitment of time and energy which I asked participants to make, particularly for the final study, was large and I very much appreciate their efforts.

I would like to thank the broader academic community in the School of Human Movement and Exercise Science at the University of Ballarat for their collective insight and encouragement throughout this project. The collegial environment in which senior staff and fellow post-graduate students interact was a vital tool in my personal development.

Finally I would like to thank my partner Mel, and my family and friends for their love, support and patience throughout this three year project. Their encouragement and inspiration throughout this time was outstanding and without it, completing this project would not have been possible.

DECLARATION

This thesis describes the original work carried out by the author in the School of Health Sciences at the University of Ballarat and subsequently Federation University Australia from January 2011 to August 2014.

Bradley Clark

(18th August, 2014)

LIST OF PUBLICATIONS

The following is a list of journal articles where this work or portions of this work have been published.

Clark, B., Paton, C.D. & O'Brien, B.J. (2014). The reliability of performance during simulated dynamic gradient cycling time-trials. *Journal of Science in Cycling, 3 (3).*

Clark, B., Costa, V.P., O'Brien, B.J., Guglielmo, G.M. & Paton, C.D. (2014). Effects of a seven day overload-period of high-intensity training on performance and physiology of competitive cyclists. *PLoS ONE 9(12): e115308. doi:10.1371/journal.pone.0115308.*

LIST OF CONFERENCE PRESENTATIONS

The following is a list of conference proceedings where this work or portions of this work have been presented.

Clark, B., Paton, C.D. & O'Brien, B.J. The reliability of power output and performance time during simulated dynamic gradient cycling time-trials. The 18th Annual Congress of the European College of Sports Science (ECSS), Barcelona, 2013.

Paton, C.D., Clark, B., Costa, V.P., O'Brien, B.J., Guglielmo, G.M. Effects of a seven day overload-period of high-intensity training on performance and physiology of competitive cyclists. The World Congress of Cycling Science (WCCS), Kent, 2014.

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CHAPTER 1.

INTRODUCTION

1.1 OVERVIEW AND SIGNIFICANCE OF RESEARCH PROJECT

The aim of this project was to identify and describe, new testing and training techniques to be used in the assessment and preparation of competitive cyclists. This dissertation is a series of studies that describes the characteristics of a novel performance test and the effects of a short block of intensified training on performance in that test. The first of four studies established the short-term reliability of the new performance measure and also examined the effects of increasing time between trials on re-test reliability. The second study was an examination of the physiological correlates of performance in the novel, variable gradient performance test. The third study was an observational analysis of the spontaneous pacing patterns used by cyclists to complete the novel performance test. In the final study, a short block of intensified training was implemented in a sample of competitive cyclists to determine the effects of intensified training on physiological variables and performance in the novel test.

Overall, the results presented by this collection of investigations define the efficacy and performance characteristics of a new computer simulated, variable gradient time-trial. Specific results from this thesis provide important evidence that justifies the use of a new performance test to assess a cyclist before and after a specific training block or experimental intervention. Additionally, results from the fourth study provide empirical evidence of the effects of a training technique commonly used by coaches and cyclists to prepare for important competitive events. Importantly, results indicate short blocks of intensified training can be useful to coaches, sports scientists and cyclists in the preparation for competition.

1.2 THEORETICAL FRAMEWORK

Two theoretical training frameworks underpin the fourth study in this series of investigations. Firstly is the theory of super compensation, a theory of training originally termed by Yakovlew in 1967. The theory suggests that in the process of restoring metabolites to normal levels following a training stimulus, the body may over restore or super compensate creating an improved physiological state and performance standard.[1] The traditional theory is demonstrated in figure 1-1 below.

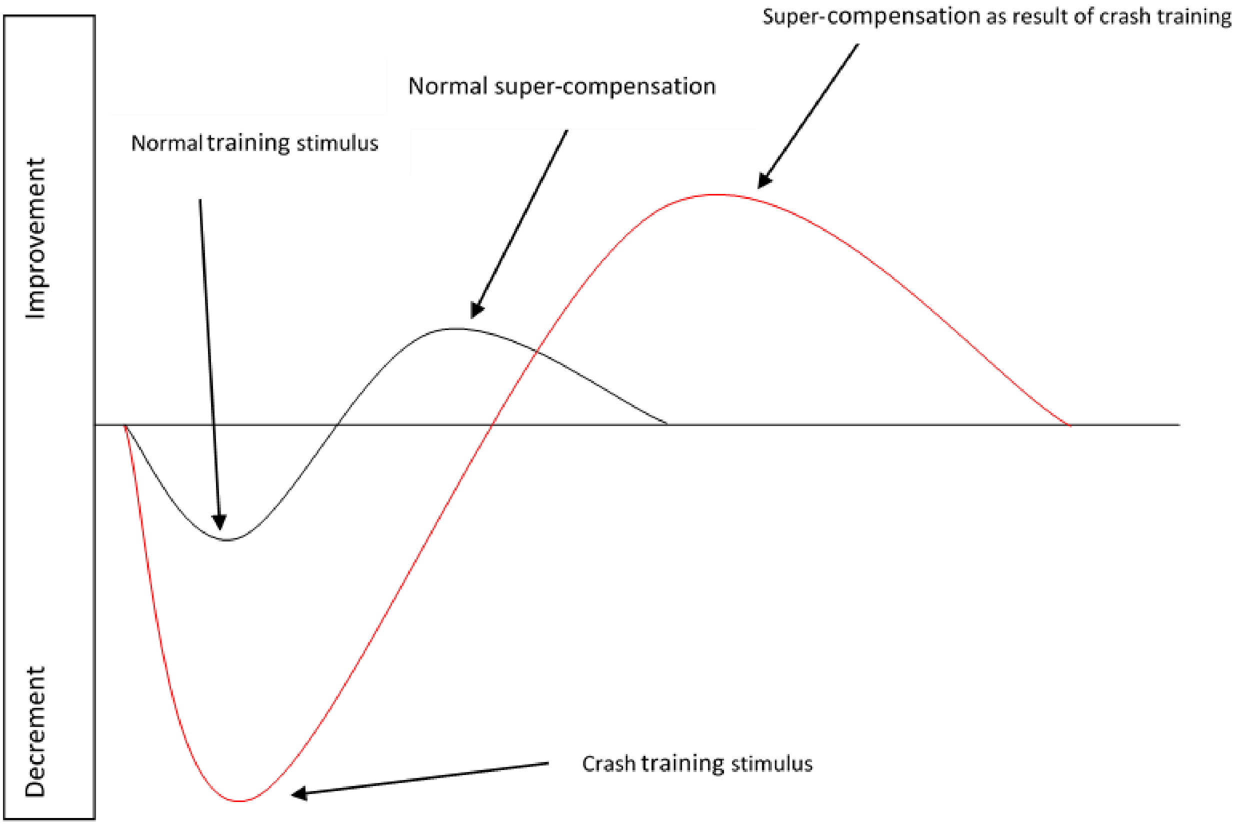

Figure 1-1 Model of Super compensation modified from Bompa[1].

Also shown in figure 1-1 is the postulated effect of the training stimulus being implemented in study four. In a similar fashion to the popular form of an overloading or shock micro cycle[2] it is proposed a short block of intensified training will result in a greater overall transitional fatigue and therefore a temporary diminishment of fitness and performance.

However, following a recovery interval it is expected an extended super-compensatory period will occur resulting in a re-bound improvement in fitness and performance.

The second theoretical training model is the fitness-fatigue theory originally proposed by Bannister.[3] In this model it is suggested there are two opposing effects of training, a fitness effect which improves physiological state and performance, and a negative effect of fatigue. However it is proposed the fatigue effect, whilst larger in magnitude, is resolved three times as fast as the duration of the fitness effect leading to an eventual improvement in preparedness or performance.[2] The figure below (Fig. 1-2) illustrates the interaction of fitness and fatigue in the fitness-fatigue model.

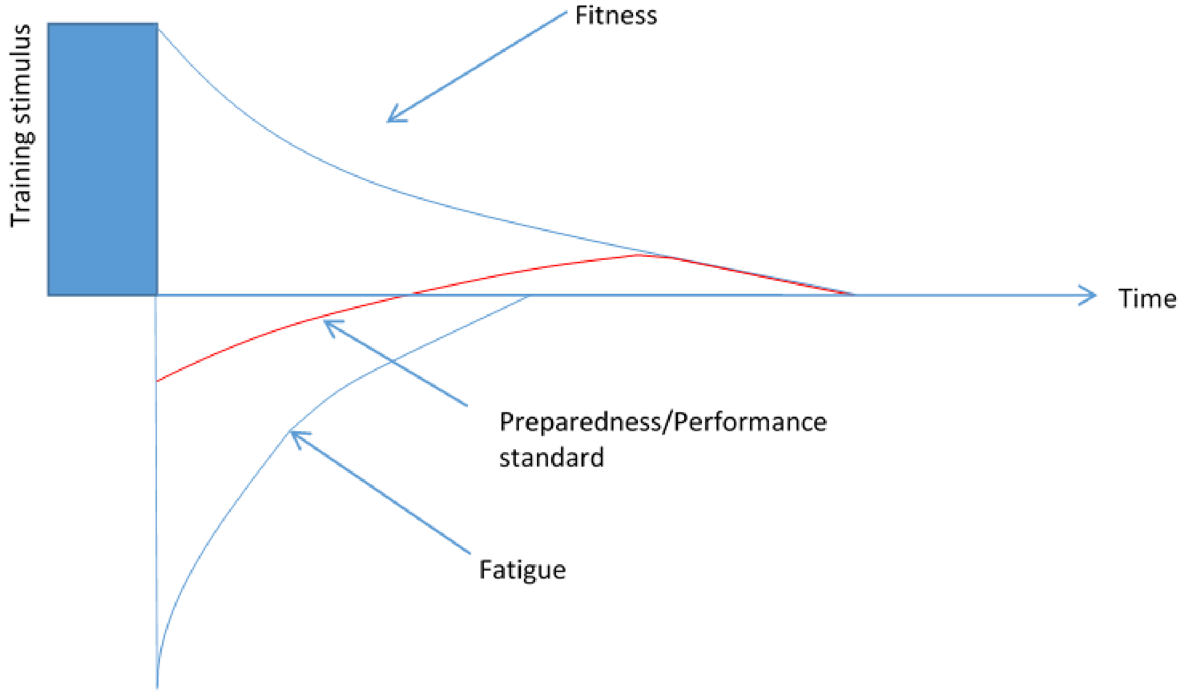

Figure 1-2 Fitness-fatigue model modified from Zatsiorsky[2].

In study four, the fitness and fatigue effect occurring as a result of overload training may be expected to be large. If the fatigue effect is resolved as quickly as suggested, it could be expected that the lasting fitness effect will result in substantial gains in fitness and an increased performance standard. In examining the fitness-fatigue model, Chiu[4] indicates that following a period of short term overreaching followed by adequate recovery, fitness can remain higher long after the fatigue effect has diminished therefore leading to performance improvements.

1.3 LIST OF ABBREVIATIONS

ATP	Adenosine triphosphate
CHO	Carbohydrate
W	Watts
RPM	Revolutions per minute (pedalling cadence)
$\mathrm{W \cdot kg^{-1}}$	Watts per kilogram of body mass.
$\dot{V}O_2$	Volume of oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
$\mathrm{mL \cdot kg^{-1} \cdot min^{-1}}$	Millilitres, per kilogram of mass, per minute
$\mathrm{L \cdot min^{-1}}$	Litres per minute
RER	Respiratory exchange ratio
PPO	Peak power output
OBLA	Onset of blood lactate accumulation
LT	Lactate threshold
VT	Ventilatory threshold

GE	Gross efficiency
ECO	Exercise economy
LSD	Long steady distance training
HIT	High intensity interval training
LIT	Long interval training
SIT	Short interval training
MIT	Maximal effort interval training
TT	Time trial
TTE	Time to exhaustion
CP	Critical power
W'	Fixed capacity to do work above the CP
PP	Power profile
MMP	Mean maximal power
kg	Kilogram
$km \cdot h^{-1}$	Kilometres per hour
km	Kilometres
s	Seconds
vs.	Versus

r	Pearson’s correlation coefficient
CV	Coefficient of variation
ICC	Intra-class correlation coefficient
ES	Effect size
CL	Confidence limits
SD	Standard deviation
n	Number
et al.	And others
%	percentage
~	Approximately
>	Greater than
<	Less than

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CHAPTER 2.

LITERATURE REVIEW

2.1 INTRODUCTION

Competitive road cycling is a multi-disciplinary sport, including massed start road races, individual time trials and criteriums, or in the instance of a stage races, a combination of these. Each competitive discipline has its own different physiological and performance demands; however all require the individual cyclist to provide forward propulsion of their bicycle against a multitude of resistive forces.

To prepare for competition, coaches, sport scientists and athletes prescribe and undertake training programs and interventions based on personal experience, empirical evidence and scientific investigation. Recent technological advances in cycling ergometers and personal cycling equipment allows for more rigorous assessment of performance, and more refined prescription and analysis of cycling training. Therefore, this review will explore articles describing performance assessment, the physiological determinants of cycling performance and the effects of specific techniques and training organisation on the physiology and performance of competitive cyclists.

2.2 PEFORMANCE TESTING OF COMPETITIVE CYCLISTS

Performance testing is a fundamental component of scientific experimentation and athletic preparation. When combined with physiological assessment, performance testing underpins our understanding of the physiological determinants of competitive events and subsequently the variables targeted for training or intervention. In the sport of road cycling, performance is the product of many variables related both to the internal and external environment of the rider, including physiology, pacing strategy, environmental resistance and equipment. Additionally, there are a variety of cycle race types, each with very distinct performance demands. Current literature describes a number of different performance measures for competitive cyclists that capture various components of competitive cycling. However, the predominant test types are time to exhaustion, fixed duration time trials and fixed distance time trials that can be self or experimenter paced. This review will examine the literature to present a description of test validity and reliability and determine areas for future research.

Time to exhaustion (TTE) tests take place on a laboratory cycling ergometer and require the cyclist to maintain constant exercise intensity until volitional exhaustion. While there are examples of TTE tests in which exercise intensity is sub-maximal,[1] they are generally completed at or above peak power output (PPO). Competitive cycling events, like TTE, require the cyclist to maintain high power outputs, often to the point of exhaustion. However, in contrast to TTE tests, the exercise intensity of competitive cycling events is often dictated by environmental conditions or other competitors, limiting the ecological validity of TTE tests.

Generally, and regardless of the exercise intensity selected, the reliability of TTE tests is poor. In an early comparison of performance tests, Jeukendrup et al. [1] reported an average coefficient of variation (CV) between consecutive tests of ~26%, far greater than the smallest worthwhile difference in performance.[2,3] Although somewhat better reliability results are reported in more recent studies,[4,5] others suggest the open ended nature of TTE tests increases the rider error associated with performance testing.[1] Rider, or more appropriately biological error, is independent of technical error associated with testing conditions or testing equipment. Importantly, it is evident TTE tests have a high degree of biological error and lack the ability to detect important beneficial changes in performance. Therefore, the low reliability and lack of ecological validity make TTE tests poor measures of cycling performance.

Fixed duration performance tests can be completed in the laboratory or in the field and require the cyclist to ride as hard as possible for a set time period. The performance outcome is then calculated as the distance completed, work completed or the average power output for the duration of the test. Several different examples of fixed duration tests are presented in current literature, the majority of which are self-paced. However, some fixed duration tests also include a fixed exercise intensity component as a prelude to a self-paced component.[1,6]

The reliability of fixed duration tests is reportedly good. In an early comparison between performance tests, Jeukendrup et al. [1] suggested work completed in a 15 minute period, preceded by a 45 minute fixed intensity pre-load, is somewhat reproducible (CV ~3.5%). Bishop [7] reported a similar level of reproducibility for power, heart rate and rating of perceived exertion (mean CV ~ 2.0-3.1%) for a fixed duration TT of one hour in a sample of 20 female cyclists. Similarly, Paton et al. [8] reported a low CV (~1.8%) between repeated trials for a shorter (5 minute) fixed duration test. However, they also reported a learning effect between the first two trials which suggests at least one habituation trial is necessary before experimental trials commence. In a more recent study, Driller et al. [6] reported strong reliability between trials for mean power and heart rate during a 15 minute pre-load, 15 minute fixed duration TT. Therefore, fixed duration tests are reliable and able to detect important changes in performance for a range of durations.

Results from fixed duration performance tests can also be applied to the power profile (PP) and critical power (CP) concepts. Using the results of laboratory based fixed duration tests, sports scientists and coaches can develop a profile of the mean power a cyclist can sustain for specific time periods.[9] The PP can be extrapolated to predict achievable mean power for a given time point as well as CP and anaerobic work capacity (W’).

In one of the first studies on application of the power profile, Quod et al. [9] reported strong agreement between mean power measured over 60-600s in the laboratory and power output for the same time periods when measured in competition. Additionally, estimations of CP and W' derived from the PP were similar to corresponding estimates from competitive events. However, mean cadence measured during PP testing in the laboratory was higher than when measured during competition. Quod et al. [9] suggested the lower cadence during competition was likely due to the variation in gradient cyclists experience when cycling in the field. The absence of gradient variation in the testing protocol of the PP may therefore limit the ecological validity of such tests.

In a series of studies, Pinot et al. [10,11] applied mean power from 12-13 field measured fixed duration time points to the PP concept. Interestingly, the authors reported differences in the PP between elite and sub-elite cyclists, changes in the PP throughout the competitive season and differences in the PP between cyclists of different specialty.[10,11] Importantly, these results indicate the PP can be used to effectively monitor changes in performance in both elite and sub-elite populations. However, the variability for repeat measures of mean power different fixed durations was quite high (CV 6.1-13.1%) which suggests field measured PP may not be reliable enough to detect small yet important changes[2,3] in performance.

An extension of the PP is the concept of CP which is defined as the maximum exercise intensity sustainable for a long time without rapid onset of fatigue.[12] Accompanying CP is W', which is defined as the limited capacity to do work above the CP.[12] Recently, the concepts of CP and W' have been applied to field and laboratory based cycling performance in order to model performance.[13-15] Estimated CP and W' from a short performance test were reported to accurately model W' exhaustion and reconstitution during intermittent exercise.[14]

Furthermore, Skiba et al. [13] applied the CP and W' concepts to accurately define the point at which cyclists are likely to become exhausted during field cycling. Although not strictly performance tests, it appears CP and W' describe important energetic interactions during high intensity and intermittent cycling. Therefore, modelling CP and W' may be used to inform pacing strategy during intermittent cycling performance and allow for accurate prediction of cycling performance. However, further validation of the CP and W' concepts and their application to laboratory and field based cycling performance is required.

Perhaps the most ecologically valid cycling performance test, fixed work time trials (TT) are completed at a self-selected pace, with instruction to complete the test as quickly as possible. The fixed work TT's most commonly used in scientific investigations take place under controlled laboratory conditions on cycling ergometers. However, there are some examples in which the TT takes place in the field on a bicycle fitted with instrumented cranks.[16,17]

Importantly, the reliability of performance measures taken from fixed duration TT's is reportedly high. The CV reported for mean power measured during fixed duration TT's varies depending on the distance of the time trial and ergometer used (CV range 1.9%-3.6%).[16,18-20] The same can be said for performance time; however reported CV is somewhat lower (CV range 0.7%-2.9%).[16,18-20] Therefore, either mean power or performance time measured during fixed work TT's are reliable enough measures to detect small worthwhile changes in performance.[2,3]

An important oversight of constant gradient self-paced protocols is a lack of variation in the external environment consistent with competitive events. To overcome this, Schabort et al. [21] and Abbiss et al. [22] described fixed distance TT's that included experimenter defined, fixed work, high intensity epochs. The reliability of mean power measured for the short version of this test is acceptable (CV ~2.4%),[22] however CV increases substantially when the test distance is tripled (CV ~3.7%).[21] Although not self-paced, stochastic performance tests provide simulation of massed start road races when cyclists must increase their intensity as would occur when responding to a breakaway or similar. However, the test protocol does not replicate the almost constant changes to environmental resistance cyclists encounter when competing in the field. Currell et al. [23] suggest a performance test should allow the athlete to adopt a similar pacing strategy to competition. Importantly, previous investigations indicate a variable pacing strategy improves performance time when cyclists encounter variation in wind conditions or gradients.[24-28] Additionally, Atkinson et al. [29] suggest athletes adjust their effort, and therefore pacing, based on internal and external feedback including perception of external environmental conditions. Therefore, it would appear commonly used constant gradient self-paced and stochastic time trials do not allow cyclists to replicate field based pacing strategy.

The previous research explored above describes a number of different performance tests, based either in a sports physiology laboratory, or less commonly, in the field. As an informative component of training and preparation, it is important that performance testing encompasses as many aspects of competition performance as possible. In this regard fixed distance time trials more closely mimic competition than other performance tests. However, as described in this review, the time trials most commonly used for performance assessment do not replicate the environmental factors cyclists encounter in the field. Therefore, great benefit will be gained from designing new performance tests more specific to competition. Subsequent studies could then establish the test’s ability to detect meaningful change in performance.

2.3 PHYSIOLOGICAL CORRELATES OF CYCLING PERFORMANCE

The fundamental physiological factors contributing to cycling success can be determined in a sports physiology laboratory by testing the cyclist's cardio-respiratory and metabolic capabilities. Laboratory assessment of competitive cyclists typically involves measuring aerobic capacity, peak power output, lactate threshold and mechanical efficiency during a graded exercise test.[30,31] Establishing the laboratory measured variables important to cycling performance enables effective and targeted fitness assessment and subsequent training prescription to maximise competition success. Therefore this review will explore the relationship between the laboratory measured variables defined above and cycling performance.

Peak power output (PPO) is a performance variable measured as part of routine laboratory assessment of a cyclist's physiology and is essentially the highest power output reached by a cyclist during a graded exercise test. Generally well correlated to maximal oxygen uptake,[32-34] PPO can be used to measure aerobic power, predict performance and for training prescription.[35]

A number of studies have investigated the relationship between PPO and constant grade, self-paced cycling TT performance. Bentley et al. [36] reported PPO output is significantly related (r = 0.91) to 90 minute TT performance. McNaughton et al. [35] reported a significant correlation between PPO and a TT of 30 minutes (r = 0.96). Similarly, Balmer et al. [17] reported a significant correlation (r = 0.99) between PPO and 16.1-km TT power output. It is apparent from the results of these studies aerobic peak power is a strong indicator of self-paced TT performance of varying durations.

Recent research indicates PPO is an important determinant of stochastic cycling performance. Levin et al. [37] reported a strong to very strong relationship between PPO and both long (100-km) and short (30-km) stochastic TT's. The nature of these TT's, during which cyclists had to complete intermittent high intensity epochs throughout the TT, is similar to a mass start road race where cyclists must adjust their efforts to stay within the peloton. Therefore, it appears PPO may also be an important indicator of performance where cyclists react to, and initiate attacks, as well as TT's where effort is more stable.

Maximal oxygen uptake ($\dot{V}O_{2max}$) is defined as the maximum rate at which oxygen can be taken up and utilised by the body during exercise in one minute.[38] Maximal oxygen uptake is considered the benchmark measure of the human body's ability to produce adenosine triphosphate (ATP) through aerobic metabolism and is reported as either an absolute ($L \cdot min^{-1}$) or relative value ($mL \cdot kg^{-1} \cdot min^{-1}$) depending on the intention of its application. The factors that limit $\dot{V}O_{2max}$ have been subject to considerable debate, although it is clearly advantageous for an individual to possess a high cardiac output, blood oxygen transport capability and have an enhanced capability to produce ATP via oxidative phosphorylation in the skeletal muscles.[39]

The relationship between $\dot{V}O_{2max}$ and both self-paced and stochastic time trial performance has been the focus of several investigations. Interestingly the results of several of these studies suggest absolute $\dot{V}O_{2max}$ is a more important determinant of performance than relative $\dot{V}O_{2max}$. Bentley et al. [36] reported a strong correlation between absolute $\dot{V}O_{2max}$ and 20 minute TT power output ($r = 0.69$), however the relationship between relative $\dot{V}O_{2max}$ and performance was only small to moderate ($r = 0.11$-0.47). Stickland et al. [40] reported similar results with a very strong correlation between absolute $\dot{V}O_{2max}$ and 20-km TT performance time ($r = -0.72$) while the corresponding relationship for relative $\dot{V}O_{2max}$ was somewhat weaker (r =

0.59). In a recent study, Levin et al. [37] reported a very strong correlation between constant grade stochastic TT performance and absolute $\dot{V}O_{2max}$ (r = 0.80). These findings suggest absolute $\dot{V}O_{2max}$ is a stronger determinant of TT power output than relative $\dot{V}O_{2max}$, particularly when the course profile is flat or when intensity is variable.

The weaker reported relationship between relative $\dot{V}O_{2max}$ and TT performance can be explained by exploring the manner in which these variables are tested and reported. As discussed earlier, relative $\dot{V}O_{2max}$ is reported in relation to a subject's total body mass, while TT performance is generally represented by absolute values for either average power output or elapsed time. The primary resistance for any cyclists travelling in excess of 13 $km \cdot h^{-1}$ on a relatively flat surface is the drag produced by their body and the equipment they use.[41] Considering flat TT's are generally completed at speeds well in excess of 13 $km \cdot h^{-1}$ it is apparent, within limits, flat TT cycling is not primarily limited by an individual's body mass. This is highlighted by Padilla et al. [42] who suggested the higher body mass values for TT specialists, compared with uphill specialists, reduces the body surface area and frontal area to body mass ratio, consequently reducing aerodynamic resistance. Therefore, $\dot{V}O_{2max}$ reported in relation to one's body mass will be limited in its capacity to predict flat TT performance, which is the manner in which many studies have assessed cycling performance in the laboratory.

The term lactate threshold (LT) refers to the final exercise intensity before lactate production exceeds lactate removal from the body and blood lactate concentration increases.[43] Generally reported as a specific power output, a percentage of $\dot{V}O_{2max}$ or velocity, LT is used as a measure of sub-maximal aerobic fitness and subsequently as a marker of exercise intensity for training prescription. A recent review article described 25 different definitions of LT used in current literature.[43] This great variety of determination methods has led to continued debate as to the validity of LT as a performance determinant.

Previous investigations into the relationship between LT and TT performance produced contrasting results. Bentley et al. [36] reported small to large relationships between cycling performance and LT that were dependant on the method of LT determination. Similarly McNaughton et al. [35] reported very strong to almost perfect correlations between short (5 min) and medium duration (30 min) TT performance. Furthermore, Morris et al. [44] described a nearly perfect relationship ($r = 0.97$) between LT and 20-km TT performance. The relationships between LT and TT performance reported by these studies suggest LT is an important determinant of TT performance. However, the results of other studies suggest otherwise. Stickland et al. [40] reported no significant relationship between 20-km TT performance and LT in a sample of 11 experienced male cyclists. Kenefick et al. [45] suggested average blood lactate, heart rate, percentage of max heart rate, $\dot{V}O_2$ and power output were significantly higher throughout a 20-km TT than when measured at LT during a graded exercise test. Dumke et al. [46] indicated heart rate during 30 and 90 minute TT's was significantly higher than when measured at several markers of LT during a laboratory exercise test. However, the comparison between heart rate from a laboratory exercise test and the heart rates recorded during TT performance is significantly limited by the variable nature of heart rate.[47] Therefore, the exact relationship between LT and self-paced, flat cycling performance is somewhat ambiguous. Additionally, the relationship between variable gradient and variable intensity cycling performance, more reminiscent of competitive cycling events is still unknown.

The physiological variable ventilatory threshold (VT) is the point at which ventilation increases non-linearly in response to an increase in prescribed work rate.[38] Similar to LT, VT is thought of as a marker of the transition from predominantly aerobic to mainly anaerobic metabolism and is used in a similar fashion to LT as a measure of sub-maximal aerobic fitness and for training prescription.

A number of studies have investigated the relationship between cycling performance and VT. Lucia et al. [48] reported a very strong negative relationship between VT and TT performance throughout three long TT stages (r = -0.86, -0.77 & -0.92 respectively) of the Tour de France. Given these TT's were performed (after a minimum of 6 and up to 19 days of ultra-endurance exercise) the results of this study are limited in their application. Additionally, Lucia et al. [48] compared the heart rates from a laboratory exercise test to those taken during a time trial which, as discussed earlier, can be problematic.

However, these results were supported by Amann et al. [49] who reported a significant relationship between VT and 40-km TT performance. Like LT, a number of determination methods exist for establishing VT. In this study, Amann et al. [49] indicated the breakpoint of the ratio between ventilation and volume of oxygen uptake ($VE/\dot{V}O_2$) method of defining VT is the most reliable and most strongly correlated (r = 0.90) to TT performance. These results are supported by Amann et al. [50] who again reported the $VE/\dot{V}O_2$ method of determination most strongly correlated (r = 0.80) to 40-km TT performance. Furthermore, Amann et al. [51] suggested the $VE/\dot{V}O_2$ method of VT determination is the best predictor of 40-km TT performance when compared to LT and other methods of VT determination. In this case the comparison of the relationship between respective variables and cycling performance is negligible as two different exercise test protocols were used to determine VT and LT. The longer stage protocol used to measure LT would have caused a greater accumulated fatigue during any given stage, which may explain why Amann et al. [51] reported disparity between the relationships of VT and LT to cycling performance.

Nevertheless, later studies further indicate VT is an important determinant of cycling performance. Levin et al. [37] reported a moderate to very strong correlation between stochastic TT performance and VT. Additionally Laursen et al. [52] reported a moderate relationship ($r = 0.42$) between an increase in VT and improvement in 40-km TT performance. Whilst the strength of this relationship is somewhat weaker than the strength of correlations reported by others, it suggests improvement in VT will lead to an improvement in the TT ability of cyclists. The results of the above studies suggest ventilatory threshold is an important determinant of self-paced and variable intensity TT performance. But, given previous investigations all compared constant gradient cycling performance to VT, the relationship between VT and variable gradient cycling performance is unknown.

The physiological variable, gross efficiency (GE) is defined by McArdle et al. [53] as the fraction of internal energy expenditure expressed as external work. Additionally, GE reflects exercise economy (ECO), which is defined as the energy required to maintain a given exercise intensity.[53] Gross efficiency and, by association ECO, are considered central determinants of endurance exercise ability and as such, likely limit cycling performance.[54]

Previous literature describing the relationship between markers of GE or ECO and cycling performance are largely equivocal. Storen et al. [55] reported a small but insignificant correlation between ECO and 15km self-paced TT. Interestingly, the relationship remained small, regardless of an increase in the degree to which $\dot{V}O_2$ was scaled to body mass. Similarly, Sassi et al. [56] indicated there was no relationship between GE or ECO and PPO, and GE did not change as a cycling season progressed from pre-competition to competition phase.

Importantly, these results suggest improvement in performance is achieved independent of physiological adaptation that improves GE. Recently, Levin et al. [37]reported only a small to moderate relationship between ECO and a short or long stochastic TT. While previous literature has measured performance in a manner somewhat unlike real competition, reported results suggest ECO and GE are not important determinants of intermittent cycling performance.[37]

However, other research suggests GE and ECO play an important role in mediating cycling performance. In a series of investigations, Hopker and colleagues reported a difference in GE between trained and untrained cyclists, an increase in GE following intensified training and change in GE as cyclists progressed through a cycling season.[57-59] The collective power of these results suggests GE, and therefore ECO, increase in association with improvement in cycling performance and can discriminate between cyclists of different abilities. Additionally, an inverse relationship between GE and $\dot{V}O_{2max}$ reported by Lucia et al. [60] suggests professional cyclists with lower $\dot{V}O_{2max}$, compensate by having a higher GE. Importantly, this relationship indicates high standards of cycling performance can be achieved via adaptation that increases GE independent of changes in oxygen uptake.

Evidence presented above suggests the precise relationship between GE or ECO and cycling performance remains largely unknown. Additionally, as previous studies have reported the relationship between GE or ECO and cycling performance based on performance tests bereft of change in gradient, the importance of GE and ECO as performance mediators may be understated. Therefore future research should further clarify what role GE and ECO play in endurance cycling performance and whether or not their importance changes as performance testing moves closer to competitive cycling events.

This review of literature reveals a number of laboratory measured physiological variables share important relationships with cycling performance. However the relative importance of the physiological variables contributing to cycling performance requires greater elaboration, as previous findings are inconsistent and not always convincing. Importantly the performance tests used in previous research to establish the physiological determinants of cycling performance lack specificity in that they have not included variations in external environment. Advancement in cycling ergometer technology allows coaches and sports scientists to add environmental variation such as changes in gradient to current laboratory performance tests. Thus a significant contribution to cycling performance would be made if the physiological profile suited to variable gradient cycling was identified.

2.4 TRAINING TECHNIQUES FOR COMPETITIVE CYCLISTS

The training and physical preparation of any elite athlete requires considered application of a number of training techniques. The sport of road cycling covers a multitude of events, all requiring proficiency in a range of physiological and performance markers. Coaches, sports scientists and athletes make use of a variety of training techniques to evoke adaptations in individual physiology and achieve optimal performance outcomes. The most common training techniques include long slow distance training and high intensity interval training (HIT) which can take many different configurations.[30]. This review will explore the impact of these forms of training on the physiology and performance standard of competitive cyclists.

2.4.1 Long Slow Distance Training

Long, steady distance (LSD) training, sometimes referred to as over distance, continuous or prolonged training, is defined by Sleamaker [61] as training sessions completed over distances or durations similar to those of major competitions at a sub-maximal intensity that can be maintained for an extended period of time. For the purpose of this literature review, LSD will be defined as any training completed at largely sub maximal (below 75% PPO) intensities for any duration longer than 90 minutes. A review of training practices suggests ~80% of all training is comprised of LSD in endurance athletes.[62]

Several studies have investigated the effects of LSD on untrained samples. In these studies, participants have demonstrated significant improvement in a number of physiological parameters associated with cycling including $\dot{V}O_{2max}$, muscle buffering capacity, metabolic enzyme activity, PPO, LT and anaerobic capacity.[63-67] Additionally, Gibala et al. [64] reported a significant improvement in TT performance in their participants following only two weeks of LSD training. All of the enhancements listed above represent important physiological adaptations that would afford the participants of these studies tangible improvement in cycling performance. Therefore research indicates the training stimulus provided by LSD training is effective and sufficient to improve the physiology and performance of untrained participants.

Studies using trained participants are not as prevalent, often uncontrolled and, in contrast to studies on untrained participants, less exhaustive in their exploration of the effects of training on physiology. Hoogeveen [68] investigated the ventilatory response to incremental exercise in both the pre-season and competition phases of a cycling season in 15 elite cyclists. There was a significant increase in $\dot{V}O_{2max}$ (~13%), PPO (~2%) and VT (~5%) from the pre-season to competition phase of the season. Whilst the training volume was reported to increase from the pre-season to the competition phase (~10 h), the intensity of exercise was uncontrolled throughout the study. Given training volume was high through the season it is likely the majority of this training was of similar intensity to traditional LSD training. However elite cyclists are more likely to undertake interval based training sessions of varying intensity and duration, as well as competing in races during the competitive season making it difficult to isolate the precise effect of the LSD training.

In contrast, Lucia et al. [69] found no significant change in $\dot{V}O_{2max}$ across the full breadth of a cycling season when investigating the metabolic and neural adaptations to training in 13 professional cyclists. However, Lucia et al. [69] did report a significant decrease in respiratory exchange ratio (RER) at 100 and 200 watts (W), decreased blood lactate concentration and enhanced motor unit recruitment as the season progressed. These adaptations indicate professional cyclists experience improvement in the recruitment and efficiency of slow twitch muscle fibres and not oxygen uptake as the season progresses. However, Lucia et al. [69]also acknowledged that extrapolation of their findings to racing situations could be difficult due to measuring variables at set cadences rather than utilising a testing procedure of dynamic cadence. Similarly to the Hoogeveen [68] study, the training performed by participants in Lucia et al. [69] was measured but uncontrolled, again making it difficult to make inferences about the specific adaptations induced by LSD.

Sassi et al. [56] completed a similar assessment of changes in aerobic fitness indices in response to a cycling season in a group of professional cyclists. There was a significant improvement in measures of maximal oxygen uptake as the season progressed from the resting phase, through to the competition phase (~10%). The only aerobic variables that did not increase throughout the season were GE and ECO. However, GE and ECO were measured in a small selection (n=8) of the overall sample which the authors acknowledged may have limited the statistical power to find any improvement in the respective variables. Indeed there was a trend towards improvement in GE, particularly between the resting and pre-competition phases of the season. Nevertheless, the significant changes in physiology reported, were associated with significant improvement in several measures of performance. While the training completed by the cyclists in the study was mostly comprised of LSD, the other interval type training included in the cyclists training make it difficult to draw conclusions on the isolated effect of LSD training.

Contrary to results stated for samples of professional cyclists, Hopker et al. [59] reported a significant increase in GE (~6.7%) in a group of competitive cyclists from the pre-competitive to the competitive phases of a cycling season. The authors also reported additional changes in $\dot{V}O_{2max}$ as well as markers of the LT during the early part of the cycling season. Interestingly, the change in GE was positively correlated with total training time in the pre-competitive phase, of which ~73% was spent at LSD training intensities. However, change in GE was also positively correlated to time spent above LT power output indicating improvements in aerobic fitness were unlikely to be the result of LSD training. Nevertheless, as the majority of training was completed below LT intensity, it is possible LSD training evoked some of the reported adaptation in physiology.

Studies investigating the effects of LSD on competitive cyclists are not as definitive as those involving untrained participants due in most part to their scarcity and uncontrolled nature. The articles employing a sample of competitive cyclists explored by this review investigated change in performance and physiology over the duration of a season. However the intensity of training was largely uncontrolled, making it difficult to isolate and identify the effects of LSD training. Therefore future studies into the effects of LSD on trained cyclists should isolate LSD as a training stimulus and control for other forms of training to identify the specific effects of the training stimulus provided by LSD training.

2.4.2 Interval Training

Interval training is defined by Brooks et al. [38] as a training session where periods of high intensity exercise are interspersed with periods of recovery. A cursory glance at popular cycling training literature presents many different forms of interval training.[70,71] Variables that can be manipulated to influence the overall training stimulus include the length and intensity of both the work interval and recovery interval. Hawley [30] suggests this form of training is generally completed in the pre-competition and competition phase of the yearly cycle.

Currently there is no scientifically validated system or formula by which the precise training load of individual intervals can be calculated. Additionally, to quantify stimulus of interval training, previous literature has simply stated the duration and intensity of the effort and recovery segments. Therefore, for the purposes of this review interval training has been categorised based on the duration and intensity of the efforts contained in a specific interval session. Long interval training (LIT) is defined as training involving any intervals of more than four minutes in duration completed at an intensity approximating LT. Short interval training (SIT) is defined as training involving intervals of less than four minutes and more than one minute in duration completed at an intensity over 90% percent of $\dot{V}O_{2max}$ or PPO with recovery periods of similar or longer length than the work interval. Maximal interval training (MIT) is any training involving intervals shorter than one minute in duration at intensities above PPO and in many cases as a maximal sprint effort. This review will explore the effects of each type of interval training as reported in current literature.

2.4.3 Long Interval Training

Evidence on the effect of LIT training on the physiological and cycling performance characteristics of untrained populations is relatively scarce. In studies that have employed untrained subjects, significant improvement in $\dot{V}O_{2max}$, oxidative enzyme activity, fat metabolism, muscle glycogen content, time to exhaustion (TTE) and repeat sprint ability has been reported after as few as seven sessions of LIT.[72-74] Clearly, the training stimulus provided by LIT is adequate to evoke significant physiological adaptation associated with aerobic metabolism in untrained populations. However, the evidence suggests these adaptations transfer more universally to performance than events where the aerobic energy system is dominant.

In an early study using well-trained subjects, significant improvement in the physiology and performance of competitive cyclists were reported after just six sessions of LIT over four weeks.[75] The cyclist's in this study demonstrated marked improvement in PPO (~4.3%) and $\dot{V}O_{2max}$ (magnitude unreported). Training adaptations transferred to substantial improvement in TTE and TT performance. Importantly the majority of improvement in TTE was evident after only two weeks, or three sessions of LIT training. An increase in TTE at a power output representative of 150 percent of PPO would likely afford participants substantial improvement in events of shorter duration, or specific periods of races requiring sustained high power output.

Using the same LIT sessions over a longer training period (6 weeks), Westgarth-Taylor et al. [76] reported similar improvement in physiological parameters and performance in eight competitive male cyclists. Following the training intervention, these researchers reported a reduction in carbohydrate (CHO) oxidation and an increase in fat oxidation at the same absolute intensities; however substrate utilisation was unchanged at the same relative intensities. When the above results are taken in combination with a significant improvement in TT performance (~12%) it appears that LIT can have a substantial impact on the performance standard of already well-trained cyclists. Interestingly the authors suggested LIT improved sustainable power through mechanisms independent of the reported change in CHO and fat oxidation. Instead they suggest the performance improvement was a result of unmeasured improvement in motor unit recruitment.

Weston et al. [77] again used the same LIT sessions when investigating the effect of LIT on the physiological characteristics of competitive cyclists. After completing four weeks of LIT, the participants demonstrated a significant increase in PPO (3.5%), skeletal muscle buffering capacity (~16%), TTE (~22%) and 40-km TT performance (~2.2%). In contrast to reported results from investigations using untrained cyclists,[73,74] there was no increase in the activity of a number of skeletal muscle enzymes (glycolytic, oxidative and fat metabolism enzymes). Therefore, it is possible that LIT is inadequate to induce large scale mitochondrial enzymatic adaptation in trained populations.

In a seminal training study, Stepto et al. [78] examined the effects of four different interval training sessions on the physiology and TT performance of competitive cyclists. In this study LIT was represented by two separate groups, performing either eight repetitions of four minute efforts or four repetitions of eight minute efforts at 80~% and 85~% of PPO respectively. Whilst the four minute group significantly improved PPO and TT performance, the eight minute group did not increase scores in either variable. Stepto et al. [78] described a curvilinear relationship between interval length and intensity, and observed change in performance that suggested the maximal improvement would occur after work intervals of three to six minutes at ~85% of PPO.

Following LIT programs of varying lengths, participants in the studies described above were reported to have improved aerobic power, increased fat oxidation, enhanced buffering capacity, increase PPO and decreased oxidation of CHO. Discrepancies evident between the results of studies involving trained participants indicate careful manipulation of the intensity of efforts and length of recovery interval is required. The major limitation in the application of the findings from a number of these studies is the lack of, or at least lack of any mention of control for other completed training. In this instance it is evident future studies should employ greater control or monitoring of training completed as an aside to the intervention. Nonetheless it appears evident that, LIT can efficiently improve the performance standard of already well-trained competitive cyclists.

2.4.4 Short Interval Training

As described earlier, for this review short interval training (SIT) is defined as training involving effort periods more than one and less than four minutes duration. These intervals are generally completed in excess of 90% percent of $\dot{V}O_{2max}$ with recovery periods of similar or longer length than the work interval. As with other forms of training, the variables manipulated to shape the training stimulus are the work rest ratio and the intensity of the work intervals. Current published research presents SIT programs of varying configurations. This review will explore the effects of each of these SIT interventions on the physiology and performance of participants.

Limited studies on the effects of SIT on the physiology and cycling performance on untrained samples have reported significant improvement in $\dot{V}O_{2max}$, LT, PPO, the activity of oxidative enzymes with associated improvement in short and long TT performance. Improvements have been reported after as little as two weeks SIT Stepto et al. [78] and indicate the potential for SIT to substantially improve the physiological and cycling performance parameters of untrained populations.[67,72,79] In contrast to the positive findings presented in studies on untrained participants Stepto et al. [78] reported minimal improvement in the performance of competitive cyclists following six sessions of SIT. A major point of difference in the composition of SIT sessions between that study and studies involving un-trained participants is the length of the recovery interval. Stepto et al. [78] used a recovery period of four minutes duration, whereas McKay et al. [67] and Little et al. [79] imposed shorter recovery intervals of 60 or 75 seconds. It is possible the shorter recovery resulted in greater stress on oxidative pathways which lead to the performance improvement. Indeed, Laursen et al. [80] reported a significant improvement in fitness parameters of competitive cyclists following a SIT intervention. Cyclists completed 20 repetitions of one minute, 100% PPO efforts and one effort to exhaustion at 100% PPO on four occasions in two weeks. On completing the training intervention, cyclists showed significant increases in ventilatory threshold one (~6%), ventilatory threshold two (~7%) and PPO (~4%). These results are further indicative of the potential for a positive impact on the physiology of competitive cyclists from an SIT program, and it could be expected significant improvements in endurance performance would arise as a result. Importantly, Laursen et al. [80] used a shorter recovery interval than Stepto et al. [78] resulting in a work rest ration of 1:2 as opposed to 1:4 respectively. When considering these results in combination with findings from studies of untrained participants,[67,79] it is likely shorter recovery intervals are an integral component of effective SIT training.

Further evidence of the need for shorter recovery intervals is presented by Laursen et al. [81] They reported a significant improvement in the physiology and performance of competitive cyclists following four weeks of a SIT program. Participants were split into two groups and performed eight efforts of 60% of the TTE at PPO twice per week. However, group one completed efforts with a work rest ratio of 1:2 whilst group two completed a recovery interval based on the time taken to return to 65% of heart rate max (work rest ratio ~1:1-2 depending on which interval in session). Whilst group two had significantly less mean total recovery time when compared to group one (~1248s & ~2028s respectively) they demonstrated similar improvements in PPO (~4.7% & ~6%), $\dot{V}O_2$ peak (~5.2% & ~8%) and TT speed (~4.7%& ~5.5%). Given Laursen et al. [81] reported a SIT bout completion rate among participants of only 64%, it appears there is a need for considered management of fatigue when implementing an SIT program.

In a follow up investigation, Laursen et al. [52] used the same SIT protocol to further investigate the effect of SIT on physiology and performance in 41 trained males. After a four week training intervention the authors described improvement in $\dot{V}O_{2max}$, PPO and TT performance similar to those reported in previous studies.[80,81] Additionally, training groups demonstrated significant improvement in VT (~15% for both groups) and anaerobic capacity (~100% & ~54% for groups 1 & 2 respectively). The improvement in short term performance is indicative of a major adaptation in anaerobic physiology that would no doubt be beneficial to performance, particularly in events of dynamic intensity. The findings suggest a need for work rest ratios of 1:1.5-2 when performing SIT to enhance cycling performance.

Whilst inconclusive, the majority of research appears to indicate a positive impact of SIT on the fitness status of competitive cyclists. Even after only four sessions of SIT over two weeks, significant improvement in power output at ventilatory thresholds, aerobic capacity, anaerobic capacity and PPO are evident; these adaptations are associated with superior performance in a 40-km TT and TTE at an intensity approximating PPO. However, studies investigating SIT often failed to mention control for training completed externally to the training intervention. Whilst it is unlikely other training lead to the changes presented in the research explored above, care should be taken to outline the control for external training. Additionally future studies involving trained cyclists would benefit from inclusion of morphological investigations into adaptations in skeletal muscle metabolism and enzyme activity.

2.4.5 Maximal Interval Training

Often referred to as supra-maximal training, maximal interval training refers to training involving all-out (or close to) maximal efforts. For the purpose of this literature review maximal interval training (MIT) is any training involving intervals shorter than one minute in duration. Typically intervals are completed at intensities close to or at maximal intensity (>100% PPO) with recovery durations dependant on the desired outcome. As the effort component of this type of training is often completed at power outputs well in excess of $\dot{V}O_{2max}$ power, they require a large contribution from anaerobic metabolic pathways and likely involve recruitment of large numbers of fast twitch muscle fibres.[64] Hawley [30] suggests this form of training should be combined with LIT and SIT in the lead up to competition as a means of peaking. A number of studies have investigated the effects of MIT on various forms of cycling using both trained and untrained participants. This review will examine the findings of current literature to establish the effect of MIT on physiology and performance.

Several studies have investigated the physiological adaptations to MIT in untrained populations. These studies have demonstrated significant improvement in physiological parameters including $\dot{V}O_{2max}$, PPO, oxidative enzyme activity and fat metabolism after as few as six MIT sessions, whilst others have reported similar adaptations over longer training periods.[64,65,82-88] These adaptations have generally been associated with significant improvement in performance in a variety of cycling disciplines including long and short TT performance. Overall MIT appears to have a substantial effect on physiological adaptation and subsequently leads to superior performance in untrained populations.

Stepto et al. [78] included a MIT intervention in their seminal training study on the effects of interval training on the endurance performance of trained cyclists. Four trained male cyclists completed six MIT sessions over three weeks. Each session consisted of 12 repetitions of 30s efforts at ~175 percent of PPO interspersed with four and a half minute recovery intervals. Stepto et al. [78] reported significant improvement in long duration (40-km TT) and short duration (30s sprint) average power. These results suggest MIT can improve the cycling performance of trained populations. However in contrast to observed adaptations in untrained participants, the authors reported no improvement in PPO following the MIT program. This would suggest MIT is not sufficient to increase aerobic power in trained populations and indicates the improvement in TT performance arose as the result adaptation in other, non-measured physiological variables. However, given PPO is reportedly the best predictor of TT performance,[17] it is possible the small sample size limited the statistical power to elucidate the true effect of MIT on PPO. Nevertheless, the findings of Stepto et al. [78] provide evidence of the ability of MIT to improve cycling performance over a variety of durations.

Similar training sessions were used by Laursen et al. [81] to investigate the effect of MIT on 10 trained cyclists. The participants completed the MIT sessions twice per week for four weeks. Unlike the earlier study,[78] Laursen et al. [81] observed a significant improvement in PPO (~3%) in addition to increases in $\dot{V}O_{2max}$ (~3%) and 40-km TT speed (~4.3%). However Laursen et al. [81] implemented a longer training block and increased the absolute exercise intensity of the efforts mid-way through the study which may explain the difference in results. Nonetheless, these results indicate that MIT is effective in improving aerobic power and subsequently endurance performance in already trained cyclists despite the brief and intense nature of the training stimulus.

In a further study Laursen et al. [52] again used the same MIT program of 12 repetitions of 30s efforts to investigate the effect of MIT on central and peripheral adaptations in trained cyclists. After the MIT program, Laursen et al. [52] reported a significant increase in PPO, ventilatory threshold one (~17%), ventilatory threshold two (~9%) and anaerobic capacity (~75%). There was also a significant improvement in 40-kmTT performance, with subsequent increases in time trial $\dot{V}O_2$, heart rate and blood lactate. Interestingly, Laursen et al. [52] indicated there was no change in plasma volume, haematocrit or haemoglobin after the MIT program. As these are common indicators of central physiological adaptations, it appears the improvement in TT performance could occur as a result of peripheral adaptation. However as there are a number of central regulators of exercise performance, it would be erroneous to suggest only peripheral adaptations led to the performance change.

Paton et al. [89] incorporated explosive single leg efforts into a MIT program to evaluate its effect on the performance and physiology of trained cyclists. After five weeks of the combined MIT and explosive leg training intervention the authors reported significant increases in PPO (~7%), one kilometre TT power (~9%), four kilometre TT power (~8%), lactate power profile (~6%) and an improvement in ECO (~3%). However due to the combined nature of the MIT program, it is difficult to isolate the training stimulus responsible for improved performance.

In trained cyclists the adaptive effects of MIT are somewhat lessened but nevertheless significant improvements are evident in PPO, VT and anaerobic capacity. These adaptations are combined with improvement in a variety of performance measures including long TT and sprint power, and also to enhanced physiological response to intense exercise. Given some studies did not control for external training; further well controlled studies involving competitive cyclists are warranted. Future studies might include investigations into the changes in muscle metabolism, oxidative and glycolytic capacity and determine the effects of concentrated periods of high volume bouts of MIT on performance. Nevertheless, it is evident that MIT evokes adaptation in a number of energy pathways and improves different cycling performance mediums. Additionally, given well-trained athletes can reach a performance plateau, it is plausible that MIT could be a catalyst to further improvement in physiology and performance standard.

2.5 ORGANISATION OF TRAINING FOR COMEPTITIVE CYCLISTS

The organisation of training within a cycling season is often dictated by one of the paradigms of periodisation; a model of training organisation.[90] While this review has described the effects of specific training techniques when they are implemented in isolation, in practice they are often implemented simultaneously to evoke physiological adaptation, despite conflicting adaptive mechanisms. In this manner, periodisation would determine how and when each specific type of training would be executed in order to achieve optimal performance, based on mechanisms of physiological adaptation.

A concept that underpins the training response, no matter how training is organised in a periodised program, is functional overreaching. Functional overreaching has been defined as a training stress that results in a short term decrement in physiological and exercise performance measures followed by a period of recovery that has a super-compensatory effect on performance.[91] The two predominant models of the physiological response to training, the super-compensation model and the fitness-fatigue model, indicate that a degree of overreaching is necessary to evoke beneficial physiological adaptation and improve performance.[90,92] However, if the period of overreaching is not followed with sufficient rest and the disturbances in physiology and performance continue, non-functional overreaching can occur.[91] One method coaches, athletes and sports scientists use to instigate functional overreaching is program a period of intensified training as would occur during a training camp.[91] Early studies on the effects of intensified training on cycling physiology and performance were limited to identifying and distinguishing between non-functional overreaching and overtraining. Nevertheless, evidence presented in some of these studies suggests performance not only returns to normal but may be enhanced after a period of intensified training and an appropriate recovery interval.

Jeukendrup et al. [93] highlighted the potential for a short bout of intensified training to rapidly improve exercise performance. In their study seven trained cyclists completed two weeks of intensified training where both volume and intensity were significantly increased. Jeukendrup et al. [93] reported that all participants displayed physiological and psychological symptoms of overtraining immediately following the two week training block. Additionally performance immediately following the training was significantly impaired and even after a two week recovery period participants still exhibited signs of mental fatigue. However, after the recovery period participants showed significant improvement in PPO and 40-km TT performance. Whilst there must be consideration for continued mental fatigue, results suggest a significant increase in the volume and intensity of training is a viable training technique for the rapid improvement of physiology and cycling performance.

In contrast Halson et al. [94] reported no improvement over baseline scores for a number of variables following a similar intensified training regimen. After two weeks of training, eight endurance trained males exhibited impairment in physiological, psychological and performance measures. Importantly, although physiological and performance measures returned to normal they were not enhanced over baseline scores following a two week recovery period. However, the cyclists who made up the sample in that study were less trained (average $\dot{V}O_{2max}$ ~58 $mL \cdot kg^{-1} \cdot min^{-1}$) when compared to the earlier study ($\dot{V}O_{2max}$ ~65 $mL \cdot kg^{-1} \cdot min^{-1}$).[93] In this instance it could be suggested the training stimulus provided is more appropriate for cyclists of superior physiological and performance standards. Nevertheless, the absence of performance decrement indicates the cyclists avoided maladaptation despite completing a substantially intensified training period. Additionally, given both Halson et al. [94] and Jeukendrup et al. [93] reported psychological signs of overreaching after only one week of training, a shorter training period could negate additional accumulated fatigue caused by the longer training intervention necessitated by the diagnostic aim of both of these studies.

Recent studies have evolved from diagnostic outcomes to focus on the physiological and performance response to intensified training in elite athletes. The first example of such investigations suggests intensified training leads to substantial improvement in physiological status and performance measures. Breil et al. [95] reported a significant increase in $\dot{V}O_{2max}$ (~6%), PPO relative to body mass (~5.5%) and VT (~9.6%) following an 11 day period of intensified cycling LIT in alpine skiers. Importantly, there was no improvement in any measure for the control group who completed conventional training. While the recovery period used by Breil et al. [95] was shorter than earlier studies that reported lingering signs of fatigue, the training volume was somewhat reduced. This suggests if the overall training volume of the intensified training period is moderated, beneficial physiological adaptation can occur. However, given the participants recruited for the study were not trained cyclists, the application of results to a competitive cycling population, or trained populations, is limited.

A similar response to intensified training was reported following a comparison between traditional and block periodisation.[96] Cyclists in the block periodised group completed a four week, two component training intervention. To instigate a functional overreaching response, the first component was one week highly populated by LIT (five consecutive sessions). The second component consisted of three weeks where the frequency of LIT was reduced to once per week and LSD training volume increased. In contrast, cyclists in the traditional periodised group completed the same LIT sessions twice a week, in addition to LSD training, for four weeks. Interestingly, physiological adaptation only occurred in the block periodised group despite both groups completing the same number of interval sessions and a similar amount of LSD training. Although there was no specific measure, performance was assessed in this study by comparing mean power outputs from the work interval of LIT sessions. Ronnestad et al. [96] suggested the performance improvement occurred only after the three week, reduced LIT volume period. However, there appeared to be a trend for improvement in mean power output during LIT in the first interval training period of the second component. Thus, it is possible the improvement in physiology and performance is a result of the first week of intensified training and not the following weeks of predominantly LSD. Any further improvements are more likely the result of a super-compensatory effect following a sufficient recovery period, an example of functional overreaching.

In a follow up study, Ronnestad et al. [97] completed a similar comparison between block and traditional periodisation. However, participants repeated each cycle a further two times giving a total intervention period of 12 weeks. Again the block periodised group demonstrated a superior adaptive response and subsequently superior performance improvement characterised by a significant increase in haemoglobin mass (~5.6%), $\dot{V}O_{2max}$ (~8.8%), LT (~22%), PPO (6.2%) and TT performance (~8.2%). Therefore, it is evident intensified training periods in well trained cyclists, evokes substantial improvement in performance as a result of important physiological adaptation. However, it is important to recognise limitations in the allocation of participants to training groups and the training stimulus provided to participants in both Ronnestad and colleagues studies. Traditional periodisation is typically characterised by a broad training focus whereby many physiological mechanisms are targeted for adaptation at once.[98] Conversely, block periodisation is characterised by highly concentrated training stimulus that progresses consecutively through a small number of targeted physiological mechanisms.[98] Given participants in the traditional groups from both studies completed only LSD and LIT, it is apparent the training stimulus doesn't truly replicate traditional periodised training. Additionally, the lack of progression in the training stimulus for the block periodised groups is more representative of a shock micro-cycle than a block periodised training program. Importantly, there appeared to be a difference in the fitness and performance standard of the two training groups in the shorter study before the training intervention commenced. Therefore, it is possible the substantial gains reported for the block group occurred as an artefact of a greater potential to improve when compared to the traditional group. Therefore, further evidence is required to define the differences in the physiological and performance response to each form of training. Nevertheless, the adaptations and performance improvements reported in both studies, suggest intensified training followed by sufficient recovery, results in effective functional overreaching and not a maladaptive response.

Overall, the articles described above suggest organisation of training into intensified periods provides an effective training stimulus for competitive cyclists. Early studies, in which the focus was on the diagnosis of maladaptation and non-functional overreaching, reported some negative ramifications following intensified training. However, a sufficient recovery period appears to resolve any lingering fatigue and in some cases, allows for functional overreaching to occur. Later investigations, in which the training stimulus is slightly mediated, demonstrated a more positive adaptive outcome that lead to substantial performance improvement following intensified training. Nevertheless, as lingering signs of fatigue were evident following intensified training in early studies, and the time course of performance improvement was ambiguous in others, further research is required to elucidate the effect such training has on competitive cyclists.

2.6 CONCLUSION

The current physiological and performance assessment techniques used by scientists and coaches are limited in that performance assessment does not truly replicate competitive cycling. Utilising the simulation capacity available in current ergometer technology will allow development of more specific and ecologically valid testing protocols that include controlled variation in external environmental conditions. Subsequently, new test protocols can be used to further study the pacing response, and how CP and W’ determine pacing response, to variable resistance cycling.

An artefact of poor test specificity is a dearth of information regarding the physiological profile best suited to variable gradient cycling. While previous studies have described the physiological variables that determine flat and uphill cycling performance, none have determined the correlates of variable gradient performance. Given competitive cycling events take place on public roadways with almost constant variation in gradient, further research into the physiological determinants of variable gradient cycling is required. The results of such research will elucidate which variables should be targeted for training intervention to maximise performance potential in competitive events.

The chronic adaptive response to specific training techniques and the changes in performance that follow are well defined. However, greater quantification of the immediate physiological response to different training is required to provide a better means to classify specific training techniques. How such techniques are organised into training programs for endurance athletes is attracting research interest. Early studies with a diagnostic approach, evident in the training prescription and analysis of training response, reported equivocal results following intensified training. Recent studies with a greater emphasis on performance, and subsequently a reduced training stimulus, have reported a more positive response following block periodisation of interval training. However, the time courses of the adaptive and performance responses to such training remains ambiguous and in some instances, training groups appear to be poorly matched before starting the intervention. Additionally, the training interventions described as traditional and block periodisation bear little resemblance to descriptions of those periodisation paradigms, limiting the ability to compare the training response. Future research should further investigate the effect of intensified training on physiology and performance, paying particular attention to methodological limitations identified above and identifying the time course of the adaptive and performance response to intensified training.

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CHAPTER 3.

THE RELIABILITY OF PERFORMANCE DURING COMPUTER-SIMULATED VARYING GRADIENT CYCLING TIME-TRIALS

ABSTRACT

Purpose: Ergometer based time trials are commonly used to assess performance changes due to training or other interventions. This investigation establishes the reliability of a novel computer simulated cycling time trial. **Methods:** Nineteen cyclists (age: 32 ± 12 years, mass 73 ± 11 kg, height 178 ± 5 cm) completed four time-trials over a 20-km course which included numerous changes in gradient. The time-trials were completed over a 4-week period in order to establish both short and long-term reliability. **Results:** Performance time (mean ± SD) for trials one to four was 2265 ± 149 s, 2252 ± 153 s, 2236 ± 146 s and 2240 ± 154 s respectively; the corresponding power output for consecutive trials was 293 ± 35 W, 297 ± 36 W, 299 ± 35 W and 299 ± 35 W. The coefficient of variation (± 90% confidence limits) of performance for trials separated by 7, 14, 21 and 28 days was 1.1% (0.8% – 1.5%), 1.3% (1.1% – 1.9%), 1.3% (1.1% – 1.9%) and 1.5% (1.1% – 2.1%) respectively for time; the corresponding values for power output were 2.0% (1.5% – 2.7%), 2.3% (1.8% – 3.2%), 2.6% (2.0% – 3.6%) and 3.2% (2.5% – 4.5%). Further analysis based on rider ability indicated slower riders were less reliable than faster riders by a factor of ~1.1. **Conclusions:** The reliability of performance in a novel simulated variable gradient time-trial is excellent and should allow sports scientists, coaches and cyclists to detect small, but worthwhile changes in performance. However, reliability of performance time and power output diminishes with increasing time between trials. Additionally, faster riders show better reliability than slower riders over time. Researchers should consider the effect of time between trials and athlete ability when making conclusions about intervention effectiveness.

3.1 INTRODUCTION

Laboratory based assessments of physiology and performance form an integral part of athlete monitoring and preparation for competition. Establishing the physiological capacities and performance standards of athletes, allows sports scientists and coaches to assess the effectiveness of training programmes and other experimental interventions. The performance capabilities of competitive cyclists are often assessed using simulated time trials completed under controlled conditions in a laboratory. Laboratory based cycling trials can take several forms,[1] and there has been considerable debate on the advantages and disadvantages of the different types of test.[2] However from an ecologically valid perspective, fixed distance self-paced time-trials most closely represent a true competitive situation and are often the preferred option when investigating athlete performance enhancement strategies.

Irrespective of the test design, any test must have good reliability to monitor the small changes in performance that matter to competitive athletes.[3,4] Several previous studies have investigated the reliability of different types of time-trial protocols. The re-test reliability (reported as a coefficient of variation) for simulated cycling time-trials of ~30-60 minutes duration, completed on a flat course and bereft of changes in gradient or prescribed changes in intensity is reportedly between 0.7%-1.5% and 1.9%-3.6% for time and power respectively.[5-7] Similar reliability measures have also been reported for time (1.4%-2.9%) and power (1.7-3.5%) during a simulated up-hill time-trial completed on a constant gradient 8-mile course.[8] In a more recent study Driller et al. [9] reported excellent reliability (~1.3% for power) for a short duration 15- minute self-paced time-trial following a 15-minute pre-load activity at a fixed intensity. However, whilst these previous studies have reported the reliability of performance measures between consecutive trials over short intervening periods (typically 1-10 days between trials), none have reported the effects of increasing time between trials on test reliability. Further, a common issue with these previous studies is they lack the variations in the external environment that are typically seen during real competitions.

Unlike traditional laboratory based time-trials, competitive cycling events typically take place on public roadways and as such consist of constant changes in road gradient. Perception of these changes in combination with internal physiological feedback mechanisms combine to determine how an individual cyclists adjusts pace and effort.[10] Pacing strategy is therefore adjusted according to perception of the internal and external environment by important brain centres.[10] Currell et al. [2] suggest that any laboratory measure of sporting performance should allow participants to adopt a pacing strategy similar to that which is required by competitive situations. By providing a constant external environment, most laboratory test protocols do not challenge the perceptive skills of the cyclists and present a testing stimulus that is unlike competitive situations. In one of the few studies to examine reliability of performance when the test required substantial changes in intensity, Schabort et al. [11] reported short-term (>7days between trials) reliability for both total time and repeated high intensity efforts (1-km and 4-km) time of ~2% during a simulated 100-km time trial. Conversion of this reliability in time to an equivalent mean power yields relatively poor reliability of ~3.7%.[3] In a more recent modification of the Schabort et al. [11] study using a shorter duration 30-km time-trial, Abbiss et al. [12] reported reliability in mean power of 2.4% after subjects had completed a familiarisation session. Interestingly in their study, Abbiss et al. [12] reported a large decrease in test reliability (~11%) when trials were separated by large intervening periods.

While these two previous studies address some of the issues associated with variations in pace during laboratory based time trials, they do not fully simulate a competition situation requiring almost constant changes in exercise intensity in response to variation in the external environment. However the development of new computer technology and bicycle ergometers which allow accurate simulation of real race course profiles provides an opportunity to study the effects of scientific interventions in a more realistic environment. Therefore the aim of this study was to establish the short and long term re-test reliability of a novel computer simulated cycling time-trial completed on a course of varying gradients.

3.2 METHOD

3.2.1 Participants:

Nineteen competitive cyclists (17 males, 2 females) volunteered to participate in this study (Age: 32 ± 12 years, mass 73 ± 11 kg, height 178 ± 5 cm). All cyclists were well-trained with a minimum of two years racing experience at an A or B grade standard. All testing was performed in the athlete's competition phase of the season. Participants were free from illness or injury and gave their written informed consent to participate in the study. The study was carried out in accordance with the ethical and procedural requirements of the journal [13] and approved by the institutional human research ethics committees.

3.2.2 Design and Procedure:

The study was a repeated measures design requiring cyclists to complete four simulated 20-km cycling time-trials at set time intervals. Trials one to two and two to three were separated by 7 days and trials three to four by 14 days. Each trial was completed at a similar time of day (±2 hours) and was preceded by a standardised 20 minute warm up. Participants were instructed to treat each trial as it was an important competition and refrain from vigorous exercise and maintain a consistent diet in the 24 hours before each trial. Cyclists were requested not to consume any alcohol, caffeine or other substances that may affect performance in the 12 hours immediately preceding each trial.

3.2.3 Methodology:

All test sessions were completed on a Velotron Dynafit Pro cycle ergometer (RacerMate Inc, WA, USA) using the company's associated 3D race course software. Prior to the first trial, the Velotron factory calibration was confirmed according to manufacturer instructions using the "Accuwatt" function. During the first session each participant was fitted to the ergometer in a manor to replicate their own racing bicycle. The fit measurements were recorded and repeated for each subsequent testing session. Cyclists initially completed a 20 minute standardised warm up consisting of three repeated increasing intensity bouts. The first two minutes were completed at 2-2.5 W·kg^{-1}, followed by two minutes at 3-3.5 W·kg^{-1} and finally one minute at 4-4.5 W·kg^{-1} repeated consecutively. For the final five minutes cyclist pedalled at a fixed intensity of 100W. The time-trial was completed on an experimenter designed course which replicated a typical racing circuit and contained numerous changes in gradient represented by both ascents and descents as shown in Figure 3-1. The total elevation gain over the 20-km was 300 meters leading to an average gradient of ~1.5%.

Distance (km)	.5	1.6	1.05	1.0	1.1	1.4	1.0	.6	1.0	1.3	1.3	1.7	1.1	1.9	2.2
Grade (%)	0	2.5	-2.0	4.0	-3.2	4.6	0	-8	10	-1.5	0	-4.7	0	-1.5	4.1

Figure 3-1 The computer simulated course profile showing the variation in gradient and specific segment information of the time-trial used in this study.

Participants were able to view 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 to remove any potential pacing feedback. 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, were not coached on how to best ride the course and in order to control for extrinsic motivation, no encouragement was given to cyclists during the trials. Throughout the trial participants were cooled by two 30 cm pedestal fans and were able to consume water *ad libitum*.

3.2.4 Statistical Analysis:

Simple descriptive statistics are shown as means ± between-subject standard deviations. All measures were log transformed to reduce bias arising from non-uniformity of error and analysed using a made for purpose Excel spread sheet for reliability analysis.[14] Typical error was determined as coefficients of variation (CV%) along with their 90% confidence intervals (CI). The spreadsheet also provided the intra-class correlation (± 90% CI) between trials. Analysis was performed for all subjects together and as separate analysis for the fastest (n=10) and slowest (n=9) sub-groups in the time trial.

3.3 RESULTS

Table 3-1. shows the time and power output (mean ± SD) for all cyclists, and the sub-groups of fastest and slowest cyclists across all four trials. The change in mean of the performance variable represents the size of any learning effect between trials. For all cyclists there was a change of -0.6%, -0.7% and 0.2% in mean performance time between consecutive trials; the corresponding change in mean power between consecutive trials was 1.3%, 0.9% and -0.1% respectively. The magnitude of the mean change between trials was largest from trial 1-2 and reduced with subsequent trials, however all changes were deemed trivial (ES<0.2) The fastest subgroup of cyclists was ~10% faster and produced ~18% more power across all four trials than the slower sub-group.

Table 3-1 Performance characteristics for all cyclists and sub-groups of fastest and slowest cyclists (mean ± SD).

	T_{all} (s)	T_{fast} (s)	T_{slow} (s)	W_{all} (W)	W_{fast} (W)	W_{slow} (W)
Test 1	2265 ± 149	2153 ± 87	2390 ± 90	293 ± 35	314 ± 28	269 ± 26
Test 2	2252 ± 153	2137 ± 85	2379 ± 98	297 ± 36	320 ± 28	271 ± 24
Test 3	2236 ± 146	2122 ± 75	2363 ± 83	299 ± 35	323 ± 23	273 ± 26
Test 4	2240 ± 154	2115 ± 68	2379 ± 85	299 ± 35	324 ± 20	271 ± 25
Mean	2248 ± 151	2132 ± 79	2378 ± 89	297 ± 35	320 ± 25	271 ± 26

Abbreviations: T_{all} = performance time all cyclists; T_{fast} = performance time fastest cyclists; T_{slow} = performance time slowest cyclists; W_{all} = mean power all cyclists; W_{fast} = mean power fastest cyclists; W_{slow} = mean power slowest cyclists.

Figure 3-2. shows the coefficient of variation of performance for trials separated by 7, 14, 21 and 28 days. The CV for seven days was calculated by taking the average CV from tests 1-2 and 2-3, 14 days by taking the average CV from tests 1-3 and 3-4, 21 days by taking the CV from tests 2-4 and 28 days the CV from tests 1-4. The variation in performance time for all cyclists' increased linearly from 1.1% to 1.5% with increasing time between trials. Similarly the variation for mean power increases from 2.0% to 3.2% with increasing time between trials. The faster cyclists were marginally more reliable than the slower cyclists over the short term (7-14 days between trials) but there were no substantial differences in reliability between sub-groups over the longer term.

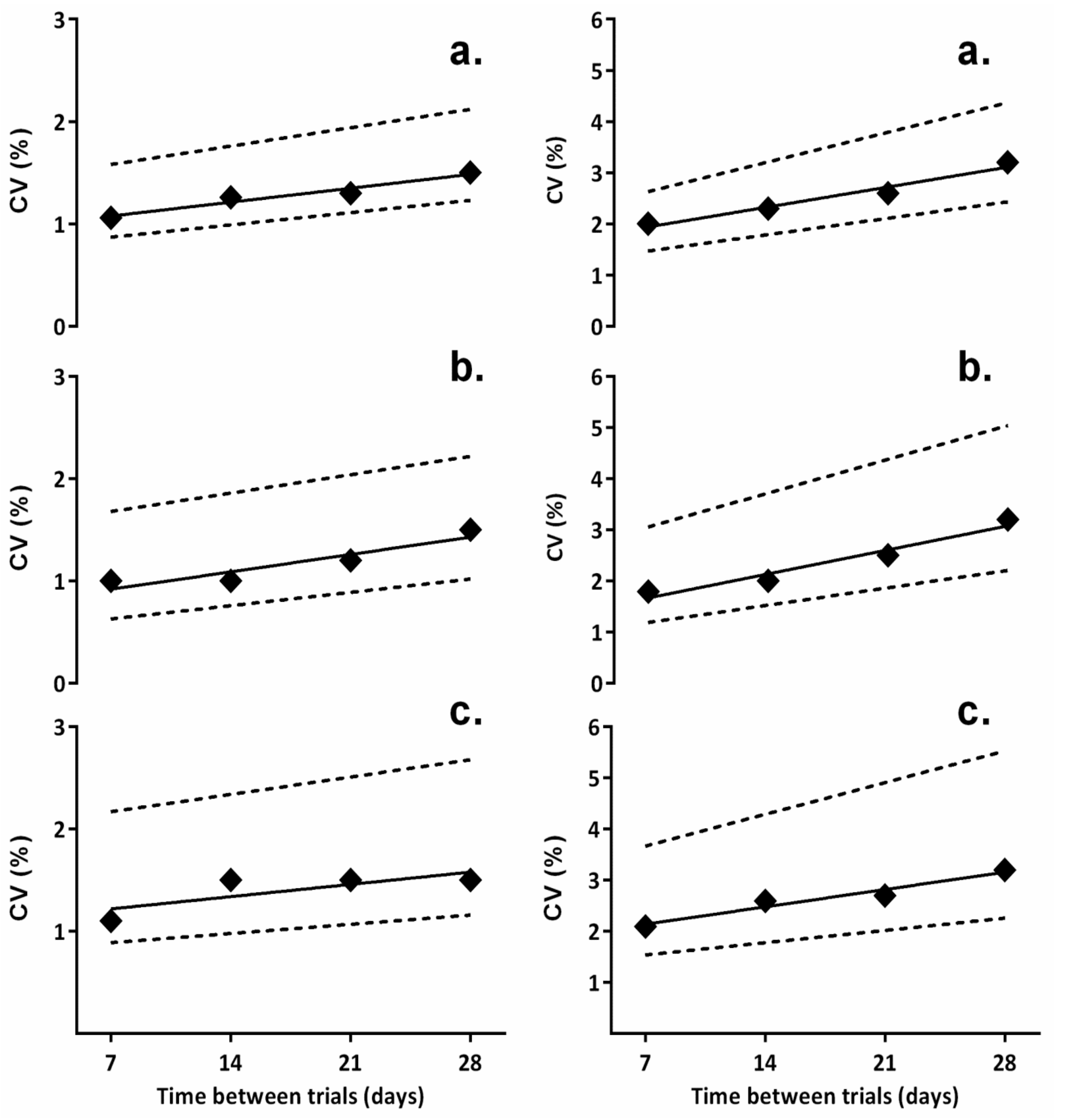

Figure 3-2 Coefficient of variation (CV) for time and power output (±90% CI) as time increases between trials for all cyclists (a), fastest cyclists (b) and slowest cyclists (c).

Table 3-2. shows the intra-class correlations (± 90% CI) for performance time and power output for all cyclists, and sub-groups of fastest and slowest cyclists as time increases between trials. A gradual decline in reliability is evident for time and power with increasing time between trials.

Table 3-2 The changes in intra-class correlation coefficient (ICC ± 90% CI) for all cyclists, fastest cyclists and slowest cyclists with increasing time between trials.

	T_{all}	T_{fast}	T_{slow}	W_{all}	W_{fast}	W_{slow}
ICC_{7days}	0.98 (0.96-0.99)	0.95 (0.81-0.99)	0.93 (0.79-0.98)	0.98 (0.95-0.99)	0.97 (0.87-0.99)	0.97 (0.89-0.99)
ICC_{14days}	0.97 (0.94-0.99)	0.95 (0.84-0.98)	0.86 (0.58-0.96)	0.97 (0.94-0.99)	0.95 (0.84-0.98)	0.95 (0.84-0.99)
ICC_{21days}	0.97 (0.93-0.98)	0.92 (0.78-0.98)	0.88 (0.65-0.97)	0.96 (0.91-0.98)	0.92 (0.76-0.97)	0.94 (0.81-0.98)
ICC_{28days}	0.96 (0.91-0.98)	0.87 (0.65-0.96)	0.88 (0.64-0.96)	0.94 (0.87-0.97)	0.87 (0.63-0.96)	0.92 (0.76-0.98)

Abbreviations: T_{all} = performance time all cyclists; T_{fast} = performance time fastest cyclists; T_{slow} = performance time slowest cyclists; W_{all} = mean power all cyclists; W_{fast} = mean power fastest cyclists; W_{slow} = mean power slowest cyclists; 7days = seven days between trials; 14days = 14 days between trials; 21days = 21 days between trials; 28days = 28 days between trials.

3.4 DISCUSSION

The major findings of the present study is that a novel laboratory based simulated cycling time-trial performed on a course of varying gradients is a reliable test in terms of time (~1.2%) and power output (~2%) with competitive cyclists when trials are separated by less than 14 days. However reliability of performance declines substantially as time between trials increases beyond this period. In addition it was evident that faster cyclists were more reliable in the short term in comparison to their slower counterparts, though this finding was not apparent when trials were separated by longer intervening trial periods. We also found evidence of a learning effect between particularly between trials 1-2; though this was deemed statistically trivial. Evidence of a learning effect, all be it small, is a finding consistent with previous studies[7,8,12] and adds support to the requirement of at least one familiarisation trial for subjects prior to performing any experimental study trials.

The observed short term (7-14 days between trials) reliability for performance in our study was similar to, and in some cases better, than the short term reliability reported in previous studies using constant grade time-trials.[5-8] However, a unique aspect of our study is the inclusion of frequent variations in terrain which we may have expected to increase performance variation compared to a constant gradient time-trial. Importantly, the similarity in short term reliability between this study and others indicates the presence of changes in gradient does not appear to adversely affect the tests reliability.

The variation in performance we report here is also substantially smaller than that reported in previous studies using dynamic changes in effort over both 100-km and 30-km distances.[11,12] The reasons for the better reliability in the current study are unclear, since both the previous studies used cyclists of similar ability. However a possible explanation relates to the differing nature of the dynamic tests. In both previous dynamic studies cyclist were required to perform set periods (0.25-4-km) of high-intensity activity during the trial when instructed by the researchers, whereas in the current study the cyclists were free to modify their intensity in response to their perceived feelings at the time. The ability to make smaller but continuous modifications to exercise intensity may have allowed the athletes in our study to adopt a more even pacing strategy and this therefore may lead to better reliability. It is also possible the shorter distance in the current study influenced reliability, as longer distances would allow for greater errors in a cyclists self-pacing strategy to manifest. Clearly changes in feeding for example during a 100-km trial would have a much bigger effect on pacing than during a 20-km trial.

We also observed a substantial decrease (Fig 3-2.) in reliability of cycling performance with increasing time between trials. The decrease in reliability over time is consistent with the findings of Abbiss et al. [12] who reported a very large decline in reliability (CV of ~11%) when time-trials were separated by six-weeks. A likely explanation for the increased variation in performance within our study (and that of previous studies) is during long intervening periods subjects simply lose their perception of the appropriate pacing strategy. It is also likely individual variations in fitness over longer time-periods contribute to greater variations in performance within a study group.

Separate analysis of reliability based on cyclist's ability in our study also indicated the faster cyclists were more reliable in performance than slower cyclists (CV~1.9% & 2.4% respectively) at least in the short term; this finding is in agreement with previous investigations.[7] However, reliability declined linearly in both groups with increasing time between trials and was similar after a 28-day period. Irrespective of athlete ability, the decrease in trial reliability over time has important implications for studies examining training and other interventions where time between experimental trials exceeds 14-days. In these situations we would recommend that researchers perform regular re-habituation trials so that subjects might remain familiar with testing conditions. Theoretically this could improve the ability to detect meaningful and important changes to performance in experimental studies with a large intervening time period between pre and post testing.

3.5 PRACTICAL IMPLICATIONS:

The novel protocol investigated in the present study may detect meaningful changes in performance that matter to athletes and can therefore be used by coaches and sports scientists to examine the efficacy of training and other scientific interventions. Continued habituation is necessary in all cyclists when a large period of time elapses between trials. Habituation could be achieved by including the performance trial as part of any training intervention in long duration experimental trials or as a prescribed training session if monitoring performance throughout a competitive season. There was also evidence of a small learning effect between trials 1-2 and we therefore recommend that all athletes undertake a familiarisation session prior to any experimental study.

3.6 CONCLUSION:

A novel computer simulated cycling time trial completed over a course of varying gradient is a reliable measure of performance, when trials are separated by short intervening periods. However a substantial decline in performance reliability was evident when more than 14 days elapsed between trials. Furthermore, faster cyclists were generally more reliable in performance than slower cyclists over the short term though any differences were insubstantial over the longer term. Future studies are needed to confirm the reliability of variable gradient time-trials and determine the effects of individual variations in fitness on test reliability.

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CHAPTER 4.

THE PHYSIOLGICAL CORRELATES OF VARIABLE GRADIENT CYCLING PERFORMANCE

ABSTRACT

Purpose: This study investigates the physiological correlates of computer simulated hilly time-trial performance with competitive cyclists. **Methods:** Twenty eight trained cyclists (age 33.7 ± 10.3 years, mass 74.4 ± 7.3 kg, and maximal oxygen uptake 64 ± 7 $mL \cdot kg^{-1} \cdot min^{-1}$) participated in this study. Cyclists initially completed a graded exercise test (GXT) to establish measures of peak power output (PPO) maximal oxygen uptake ($\dot{V}O_{2max}$), 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 hilly course from which performance time and 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. **Results:** There were large to very large ($r= 0.51-0.9$) correlations between performance time and mean power in the time-trial and measures of absolute $\dot{V}O_{2max}$ and PPO from the graded exercise test. Correlations between time-trial performance 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 and measures of the anaerobic threshold when threshold parameters were reported as fractional utilisations of peak power. **Conclusions:** These findings support the use of body mass corrected variables for predicting performance in hilly time-trials. Cyclists preparing for hilly races are recommended to optimise their power to weight ratio to gain a performance advantage when competing over hilly terrain.

4.1 INTRODUCTION

The performance outcome for competitive cyclists during road cycling events is largely mediated by the type of event, interaction with other competitors and the environmental conditions. Competitive cycling events have previously been well described,[1-4] and it is clear that different events have specific performance demands and are therefore suited to cyclists of different physiological characteristics. 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.[5] For example Padilla et al. [5] 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.

Laboratory based time-trials are commonly used to determine the performance capacities of competitive cyclists. Previous researchers have described the physiological correlates of time trial performance via comparison between graded exercise tests (GXT) and laboratory simulation of a cycling time-trial.[6-21] 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 ($\dot{V}O_{2max}$).[6,14] However, these studies generally report weaker correlation ($r = 0.11$-0.59) between relative $\dot{V}O_{2max}$ and time-trial performance. Similarly, strong to nearly perfect correlations have been reported between lactate threshold ($r = 0.67$-0.97)[6,7,13,15,17] or ventilatory threshold ($r = 0.61$- 0.90)[10-12] reported as absolute power output and flat time-trial performance of various distances. Conversely, several studies,[17,18,21] 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.

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 variable gradient cycling performance during which cyclists must respond to frequent variations in terrain. Fortunately, recent advances in ergometer technology allow for test protocols that better mimic changes in resistance that cyclists face when cycling over varying terrain. Therefore, whilst the physiological profile best suited to constant gradient self-paced time-trials and constant gradient, experimenter paced stochastic time-trials is well established, it is unclear whether variable gradient time-trial performance, requires specific development of a similar physiological profile. Therefore the principal aim of this investigation was to establish the physiological correlates of hilly time-trial performance to describe the physiological predictors of hilly cycling performance

4.2 METHOD

4.2.1 Participants

Twenty eight competitive male cyclists (Mean ± SD. age: 33 ± 10 years, mass 74 ± 7 kg, height 178 ± 5 cm) gave their written informed consent to participate in this study. All cyclists had a minimum of two years 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 pre-approved by the participating institutions human research ethics committee in accordance with the declaration of Helsinki.

4.2.2 Design

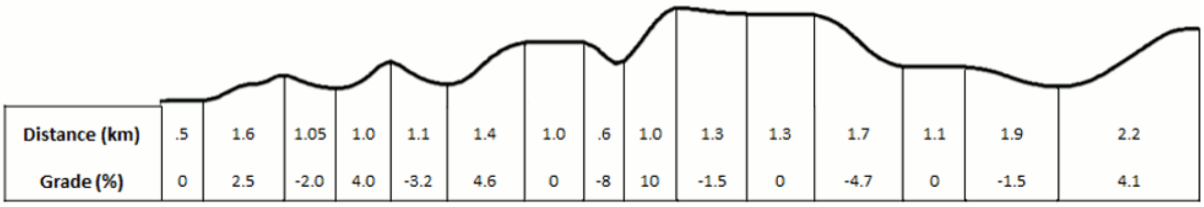
The study was a repeated measures experimental trial where each cyclist completed a graded exercise test and two computer simulated 20-km variable gradient time-trials, the first trial served as a habituation trial and the second as the experimental trial. All tests were completed on a Velotron Dynafit Pro cycle ergometer (RacerMate Inc, WA, USA) using the company's associated software package. Prior to testing each participant was fitted to the ergometer in a position to replicate as closely as possible 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 ~20^{o}C with a relative humidity of ~50-60%.

4.2.3 Incremental Exercise Test

Cyclists completed an incremental exercise test to volitional exhaustion, from which measures of peak power output (PPO), maximal oxygen uptake ($\dot{V}O_2$ max), power at the 4 mmol/L lactate point (OBLA), ventilatory threshold (VT) and efficiency (GE) were assessed. During the incremental exercise test 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 100W increasing by 40W every four minutes thereafter until reaching volitional exhaustion. The ergometer was set to isokinetic mode during the incremental test so that power output remained constant regardless of changes in pedal cadence. Cyclists were allowed to freely vary there cadence during the test though were encouraged to maintain a cadence of ~90 revolutions per minute. During the final 30 seconds of each stage 25µL 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 incremental test was determined as the final completed stage plus the proportion of any uncompleted stage reached during the graded exercise test in accordance with Lucia et al. [22] 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. Ventilatory threshold was determine 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. [10]. Gross efficiency (GE) was determined from respiratory data at 220W in accordance with the methods of Horowitz et al. [23]

4.2.4 Variable Gradient Time-Trial

The time-trial was completed on a computer simulated course using the same ergometer as previously described. 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 4-1.



Distance (km)	.5	1.6	1.05	1.0	1.1	1.4	1.0	.6	1.0	1.3	1.3	1.7	1.1	1.9	2.2
Grade (%)	0	2.5	-2.0	4.0	-3.2	4.6	0	-8	10	-1.5	0	-4.7	0	-1.5	4.1

Figure 4-1 The computer simulated course profile showing the variation in gradient and specific segment information of the time-trial used in this study.

Participants were able to view 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 to remove any potential pacing effect. 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*.

4.2.5 Statistical Analysis

All descriptive statistics are reported as means ± standard deviation. The relationship between physiological variables measured during the graded exercise test and performance 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.[24] Correlation coefficients below 0.1 were considered trivial. 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.[25] Magnitudes of the standardised differences were interpreted and reported using the effect thresholds of: 0.2, 0.5, and 0.8 for small, moderate, and large differences respectively in accordance with the recommendations of Cohen [26]. Effect size values <0.2 were considered trivial differences.

4.3 RESULTS

Cyclist performance and physiological characteristics are shown in table 4-2.

Table 4-1 Performance and physiological characteristics of cyclists (mean ± SD).

Variable	Mean ± SD
Time-trial time (mm:ss)	37:39 ± 2:28
Time-trial power (W)	288 ± 29
Time-trial power/mass ($W{\cdot}kg^{-1}$)	3.9 ± 0.6
Peak power output (W)	352 ± 29
Peak power-mass ($W{\cdot}kg^{-1}$)	4.8 ± 0.6
Maximal oxygen uptake ($L{\cdot}min^{-1}$)	4.8 ± 0.4
Maximal oxygen uptake ($mL{\cdot}kg^{-1}{\cdot}min^{-1}$)	64 ± 7
Onset Blood Lactate Accumulation (OBLA) power (W)	289 ± 35
OBLA power-mass ($W{\cdot}kg^{-1}$)	3.9 ± 0.6
OBLA as % of PPO (%PPO)	82 ± 6
Ventilatory Threshold (VT) power (W)	288 ± 29
VT power/mass ($W{\cdot}kg^{-1}$)	3.9 ± 0.6
VT as % of PPO (%PPO)	82 ± 4
Gross Efficiency (%)	21.5 ± 1.1

4.3.1 Time-Trial Segment Power Output

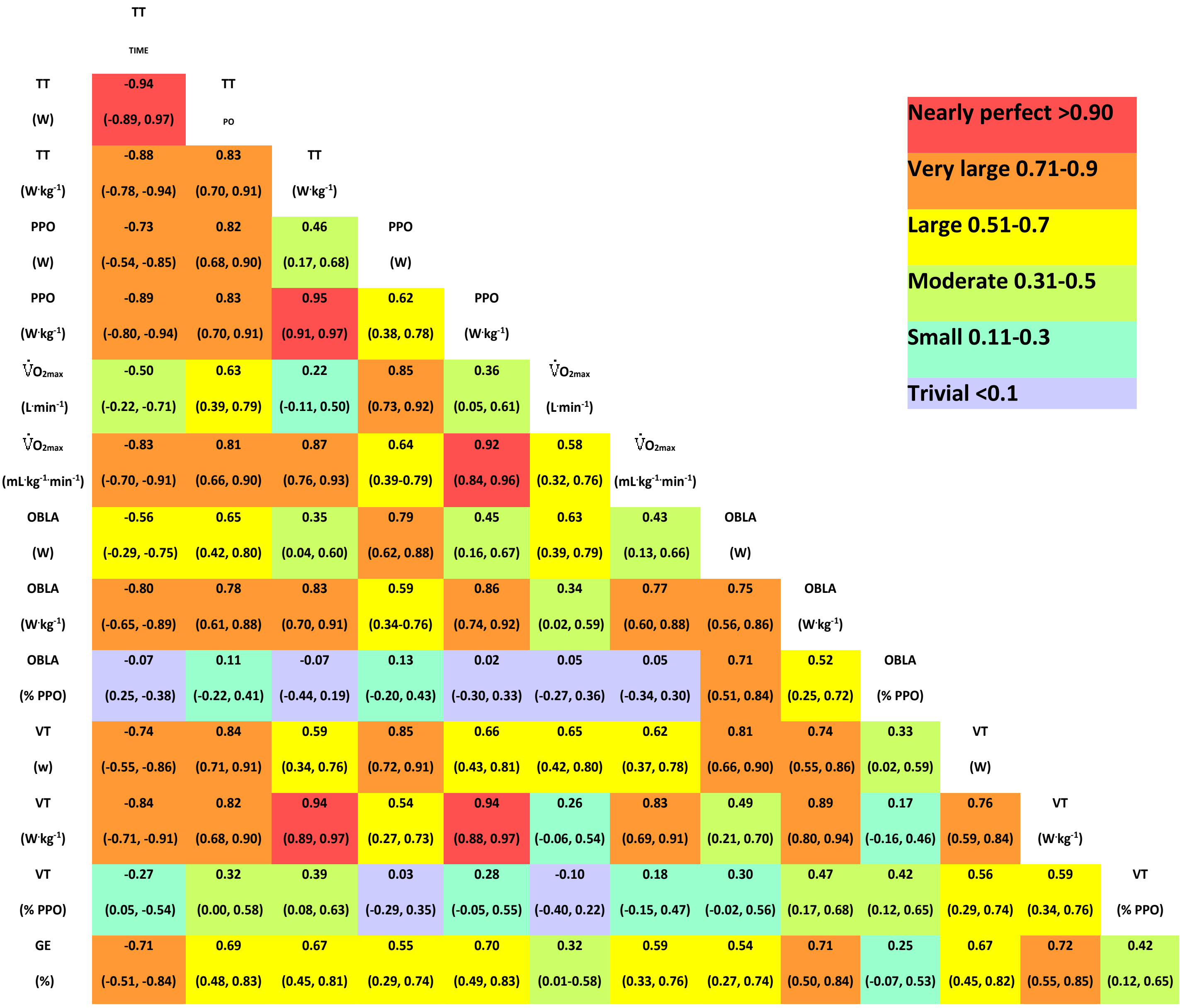
There were a moderate to large differences (4.6-10.9%, ES=0.50-1.22) between overall mean power output and mean power output for each segment category (table 4-2). Similarly there were moderate to large differences (6.6-12.1%, ES=0.72-1.36) in mean power output between flat and both uphill and downhill segments, and there was a large difference (17.9%, ES=2.09) in mean power output between uphill and downhill segments.

Table 4-2 Characteristics and mean power 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	6.3	7.1	6.6
Grade (%)	0.5%	0	4.7 ± 2.7	-3.8 ± 2.7
Power (W)	294 ± 28.9	281 ± 36.7	318 ± 28.6	263 ± 33.0

4.3.2 Correlations Between Anthropometric, Physiological and Performance Variables

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 4-2).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 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 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 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). Peak power output relative to body mass was more strongly correlated to variables expressed relative to body mass and absolute peak power output was more strongly correlated to variables expressed as an absolute value. There was a large to very large correlation between time and relative time-trial power output and body mass (kg) (r = 0.55 & -0.81 respectively). However the correlation between time-trial power output and body mass was only moderate (r = -0.37).



	TT TIME												
TT (W)	-0.94 (-0.89, 0.97)	TT PO											
TT (W·kg^{-1})	-0.88 (-0.78, -0.94)	0.83 (0.70, 0.91)	TT (W·kg^{-1})										
PPO (W)	-0.73 (-0.54, -0.85)	0.82 (0.68, 0.90)	0.46 (0.17, 0.68)	PPO (W)									
PPO (W·kg^{-1})	-0.89 (-0.80, -0.94)	0.83 (0.70, 0.91)	0.95 (0.91, 0.97)	0.62 (0.38, 0.78)	PPO (W·kg^{-1})								
$\dot{V}O_{2max}$ (L·min^{-1})	-0.50 (-0.22, -0.71)	0.63 (0.39, 0.79)	0.22 (-0.11, 0.50)	0.85 (0.73, 0.92)	0.36 (0.05, 0.61)	$\dot{V}O_{2max}$ (L·min^{-1})							
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	-0.83 (-0.70, -0.91)	0.81 (0.66, 0.90)	0.87 (0.76, 0.93)	0.64 (0.39-0.79)	0.92 (0.84, 0.96)	0.58 (0.32, 0.76)	$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})						
OBLA (W)	-0.56 (-0.29, -0.75)	0.65 (0.42, 0.80)	0.35 (0.04, 0.60)	0.79 (0.62, 0.88)	0.45 (0.16, 0.67)	0.63 (0.39, 0.79)	0.43 (0.13, 0.66)	OBLA (W)					
OBLA (W·kg^{-1})	-0.80 (-0.65, -0.89)	0.78 (0.61, 0.88)	0.83 (0.70, 0.91)	0.59 (0.34-0.76)	0.86 (0.74, 0.92)	0.34 (0.02, 0.59)	0.77 (0.60, 0.88)	0.75 (0.56, 0.86)	OBLA (W·kg^{-1})				
OBLA (% PPO)	-0.07 (0.25, -0.38)	0.11 (-0.22, 0.41)	-0.07 (-0.44, 0.19)	0.13 (-0.20, 0.43)	0.02 (-0.30, 0.33)	0.05 (-0.27, 0.36)	0.05 (-0.34, 0.30)	0.71 (0.51, 0.84)	0.52 (0.25, 0.72)	OBLA (% PPO)			
VT (w)	-0.74 (-0.55, -0.86)	0.84 (0.71, 0.91)	0.59 (0.34, 0.76)	0.85 (0.72, 0.91)	0.66 (0.43, 0.81)	0.65 (0.42, 0.80)	0.62 (0.37, 0.78)	0.81 (0.66, 0.90)	0.74 (0.55, 0.86)	0.33 (0.02, 0.59)	VT (W)		
VT (W·kg^{-1})	-0.84 (-0.71, -0.91)	0.82 (0.68, 0.90)	0.94 (0.89, 0.97)	0.54 (0.27, 0.73)	0.94 (0.88, 0.97)	0.26 (-0.06, 0.54)	0.83 (0.69, 0.91)	0.49 (0.21, 0.70)	0.89 (0.80, 0.94)	0.17 (-0.16, 0.46)	0.76 (0.59, 0.84)	VT (W·kg^{-1})	
VT (% PPO)	-0.27 (0.05, -0.54)	0.32 (0.00, 0.58)	0.39 (0.08, 0.63)	0.03 (-0.29, 0.35)	0.28 (-0.05, 0.55)	-0.10 (-0.40, 0.22)	0.18 (-0.15, 0.47)	0.30 (-0.02, 0.56)	0.47 (0.17, 0.68)	0.42 (0.12, 0.65)	0.56 (0.29, 0.74)	0.59 (0.34, 0.76)	VT (% PPO)
GE (%)	-0.71 (-0.51, -0.84)	0.69 (0.48, 0.83)	0.67 (0.45, 0.81)	0.55 (0.29, 0.74)	0.70 (0.49, 0.83)	0.32 (0.01-0.58)	0.59 (0.33, 0.76)	0.54 (0.27, 0.74)	0.71 (0.50, 0.84)	0.25 (-0.07, 0.53)	0.67 (0.45, 0.82)	0.72 (0.55, 0.85)	0.42 (0.12, 0.65)

Nearly perfect >0.90

Very large 0.71-0.9

Large 0.51-0.7

Moderate 0.31-0.5

Small 0.11-0.3

Trivial <0.1

Figure 4-2 Pearson's correlation matrix (r ± 90% CI) between 20-km time-trial performance and physiological variables.

4.4 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 hilly time-trial performance is most strongly related to physiological and performance variables measured during a graded exercise test when measured variables are expressed relative to body mass. Further, results indicate physiological variables expressed as a fractional utilisation of PPO correlate poorly with hilly time-trial performance and are therefore poor predictors of performance.

Similar to previous studies that have used flat profile performance tests, the measure from a graded exercise test that was most strongly related to variable gradient time-trial performance was PPO.[6-8,27] 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 performance when PPO is expressed relative to body mass.[17,18,21,28] However, in contrast to earlier studies in which the time-trial was exclusively uphill, the uphill segments of the protocol used in this study only comprised one third of the total course distance (7.1-km), the rest being either flat (6.3-km) or downhill (6.6-km). Therefore, even with the inclusion of segments where greater mass may yield higher speeds, and subsequently better performance time,[29] PPO scaled to body mass is an important determinant of variable gradient cycling performance. Subsequently, it is important that cyclists who are targeting hilly 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 $\dot{V}O_{2max}$,[6,9,13,14] OBLA[6,7,13,15] and VT.[10-12] However, similar to PPO, when variables were expressed relative to body mass, the strength of relationships was increased. Gregory et al. [30] reported similar correlations between physiological variables expressed relative to mass and mountain bike performance which included multiple changes in gradient.

Therefore, the inclusion of uphill segments in self-paced performance tests also increases the importance of expressing physiological variables relative to a proponent of body mass. The strength of the correlation between scaled variables and hilly cycling was stronger than those reported for self-paced and experimenter paced cycling performance. Importantly, comparisons based on self-paced constant gradient time-trial, may have under represented the importance of some physiological variables to field cycling performance, particularly relative $\dot{V}O_{2max}$.

In contrast to earlier research[9] there was a very strong correlation between cycling efficiency and time-trial performance. Given the sample of cyclists recruited to participate in this study differed in performance ability (as indicated by their Oceania National Level grading), and previous investigations that indicate more experienced cyclists have greater aerobic efficiency than less experienced cyclists,[31] this result is not surprising. Additionally, GE is trainable,[32] improves throughout a competitive cycling season[33] and is defined as an important determinant of endurance performance.[34] Like other physiological variables, it is possible constant grade performance tests, under estimate the importance of GE to field cycling performance. Importantly, muscle fibre type recruitment and substrate utilisation are different for variable intensity cycling.[35] Furthermore, GE decreases when cycling up steep hills (> 4%),[36] a similar grade to the uphill segments included in the performance test of the current study. It is possible that cyclists with higher GE are less affected by changes in cycling efficiency when completing hilly, variable intensity cycling. However, further research is required to determine the nature of the relationship between the decline in GE and gradient and the effects of variable intensity cycling on GE. Nevertheless, 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,[9,13] 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 unresponsive to training.[37] 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.

4.5 PRACTICAL IMPLICATIONS:

- These data highlight the physiological variables that underpin hilly cycling performance and indicates cyclists targeting hilly events need to produce high power relative to body mass and have a high relative $\dot{V}O_{2max}$.
- Coaches and sports scientists should consider ways to optimise body mass when preparing cyclists for hilly competitive events.
- When assessing performance and physiology sport scientists should evaluate and report results as absolute and relative values to better predict performance potential in hilly events.
- 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 hilly.
- Ventilatory threshold and OBLA expressed as a percentage of PPO (fractional utilisation) were poorly correlated with performance and were 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 hilly events

4.6 CONCLUSION

Performance in hilly 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 hilly time-trial performance are relative PPO and relative $\dot{V}O_{2max}$. Conversely, the correlation between fractional utilisation and performance was poor. Therefore cyclists targeting hilly events require a highly developed, efficient aerobic energy system and the ability to generate high power output relative to body mass.

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CHAPTER 5.

THE DISTRIBUTION OF WORK DURING VARIABLE GRADIENT CYCLING TIME-TRIALS

ABSTRACT

Purpose: Pacing is an important determinant of cycling time-trial performance and the optimal pacing strategy is often dependent on many factors including changes in road gradient. However, the pacing response to variable gradient cycling performance is currently unknown. The purpose of this study is to describe the self-selected pacing pattern in competitive cyclists during computer simulated variable gradient time-trial performance. **Methods:** Twenty-five competitive male cyclists (age 33.8 ± 10.8 years, mass 74.8 ± 7.8 kg, and maximal oxygen uptake 64 ± 7 $\mathrm{mL{\cdot}kg^{-1}{\cdot}min^{-1}}$) participated in this study. Cyclists initially completed a graded exercise test (GXT) to establish measures of peak power output, maximal oxygen uptake, onset blood lactate accumulation and gross efficiency. Following an initial habituation trial, subjects completed a 20-km time-trial over a computer simulated hilly course. Power output was measured continually throughout the trial and then dissected into 1 km segments. Differences in mean power output over each segment were then determined to describe the overall pacing pattern during a variable gradient cycling test. **Results:** Power output tended to be higher in the first 4 and last 2-km of the time-trial, while power output throughout the middle segments (4-18-km) was moderated. Additionally, there were large differences in mean power output between consecutive segments 2-3, 3-4, 4-5, 5-6, 9-10, 14-15, 18-19 (ES = 0.81-1.71). **Conclusions:** Cyclists self-selected a variable-parabolic distribution of exercise intensity to complete a computer simulated variable gradient cycling test. Importantly, results indicate power output during variable gradient cycling is largely determined by distance and road gradient. However, the presence of a parabolic distribution of exercise intensity supports an anticipatory mechanism of pacing regulation.

5.1 INTRODUCTION

The, pacing strategy adopted by cyclists during competitive time trial plays an important role in overall performance.[1] Competitive cyclists are believed to pre-determine their pacing strategy by using previous performance experience and knowledge of the expected performance duration.[2-4] Throughout an event, pacing is then regulated via integrative afferent feedback relating to distance remaining, internal condition, perception of physiological strain and environmental cues.[1,5,6]

Experimental examination of the spontaneous pacing response to cycling exercise has been largely limited to laboratory observation of simulated cycling performance.[4,7,8] Foster et al. [7] reported two distinct pacing strategies in response to short (500-1500m) and medium (3000m) distance cycling performance tests. During shorter tests, Foster et al. [7] indicated cyclists used an "all-out" start after which power output declined to the finish of the trial. Conversely, during the middle distance test, cyclists used a more even pacing strategy so that power output was even throughout the trial. In a slightly longer performance trial (4000m), Ansley et al. [4] observed a parabolic pacing response whereby power output peaked early, decreased through the middle part of the trial, then increased again in the final minute of exercise. Chaffin et al. [8] also reported a similar increase in power towards the end of a 30 minute self-paced performance test. Cyclists in that study employed an even pacing strategy from the outset of the trial, with power varying by no more than ~5% until the final minutes when power output increased by ~28%, an example of a negative pacing strategy[9] and an end spurt.[6] The changes in pacing response between events of different duration indicates the adopted pacing strategy is largely determined by the distance of the trial. However, the pacing patterns described in previous literature were all observed in flat race conditions in the absence of variation in external resistance such as wind speed or gradient that could alter the pacing response.

Recently, consideration for the effect of external resistance has revealed the benefits of variable pacing strategies.[10-12] Mathematical modelling of cycling performance suggests cyclists need to vary power output in response to changes in environmental resistance caused by wind conditions or changes in road gradient.[10-12] Additionally, performance models suggest that greater amplitude of power output variation is required when there are larger increases or decreases in external resistive forces to maintain cycling speed. [10-12] It is therefore important that cyclists select a variable intensity pacing strategy to achieve optimal performance in cycling events that occur in variable environments.

Investigations of the pacing response to constant resistance performance tests indicate the predominant pacing strategy used by competitive cyclists is characterised by even distribution of energy with an end spurt during which exercise intensity increases markedly. Additionally, cyclists use prior knowledge of performance in combination with physiological and environmental feedback to adjust effort during testing and competition. However, while it is evident that optimal pacing strategy for competitive cycling events is different between courses of different gradient profile, there is a dearth of research that examines the spontaneous pacing response to variable environmental resistance. Recently a simulated time-trial in which gradient variation was achieved by controlled manipulation of the course profile was found to be reliable in a sample of competitive cyclists.[13] Therefore the aim of this study was to determine if the pacing profile common to flat cycling performance tests is maintained when gradient changes and exercise intensity variation would be beneficial to performance. The results of this study will provide initial insight into the regulation of exercise intensity during endurance events where environmental resistance varies.

5.2 METHOD:

5.2.1 Participants:

Twenty-five competitive cyclists gave their informed written consent to participate in this study. All cyclists had a minimum two years racing experience, including time trials, and were competitive at an A or B grade Oceania National Level. This study was completed during the cyclists' competitive phase and was pre-approved by the institutions human research ethics committee in accordance with the declaration of Helsinki.

5.2.2 Design:

This study was a repeated measures experimental trial where each cyclist completed a graded exercise test and two computer simulated 20-km variable gradient time-trial's; the first trial served as a habituation trial and the second as the experimental trial. All tests were completed on a Velotron Dynafit Pro cycle ergometer (RacerMate Inc, WA, USA) using the company's associated software package. Prior to testing each participant was fitted to the ergometer in a position to replicate as closely as possible 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 ~20°C with a relative humidity of ~50-60%.

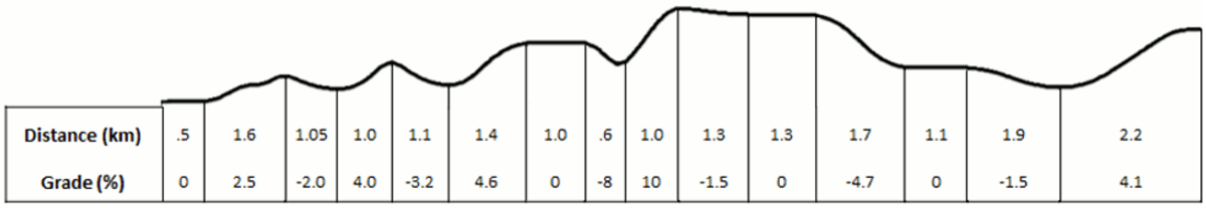
5.2.3 Incremental Exercise Test

Cyclists completed an incremental exercise test to volitional exhaustion, from which measures of peak power output (PPO), maximal oxygen uptake ($\dot{V}O_2$ max), power at the 4 mmol/L lactate point (OBLA), ventilatory threshold (VT) and efficiency were assessed. During the incremental exercise test 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 40W every four minutes thereafter until reaching volitional exhaustion. The ergometer was set to isokinetic mode during the incremental test so that power output remained constant regardless of changes in pedal cadence. Cyclists were allowed to freely vary there cadence during the test though were encouraged to maintain a cadence of ~90 revolutions per minute. During the final 30 seconds of each stage 25µL 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 incremental test was determined as the final completed stage plus the proportion of any uncompleted stage reached during the graded exercise test in accordance with Lucia et al. [14]. 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. Ventilatory threshold was determine 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. [15].

Gross efficiency (GE) was determined from respiratory data at 220W in accordance with the methods of Horowitz et al. [16].

5.2.4 Variable Gradient Time-Trial

The computer simulated, 20-km variable gradient time-trial was completed on a computer simulated course using the same ergometer as previously described. 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 5-1.



Distance (km)	.5	1.6	1.05	1.0	1.1	1.4	1.0	.6	1.0	1.3	1.3	1.7	1.1	1.9	2.2
Grade (%)	0	2.5	-2.0	4.0	-3.2	4.6	0	-8	10	-1.5	0	-4.7	0	-1.5	4.1

Figure 5-1 The computer simulated course profile showing the variation in gradient and specific segment information of the time-trial used in this study.

Participants were able to view their progress over the course on a computer monitor and were provided with information on distance completed and gear selected, however all other information was blinded. Participants were instructed to complete the time-trial as quickly as possible with no restriction on gear selection, cadence or cycling posture (seated or standing). Participants self-selected pacing strategy and were not coached on how to best ride the course. Throughout the trial participants were able to consume water *ad libitum*.

5.2.5 Statistical Analysis:

The performance time, mean power output and cadence for the complete time-trial were recorded for each subject. The complete trial was then divided into 20 segments of 1-km and the mean power output, elapsed time and cadence for each segment were recorded for analysis. Heart rate data for 12 of the 25 cyclists contained multiple erroneous results (spikes or dropout) and were therefore removed, leaving 13 files for the analysis of heart rate. Simple descriptive statistics are displayed as means ± standard deviations. To describe the pacing response, the standardised differences in mean power, time, cadence and heart rate between segments were interpreted and reported using the effect thresholds of: 0.2, 0.5, and 0.8 for small, moderate, and large effects respectively in accordance with the recommendations of Cohen [17]. Effect size values <0.2 were considered trivial.

5.3 RESULTS:

Cyclist physiological and performance characteristics from the GXT are displayed in table 5-1.

Table 5-1 The physiological and performance characteristics (mean ± SD) of the participants.

Variable	Mean ± SD
Age (years)	33.3 ± 10.8
Body mass (kg)	74.5 ± 7.5
PPO (W)	350 ± 31
$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})	64 ± 7
OBLA (W)	288 ± 35
GE (%)	21.4 ± 1.2

The power output, performance time, relative power output (as a percentage of full trial mean power) and cadence for the 20 segments from the simulated variable gradient 20-km time-trial are shown in table 5-2. Overall, cyclists increased their power output during uphill segments, however there was an overall decline in power output for all segments from kilometre four to kilometre 18, after which power increased substantially (figure 5.2). Analysis revealed large differences in mean power output between consecutive segments 2-3 (ES and their 95% CL) (ES = 1.10 [0.49, 1.68]), 3-4 (ES = 1.14 [0.52, 1.72]), 4-5 (ES = 1.71 [1.04, 2.33]), 5-

6 (ES = 1.09 [0.50, 1.69]), 9-10 (ES = 0.81 [0.23, 1.28]), 14-15 (ES = 1.23 [0.61, 1.82]), 18-19 (ES = 0.83 [0.24, 1.39]).

Table 5-2 Segment specific results (mean ± SD) from the computer simulated, variable gradient 20-km time-trial.

Distance (km)	Gradient (%)	Power Relative to Mean (%)	Performance Time (mm:ss)	Cadence (RPM)
1	1.2	110 ± 14	1:46 ± 0:07	93 ± 7
2	2.5	111 ± 10	2:03 ± 0:08	87 ± 8
3	-1.7	100 ± 11	1:26 ± 0:03	92 ± 8
4	3.1	112 ± 10	2:12 ± 0:12	83 ± 6
5	-2.6	94 ± 10	1:38 ± 0:05	92 ± 6
6	1.9	105 ± 10	2:00 ± 0:09	84 ± 6
7	4.3	101 ± 12	2:50 ± 0:20	83 ± 8
8	0.0	97 ± 12	1:38 ± 0:04	90 ± 6
9	-2.3	93 ± 13	1:31 ± 0:05	93 ± 6
10	7.3	103 ± 12	4:03 ± 0:32	77 ± 11
11	-0.8	94 ± 13	1:30 ± 0:04	92 ± 7
12	0.0	98 ± 12	1:35 ± 0:04	87 ± 6
13	-2.0	95 ± 12	1:31 ± 0:04	88 ± 6
14	-5.9	85 ± 11	1:02 ± 0:02	98 ± 4
15	-1.3	99 ± 11	1:25 ± 0:03	89 ± 5
16	-0.3	95 ± 12	1:35 ± 0:04	89 ± 5
17	-2.2	90 ± 13	1:19 ± 0:02	92 ± 6
18	-0.2	98 ± 11	1:38 ± 0:05	87 ± 6
19	4.4	107 ± 12	2:38 ± 0:18	82 ± 7
20	3.8	113 ± 14	2:07 ± 0:16	84 ± 9
Full Trial	**1.5**	**-**	**37:27 ± 2:40**	**88 ± 7**

Similarly, there were large differences in cadence between consecutive segments (ES = 0.83-2.12), particularly when the difference in gradient between two consecutive segments was greater. After a large increase between segments one and two (ES = 1.54 [0.62, 2.36]), heart rate stabilised and there were no further differences between consecutive segments for the rest of the trial (figure 5-3). However, heart rate was higher for the final 1-km segment when compared to all others (ES = 0.52-2.94). Overall, time to complete each segment was substantially slower for the uphill when compared to the flat (ES = 1.63[0.97, 2.24]) and downhill segments (ES = 1.93 [1.24, 2.57]). Additionally, segment completion time was slower for flat when compared to downhill segments (ES = 1.31 [0.68. 1.90]).

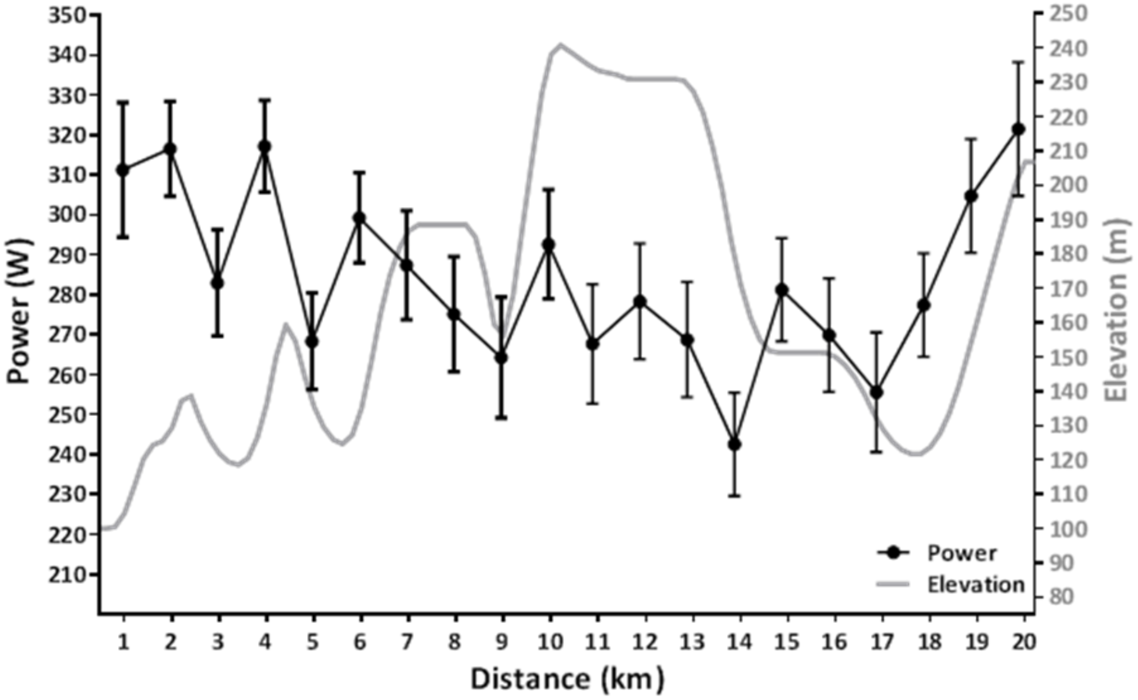


Figure 5-2 Mean power output (±95% CL) for each 1-km segment from the variable gradient time-trial.

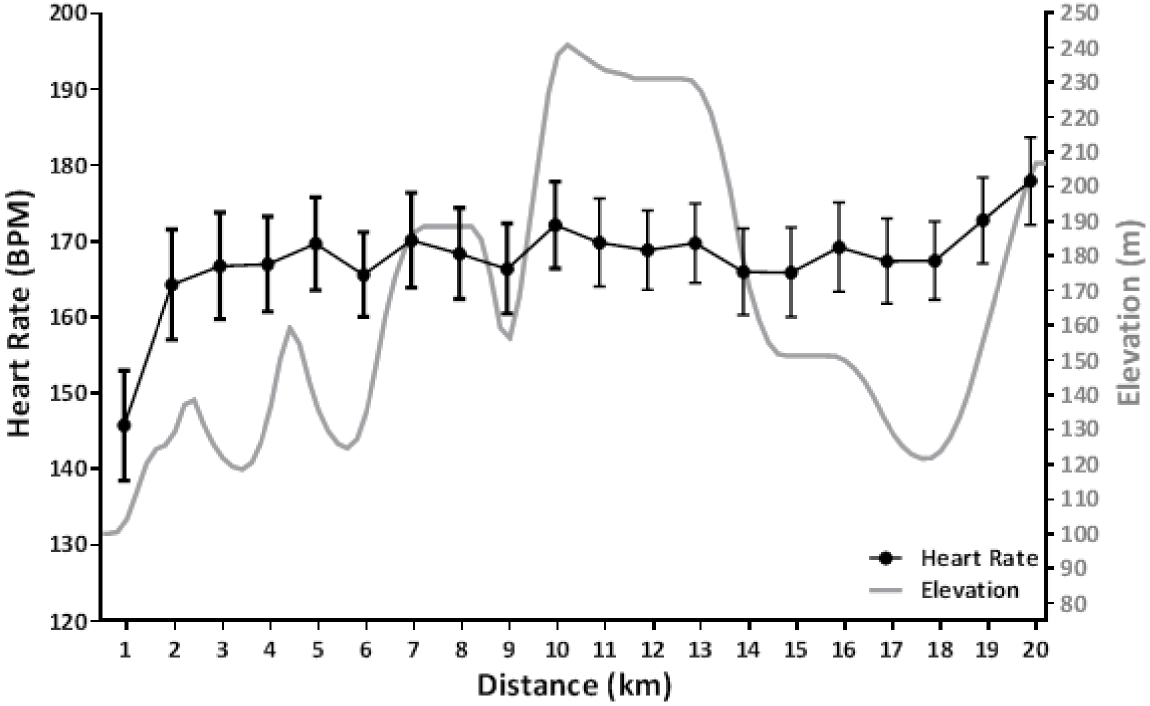


Figure 5-3 Mean heart rate (±95% CL) for each 1 km segment from the variable gradient time-trial.

5.4 DISCUSSION:

The aim of the present study was to determine if the even pacing profile common to flat cycling performance tests is maintained when gradient varies and exercise intensity variation would be beneficial to performance. Results from this study show large variations in power output during variable gradient cycling. The extent of the variations in power appears to be largely influenced by both changes in road gradient and elapsed time. Additionally, the pacing pattern was characterised by a high initial (fast start) and end power outputs despite the large variation in power output throughout the trial.

Previous investigations have described the spontaneous pacing response to cycling tests of a constant gradient for short to long durations.[4,7,8,18-20] The pacing strategies commonly observed in these studies differs according to the duration of the trial. The pacing pattern observed in the current investigation is similar to that seen in other constant gradient time-trials[8] with the highest power outputs recorded during the first and last 10% of the trial. However unlike other constant gradient time-trial, we observed large variations in the cyclists power output (~6%) throughout the trial in response to changes in road gradients. Therefore, the self-selected pacing response to variable gradient cycling is a mixture of the parabolic and variable pacing patterns described by Abbiss et al. [9] The results indicate that pacing is regulated not just by distance, but also by changes in external resistance, represented in the current investigation by variations in gradient.

Parabolic pacing patterns are characterised by a fast start and end-spurt at the start and end of a trial respectively, separated by a period of moderated exercise intensity.[9] In the current study there was a decline in cycling exercise intensity from 4-18-km after which intensity increased substantially for the final 2-km of the time-trial. The results indicate exercise intensity was moderated throughout the middle segments of the trial, even when cycling against increased resistance. The moderation of exercise intensity through middle segments, and subsequent increase of power output for final kilometres of the time-trial, is similar to the pacing response previously reported for medium and long distance cycling.[4,7,8,20-22] A pattern of moderated exercise intensity through the middle part of a competitive or experimental trial is said to be the result of an anticipatory control mechanism that acts to protect the body from severe homeostatic disturbance or competitive failure.[23] This mechanism likely exists to preserve some exercise capacity that is then utilised towards the end of exercise as an end-spurt when the perceived risk of physiological or competitive failure is mitigated by the short remaining duration of exercise.[6,23,24] Interestingly, the presence of a moderated middle portion and an end-spurt in which power output was 110% of the overall mean in the current study provides further evidence for an anticipatory pacing control mechanism.

Although exercise intensity was somewhat moderated throughout the middle segments of the trial, there were large variations in power output, due mainly to changes in the road gradient between segments. Previous research using models of cycling performance indicate power output should move from an even to variable pattern to optimise cycling performance over hilly terrain.[10-12] Additionally, research has validated model predictions by implementing model defined optimal variable pacing strategies during hilly cycling to improve simulated cycling performance.[25,26] However, to our knowledge, this is the first study to demonstrate that cyclists self-select a pacing strategy where exercise intensity changes in a manner that reflects the course profile. In contrast, Terblanche et al. [27] indicated power output did not track the variation in the course profile during a self-paced laboratory cycling simulation. However, cyclists in that study were asked to complete the course at a “comfortable speed” which likely attenuated variation in power output in response to changes in road gradient. Conversely, in the present study cyclists were asked to complete the course as quickly as possible and as a result, power output was seen to increase during uphill segments and decrease during downhill segments. Therefore, it is evident that changes in external environmental resistance are important determinants of the pacing response and should be included to improve the ecological validity of performance testing for competitive cyclists.

Interestingly, mean power output for uphill segments through the middle portion of the trial were lower (ES = 0.62–0.98) than uphill segments in the first and final sections of the trial. The lower power for these segments could be the result of the very high power outputs observed at the beginning of the trial. Indeed mean power output for the first four kilometres was 108%, 107% and 96% of overall time-trial mean power, OBLA power output and PPO respectively. Earlier investigations report an elevated physiological response and rating of exertion after a fast start during cycling time trials.[28] The anticipatory model suggests pacing is controlled based on instantaneous afferent feedback from central and peripheral systems to protect the athlete from catastrophic physiological or competitive failure.[6,24] Importantly, no cyclists in the current study reached a state of absolute fatigue and all were able to maintain a power output equivalent to or greater than ~76% of PPO for all segments during the trial. Therefore it is possible the fast start observed in the current study lead to down regulation of power output in later segments by a central pacing control mechanism. Importantly, given this trial included segments of steep gradient during which ability to generate higher power outputs would be beneficial, it is possible a fast start may have negatively influenced overall performance time. Indeed, other research has reported best overall performance following a slower start during a 20-km cycling time-trial.[28] Therefore, further research is necessary to determine the effect of different starting strategies on variable gradient cycling performance.

After an initial increase at the beginning of the trial, heart rate stabilised during the middle portion of the trial and then steadily increased during the end-spurt at the end of the trial. Interestingly there was only one moderate difference between consecutive segments despite large differences in power output between multiple sets of consecutive segments throughout the trial. A similar heart rate response to cycling performance tests has been reported in previous investigations.[2,8,19,20,29] However, unlike the present study, power output and exercise intensity observed in earlier studies was stable. It is likely heart rate remained stable due to a relatively long half-life when compared to power output which changes dramatically depending on exercise intensity.[30] As a result, it is possible the long duration of some segments and the brevity of others masked more severe changes to heart rate as a result of changes in exercise intensity. However, it is also possible that heart rate is not sensitive to frequent changes in power output during variable gradient cycling. Therefore, its use as an indicator of underlying physiological response to immediate changes in exercise intensity is limited.

One limitation of the ergometer used in the current study is that resistance is only reduced, and not assisted during negative gradient cycling. Cyclists often choose to, or are forced to coast during downhill cycling in the field. As a result, field cycling likely affords greater opportunities for recovery between high intensity segments that, with the ergometer technology used in the current study, we were unable to replicate. Furthermore, to minimise disruptions to the time-trial effort and ensure a spontaneous pacing response, we did not include other invasive physiological measures or rating of perceived exertion in this study.

Given pacing is regulated based on feedback relating to physiological status and the perception of effort,[1] future investigations could include measures of the acute physiological response to exercise and rating of perceived exertion to better describe the characteristics of variable gradient cycling. Additional studies could investigate the effect of coaching, particularly to mitigate the fast start observed in the current study, on the pacing response and overall variable gradient time-trial performance.

5.5 PRACTICAL APPLICATIONS:

- Although power output varied in response to changes in gradient, a parabolic pacing pattern was still evident which suggests energy distribution during endurance cycling events is dominated by an anticipatory control system.
- The results of this study may help sport scientists and coaches to understand the distribution of work used by cyclists to complete hilly events.
- The variable-parabolic pacing pattern observed in the current study indicates performance testing of cyclists should include some variation in environmental resistance to remain specific to competitive events.
- Heart rate monitoring is not sensitive enough to describe the frequent changes in power output during variable gradient cycling and may therefore under or overestimate exercise intensity and training load.

5.6 CONCLUSION:

The pacing pattern observed in the current study during a computer-simulated, variable gradient 20-km cycling time-trial was influenced largely by distance and gradient. Previous studies suggest intensity throughout time-trial is relatively even until the final 10% when a brief finishing burst is evident. In the present study cyclists increased power output a number of times throughout the time-trial often in response to steep gradients as they cycled uphill. However, power output was moderated throughout the middle portions of the trial and a fast start and end-spurt were still evident. The result was a variable-parabolic pacing pattern that supports the anticipatory model of pacing control. Therefore, it is evident both distance and changes in the external resistive forces are important determinants of pacing regulation and strategy during cycling.

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CHAPTER 6.

EFFECTS OF A SEVEN DAY OVERLOAD-PERIOD OF HIGH-INTENSITY TRAINING ON PERFORMANCE AND PHYSIOLOGY OF COMPETITIVE CYCLISTS

ABSTRACT

Objectives: Competitive endurance athletes commonly undertake periods of overload training in the weeks prior to major competitions. This investigation examined the effects of two seven-day high-intensity overload training regimes (HIT) on performance and physiological characteristics of competitive cyclists. **Design:** The study was a matched groups, controlled trial. Methods: Twenty-eight male cyclists (mean ± SD, Age: 33 ± 10 years, Mass 74 ± 7 kg, $\dot{V}O_{2max}$ 4.7 ± 0.5 $L \cdot min^{-1}$) were assigned to a control group or one of two training groups for seven consecutive days of HIT. Before and after training cyclists completed an ergometer based incremental exercise test and a 20-km time-trial. The HIT sessions were ~120 minutes in duration and consisted of matched volumes of 5, 10 and 20 second (short) or 15, 30 and 45 second (long) maximal intensity efforts. **Results:** Relative to the control group, the mean changes (± 90% confidence limits) in time-trial power were 8.2% ± 3.8% and 10.4% ± 4.3% for the short and long HIT regimes respectively; corresponding increases in peak power in the incremental test were 5.5% ± 2.7% and 9.5% ± 2.5%. Both HIT (short vs long) interventions led to increases (mean ± SD) in $\dot{V}O_{2max}$ (2.3% ± 4.7% vs 3.5% ± 6.2%), lactate threshold power (3.6% ± 3.5% vs 2.9% ± 5.3%) and gross efficiency (3.2% ± 2.4% vs 5.1% ± 3.9%) with only small differences between HIT regimes. **Conclusions:** Seven days of overload HIT induces substantial increases in time-trial performance and physiology with competitive cyclists.

6.1 INTRODUCTION

For many endurance athletes training is periodised across the season in order to prepare for competitions. The structure of training within a specific phase of a season often varies, and can include a combination of training techniques which are ultimately designed to enhance the athlete's performance capacity through increases in maximum oxygen consumption ($\dot{V}O_{2max}$), the sustainable percentage of maximum oxygen consumption (anaerobic threshold) or aerobic economy. Whilst low intensity, high volume training plays a major role in an endurance athlete's preparation there is little doubt that bouts of higher intensity training (HIT) are necessary in order to enhance athletic form and particularly $\dot{V}O_{2max}$.[1] Further a common practice observed amongst competitive athletes is to include short periods of heavily intensified training (often in the form of overload HIT or minor competitions) immediately prior to important competitions in order to further enhance race performance.

The structure of HIT sessions are diverse but generally involve short (< 5 minutes) repeated bouts of maximal intensity exercise at or above an athlete's maximum oxygen consumption power.[2] In recent years there have been a number of studies investigating the effects of various specific HIT regimes on an athletes' performance and physiological characteristics. In an early study Stepto et al. [3] examined the effects of six sessions (completed over two weeks) of different varieties of HIT programmes on 40-km time-trial performance with well-trained cyclists. Interestingly this study reported that the largest improvements in time-trial performance occurred from two quite diverse (30-s vs 240-s) HIT programmes, unfortunately this study did not examine the physiological mechanisms underlying any of the observed performance enhancements from the HIT sessions. Similarly in a series of related HIT studies with competitive cyclists, Laursen and colleagues[4-6] reported significant improvements in time-trial performance following 2-4 weeks of different duration (>30-s) maximal intensity intervals. The improvements in performance, in this series of studies, were associated with a significant increase in two of the recognised determinates of endurance performance, namely maximal oxygen consumption and lactate threshold power. Combining short duration (30-s) sport specific HIT with non-specific explosive training has also been shown to substantially enhance the third physiological determinant associated with endurance performance, namely aerobic economy, in both cyclists[7] and runners.[8]

As it is apparent that quite diverse forms and durations of HIT are an effective training strategy,[2] more recent research has focussed on the organisation and distribution of the HIT sessions within a periodised training program. In a study examining the effects of three weeks (nine sessions) of HIT performed on either consecutive or non-consecutive days, Gross et al. [9] reported similar improvements in performance and physiology following either strategy with recreational level cyclists. Furthermore two other recent studies indicate performance may be enhanced if a short block of concentrated interval training is followed by a three week period of less frequent interval training.[10,11] Interestingly in the study by Ronnestad et al. [10] the changes in the cyclists recorded training intensity (power) appear to indicate that the majority of performance enhancement occurs immediately following the first week of intensified training.

Regardless of its configuration, training is often organised to induce a state of temporary but functional overreaching. Functional overreaching is a training state that results in a short term performance decrement that, when followed by an adequate period of recovery, results in super-compensation and subsequent performance enhancement.[12] To evoke short term functional overreaching coaches and athletes often include short periods of highly intensified training, such as a training camp or low priority competition, in the weeks preceding a major competition. For example elite professional cyclists will often ride the week long Criterium du Dauphine in final preparation for the Tour de France. Previous research has established the potential for a very short period of intensified block training, such as would occur during a training camp or race, to improve performance. Jeukendrup et al. [13], reported significant improvements in performance after competitive cyclists had undertaken two weeks of recovery following a two-week period of intensified training. In a similar study investigating the effects of induced overreaching, Halson et al. [14] found brief periods of highly intensified training can lead to a decline in performance that may be sustained for periods of up to two weeks following the training period. However, this study did not include any longer term monitoring so it is unknown if any super-compensation effects occurred after the two week recovery period. Importantly in both the studies by Jeukendrup et al. [13] and Halson et al. [14], the authors reported physical and mental signs of overreaching and fatigue in the cyclists after only one week of intensified training which were amplified after an additional week of training and persisted through the early recovery period. Consequently it appears from observation and previous research that approximately seven days of intensified training maybe the optimal duration for improving performance without causing undue long term fatigue. The use of a seven day training period is also consistent with the common micro-cycle length utilised by athletes using periodised training programmes. Therefore while it appears different forms of HIT can lead to substantial performance gains, further research is warranted to determine the effects of shorter block periods of intensified training on the physiology of trained cyclists and the time course of any performance enhancements. To our knowledge no previous study has examined the magnitude of performance gains possible following a typical seven day intensified training period. Therefore the aim of this study was to determine the effects of seven consecutive days of two different HIT programs which simulated the intensity of efforts seen in competition, on the physiological and performance adaptations of competitive cyclists, and also to examine the time course of any adaptations during the post-training recovery period.

6.2 METHODS

6.2.1 Subjects

Thirty competitive male cyclists initially volunteered to participate in this study. Two cyclists failed to complete all sessions due to illness unrelated to the study and were therefore excluded from the final analysis leaving a total of 28 cyclists (Mean ± SD, age: 33 ± 10 years, mass 74 ± 7 kg, height 178 ± 5 cm, $\dot{V}O_{2max}$ 4.7 ± 0.5 $L\cdot min^{-1}$) at completion. All cyclists gave their written informed consent to participate in the study which was prior approved by the participating Universities human research ethics committees in accordance with the declaration of Helsinki. The cyclists were well-trained with a minimum of two years competitive experience at grade A or B (Oceania amateur grading). The study was performed in the competitive season following a period of base and pre-competition training. Due to the nature of each cyclist's competition programme it was not possible to control their individual training leading up to the study. However immediately prior (2 weeks) to the start of the study cyclists were completing individual self or coach-determined training regimes consisting of a minimum of ten hours (~300-km) mixed intensity training per week. At the start of laboratory testing cyclists were required to be in a well-prepared and non-fatigued state.

6.2.2 Testing Procedures

Cyclists were matched as closely as possible based on peak power output and maximum oxygen consumption ($\dot{V}O_{2max}$) from the initial incremental test, and assigned to one of three conditions; a control group (n=9), short sprint (n=9) and long sprint (n=10) HIT groups. The control group completed two physiological and performance assessments separated by three weeks during which they continued with their normal prescribed training (minimum of ten hours per week). The cyclists in the training groups completed a series of physiological and performance assessments before and after completing a seven day block of intensified training. Figure 6-1 outlines the sequence of testing and training for all subject groups.

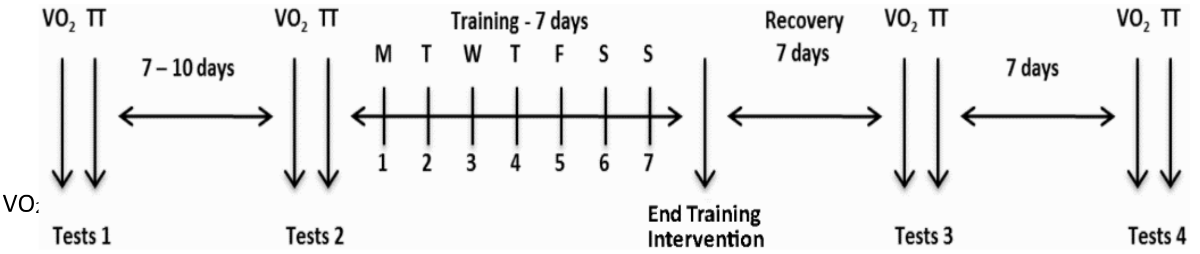


Figure 6-1 Sequence of training and testing followed by the cyclists in the experimental groups; control group subjects completed tests 2 and 4 only.

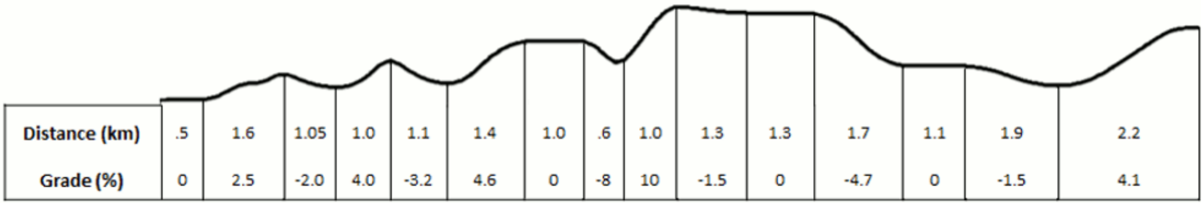
All physiological and performance assessments were completed on a Velotron Dynafit Pro cycle ergometer (RacerMate Inc, WA, USA) using the company's associated 3D race and coaching software. Prior to testing each participant was fitted to the ergometer in a position to replicate their own racing bicycle; 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 potential performance altering supplements (e.g. caffeine). 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 30cm pedestal fans and the ambient temperature of the laboratory was controlled at ~20^{o}C with a relative humidity of ~50-60%.

6.2.3 Incremental Exercise Test

The physiological assessment consisted of an incremental exercise test to volitional exhaustion, from which measures of peak power output (PPO), $\dot{V}O_{2max}$, power at the 4 mmol/L lactate point (OBLA), aerobic economy and efficiency were assessed. During the incremental exercise test respiratory gases were continuously measured 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 watts (W) increasing by 40W every four minutes thereafter until reaching volitional exhaustion. The ergometer was set to isokinetic mode during the incremental test so that power output remained constant regardless of changes in pedal cadence. Cyclists were allowed to freely vary there cadence during the test though were encouraged to maintain a cadence of ~90 revolutions per minute. During the final 30 seconds of each stage 25µL 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 incremental test was determined as the final completed stage plus the proportion of any uncompleted stage reached during the graded exercise test in accordance with Lucia et al. [15]. 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 output at which blood lactate reached a concentration of 4 mmol/L. Aerobic economy ($W \cdot L^{-1}$) was determined as the oxygen consumption at 220W for all subjects as this was the highest intensity achieved in all subjects where oxygen consumption remained at steady state and the respiratory quotient <1.0; similarly gross efficiency (GE) was determined from respiratory data at 220W in accordance with the methods of Horowitz et al. [16].

6.2.4 Time-Trial Test

The time trial (TT) was completed on a computer simulated 20-km course using the same ergometer as previously described. 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 7-2. Studies from our laboratory (unpublished observations) indicate a coefficient of variat6on for this test of ~1% for time and ~2% for mean power output. Participants were able to view 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 to remove any potential pacing effect. 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.* Performance time (TT TIME) and mean power output (TT PO) recorded from the variable gradient time-trial were the main performance measures in this study.



Distance (km)	.5	1.6	1.05	1.0	1.1	1.4	1.0	.6	1.0	1.3	1.3	1.7	1.1	1.9	2.2
Grade (%)	0	2.5	-2.0	4.0	-3.2	4.6	0	-8	10	-1.5	0	-4.7	0	-1.5	4.1

Figure 6-2 The computer simulated course profile showing the variation in gradient and specific segment information of the time-trial used in this study.

Cyclists in the two experimental training groups completed seven consecutive days of HIT. The composition of the training sessions was designed to replicate the intensity and duration of efforts seen in real competition and was determined in conjunction with two elite level coaches, using power data collected from competitive cyclists during racing and on previous competition based performance analysis by Ebert et al. [17]. The training sessions, consisted of multiple sets of self-paced maximal intensity sprints and corresponding recovery periods. The work to rest ratio was matched for both groups at 1:5 and the total session time was ~120 minutes including a self-selected 15 minute warm up and cool down period. Cyclists in the short training group completed 25 sets of sprints lasting 5, 10 and 20 seconds (each set) completed in sequence for a total work period of 14.6 minutes and corresponding recovery period of 73 minutes. Cyclists in the long training group completed 10 sets of sprints lasting 15, 30 and 45 seconds for a total work period of 15 minutes and corresponding recovery period of 75 minutes. Cyclists in both groups were asked to complete each effort at the highest possible intensity and in the recovery periods, maintain a work rate of ~30-40% PPO. All training sessions were controlled using pre-recorded audio signals which indicated the exercise and recovery periods. Cyclists completed the first, fourth and seventh training session under the supervision of one of the researchers using the laboratory ergometer previously described. The remaining sessions were performed by the cyclists on their own bicycle either on the road or using a stationary ergometer. In the recovery period post the training intervention cyclists were able to resume light recovery intensity training (<120 mins) but were required to refrain from engaging in high intensity exercise or competitions in the 7 days immediately post HIT. The control group continued with their own personal training programmes for a minimum of 10 hours per week to ensure that total training volume was similar to that of the experimental groups.

6.2.6 Statistical Analysis

Simple descriptive statistics are shown as means ± between-subject standard deviations. Mean effects of training and their 90% confidence limits were estimated with a made for purpose spreadsheet[18] via the unequal-variances t statistic computed for change scores between the mean of the two pre-tests and each post-test in the two training groups and between the single pre and post-test in the control group. Each subject's change score between trials was expressed as a percent of baseline score via analysis of log-transformed values. Data were log-transformed in order to reduce bias arising from any non-uniformity of error in the data. The spreadsheet also computes chances that the true effects are substantial, when a value for the smallest worthwhile change is entered. We used a value of 1% for the performance power measures, as previous research has shown that this value represents the smallest worthwhile enhancement in power for cyclists competing in time-trial events.[19] To date no research has established how percentage changes in physiological measures would translate directly to percent changes in cycling performance, therefore we interpreted changes in our physiological measures using standardised effects (change in mean divided by the between subject standard deviation). The magnitudes of the standardised effects for physiological measures only were interpreted and reported using the established effect thresholds of: 0.2, 0.5, and 0.8 for small, moderate, and large effects respectively in accordance with the recommendations of Cohen [20]. Effect size values <0.2 were deemed trivial differences and considered to be not worthwhile.

6.3 RESULTS

Both HIT groups successfully completed 100% of the prescribed training regime over the allotted 7-day period. Table 6-1 shows the mean ± SD results for the performance and physiological measures for each of the groups at baseline (Pre) and following (Post) the training period. The control group experienced trivial to small (ES= 0.15-0.23) decreases in performance variables during the monitoring period whilst both training intervention groups reported moderate (ES=0.51-0.76) enhancements in performance following the HIT interventions. Further, both HIT groups reported small (ES=0.24-0.47) increases in $\dot{V}O_{2max}$ and power output at OBLA and moderate to large (ES=0.64- 1.02) improvements in aerobic economy and gross efficiency, whilst the experimental controls experienced trivial to small (ES= 0.05-0.34) decrements in most physiological measures (in line with the performance decrease) with the exception of aerobic economy and efficiency.

Table 6-1 The mean (± SD) for all measured variables and the % change between Pre and Post testing for each experimental group, and the effect size for the observed % change.

	Control pre	Control post	Change (%) (ES)	Short pre	Short post	Change (%) (ES)	Long pre	Long post	Change (%) (ES)
TTPO (W)	286 ± 38	277 ± 39	-3.3 ± 4.2 (-0.23)	279 ± 24	291 ± 19	4.6 ± 4.4 (0.51)	277 ± 26	296 ± 25	6.8 ± 5.8 (0.63)
TT time (s)	2290 ± 205	2338 ± 213	1.8 ± 2.2 (0.18)	2299 ± 104	2232 ± 84	-2.9 ± 2.6 (-0.59)	2320 ± 135	2216 ± 103	-4.4 ± 3.7 (-0.74)
PPO (W)	345 ± 36	339 ± 37	-1.7 ± 3.3 (-0.15)	341 ± 21	353 ± 19	3.6 ± 3.0 (0.57)	337 ± 27	362 ± 28	7.6 ± 2.3 (0.76)
$\dot{V}O_{2max}$ ($L{\cdot}min^{-1}$)	4.6 ± 0.5	4.6 ± 0.5	-0.6 ± 6.3 (-0.05)	4.6 ± 0.3	4.7 ± 0.4	2.3 ± 4.8 (0.27)	4.7 ± 0.4	4.9 ± 0.5	3.5 ± 6.2 (0.34)
OBLA (W)	292 ± 34	282 ± 37	-3.6 ± 6.4 (-0.27)	266 ± 21	276 ± 28	3.6 ± 3.5 (0.47)	298 ± 34	306 ± 34	2.9 ± 5.3 (0.24)
ECO ($W{\cdot}L^{-1}$)	72.5 ± 4.0	74.1 ± 4.3	2.2 ± 4.3 (0.34)	71.3 ± 4.5	74.0 ± 3.6	3.9 ± 2.8 (0.64)	71.9 ± 3.3	75.3 ± 3.9	4.6 ± 3.5 (0.84)
GE (%)	21.1 ± 1.2	21.4 ± 1.3	1.5 ± 4.3 (0.22)	20.7 ± 1.2	21.3 ± 1.0	3.2 ± 2.4 (0.53)	20.8 ± 0.9	21.8 ± 1.1	5.1 ± 3.9 (1.02)

(ES) = effect size; TTPO = Time-trial mean power output; TT time = performance time; PPO = peak power output; VO_{2max} = maximal oxygen uptake; OBLA = onset blood lactate accumulation; ECO = exercise economy; GE = gross efficiency.

Table 6-2 shows the relative change score (as a percentage) for all measured variables between the three groups. There were moderate to large (ES =0.57-0.89) gains in performance measures for both training groups relative to the control condition; however the magnitude of changes in performance measures between the two training conditions were all considered small (ES <0.50). Differences in the change scores for $\dot{V}O_{2max}$, power at the lactate threshold and aerobic economy between the two training groups were trivial, whilst the long HIT group experienced a small (ES = 0.34) increase in gross efficiency relative to the short HIT group.

Table 6-2 Comparison of changes in performance and physiological measures between all experimental groups.

	Long - Control % difference ± 90% CL[†] (ES)	Short –Control % difference ± 90% CL (ES)	Short – Long % difference ± 90% CL (ES)
TTPO (W)	10.4 ± 4.3 (0.82)	8.2 ± 3.8 (0.67)	-2.1 ± 3.9 (-0.22)
TT time(s)	-6.1 ± 2.2 (-0.80)	-4.6 ± 1.9 (-0.62)	1.6 ± 2.6 (0.28)
PPO (W)	9.5 ± 2.5 (0.89)	5.5 ± 2.7 (0.57)	-3.7 ± 2.1 (-0.48)
$\dot{V}O_{2max}$ (L·min^{-1})	4.2 ± 5.1 (0.37)	2.9 ± 4.6 (0.27)	-1.2 ± 4.2 (-0.15)
OBLA (W)	6.8 ± 4.9 (0.53)	7.5 ± 4.5 (0.60)	0.7 ± 3.5 (0.05)
ECO (W·L^{-1})	2.3 ± 3.2 (0.43)	1.7 ± 3.0 (0.26)	-0.6 ± 2.4 (-0.11)
GE (%)	3.6 ± 3.3 (0.65)	1.7 ± 2.9 (0.26)	-1.9 ± 2.5 (-0.34)

[†] ± 90% confidence limits: add or subtract this number to the mean effect to obtain the 90% confidence limits for the true difference. (ES) = effect size; TTPO = Time-trial mean power output; TT time =

Figure 6-3 shows the mean (±90% confidence limits) percentage changes in performance and physiological measures at both one week and two weeks post training. Whilst both experimental training groups experienced substantial gains in performance at the final post training (14 days) tests relative to the control group, Figure 6-3 shows the short HIT group experienced a delayed improvement in their time trial performance in the first post training test (7 days) in comparison to the long HIT group.

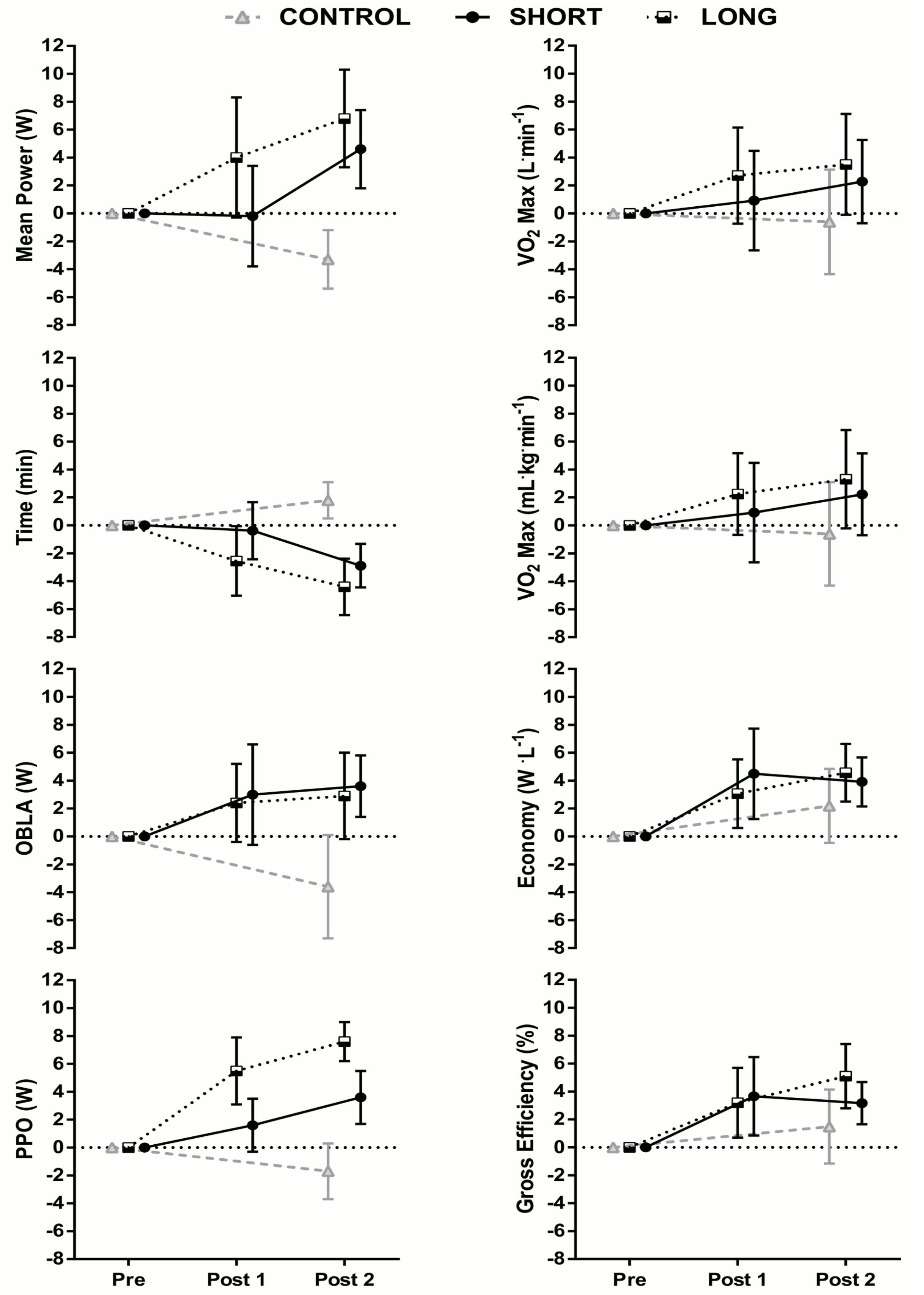


Figure 6-3 Mean (±90% CL) percentage change in performance and physiological measures from baseline (pre) at 7 days (post 1) and 14 days (post 2) the HIT training period.

6.4 DISCUSSION

The aim of the present study was to examine the effects of 7-days of two pre-competition HIT regimes on the physiological and performance characteristics of competitive cyclists. Results from this study show that multiple sets of maximal short or long-duration efforts completed on consecutive days leads to substantial improvement in 20-km time trial performance in competitive cyclists. In addition both HIT regimes examined lead to enhancements in the key physiological determinates commonly associated with endurance performance.

Several previous authors have reported substantial performance gains following HIT in trained cyclists. [3-6,21-24]. In these studies HIT was associated with improvements in the main physiological variables associated with endurance performance, namely $\dot{V}O_{2max}$[4,6,22,24,25] anaerobic threshold power[6,22] aerobic economy [7] and gross efficiency.[26]. However in all of these previous investigations, HIT was implemented over several weeks to months and typically in regimes that included just 2-3 interval training sessions per week. In comparison, cyclists in the current study experienced similar gains to those in previous studies after completing only seven consecutive days of HIT sessions. The findings in the current study therefore add empirical support to our observations that competitive athletes commonly use short blocks of intensified training to improve form prior to major competitions.

Similar rapid and substantial gains in performance and physiology have previously been reported with alpine skiers who performed 15 session of HIT over 11-days.[27] However a major difference between the current study and that of Breil et al. [27] is the latter study was completed with non-endurance trained individuals (alpine skiers) and in the athletes off season where there is much greater range for improvement due to their lower level of fitness. We also believe further evidence for the efficacy of short blocks of HIT comes from a more recent study by Ronnestad et al. [10]. While this previous study actually reported changes over a longer training period than the current study, they did include an initial 5-day intensified training block at the beginning of their 4-week training period. While it lacks specific performance testing following the initial HIT block, training data presented in these authors paper appears to indicate significant increases in training power output in the three weeks following the initial 5-days of training. We would therefore expect these increases in training power to also manifest as improvements in performance tests.

Whilst both the short and long HIT programmes in the current study led to substantial performance enhancements relative to the control group, the magnitude of change in performance measures between the two HIT programmes 2-wks post training were assessed as qualitatively small (ES~0.2). Similarly differences in changes in physiological measures between the two HIT regimes were assessed as being trivial (ES <0.2) with the exception of gross efficiency (ES =0.34) which tended to a larger improvements in the long HIT group. Whilst the magnitude of performance difference between the two HIT strategies was small, this difference may be substantial enough to provide a worthwhile advantage during a real competition.[19] However while we tentatively suggest that there is a potentially greater improvements in the group performing the longer form of HIT, a study with a much larger sample size and clearer confidence limits would be required to verify this suggestion.

Further support for our opinion of the superiority of the long HIT form as the preferred training regime also comes from the differences in the rate of post training recovery in performance between the two HIT regimes. During the first post-training testing subjects in the short HIT showed no improvement in time trial performance relative to their pre-training test

(Fig. 7-3) despite small improvements in performance measures during the short duration incremental test. We interpret this finding to indicate that the short HIT group had residual fatigue and insufficient recovery to gain any benefits from the training regime at this stage. Indeed, previous research examining the effects of short term overreaching has reported similar performance decrements in cyclists one week post a HIT intervention.[13,14] A possible explanation for the performance difference between the two groups at this stage could relate to differences in the intensity of efforts in the training sessions. Whilst both groups were matched closely for total duration (volume) of both exercise and recovery, it is possible that the overall intensity of shorter sprints was somewhat higher than the longer efforts and therefore the short HIT is likely to have experienced greater cumulative fatigue. Indeed case study evaluations (unpublished observations) after the main study indicate that mean power in the short intervals was ~10% higher than in the long intervals for the same total duration of effort. However we cannot exclude the possibility that the delayed improvement in the short HIT group is simply due to individual differences in the groups and sampling variation.

The contributions of physiological mediators underpinning the enhancement in time trial performance in both the HIT groups are unclear. While both HIT forms enhanced all measured physiological characteristics, the range of individual responses makes a precise determination of the contribution from any single mechanism difficult. Nevertheless a cursory analysis of the improvements in the groups suggests improvements in the long HIT group are more likely associated with increases in aerobic economy (4.6%) and gross efficiency (5.1%) while improvement for the short HIT group appear associated with an increase in lactate threshold (OBLA) power (3.6%). Further it is possible other un-measured mechanism variable contributed to the performance enhancements. Indeed given the HIT interventions in the current study involved repeated maximal sprints, an increase in anaerobic and muscle buffering capacity could be expected as has been reported in previous studies examining the effects of HIT on time trial performance.[6,24]. However further investigations with a larger sample size, and additional measures related to biochemical adaptations[28] and mitochondrial biogenesis[29] would be necessary to further elucidate the potential mechanisms responsible for any performance enhancements.

6.5 PRACTICAL APPLICATIONS

- Short blocks of intensified training can be used to evoke substantial physiological adaptation and performance improvement in cyclists preparing for competition.
- Sport scientists, coaches and cyclists should ensure there is adequate time for recovery prior to competition if using the short duration sprints. If sufficient recovery time is not available (minimum 2 weeks), only longer duration sprint intervals should be used to ensure performance is not compromised by ongoing fatigue.
- Coaches, cyclists and sport scientists should use care when prescribing short blocks of intensified training paying particular attention to signs and symptoms of ongoing fatigue and potential non-functional overreaching.

6.6 CONCLUSION:

In conclusion one week of self-paced high-intensity overload training performed as multiple sets of short (5-20s) or long (15-45s) duration efforts led to substantial improvements in time-trial performance with competitive cyclist. The increases in performance were associated with enhancements in the three main mediators of endurance performance, $\dot{V}O_{2max}$, power output at the lactate threshold, and economy. While both long and short HIT sessions led to substantial increases in performance compared to the control group, the differences between the two training groups were generally small. However, although both the short and long interval programmes were closely matched for total exercise and recovery duration it appears the shorter intervals led to greater short-term decrements in performance and required a longer post-training recovery period in order for any benefits to be realised. In light of the current findings we would advise athletes planning to undertake block periods of intensified training, prior to competition, to opt for a combination of longer intervals or allow more recovery prior to the competition if using shorter more intense intervals during their block training period. The findings of this study are limited to the training of competitive cyclists, but may be applicable to similar non-weight bearing aerobic sports (e.g. swimming and rowing). However caution is advised if trying to apply such an intense training routine to other sports, such as running, as the increased impact may lead to a greater injury potential. Future studies are warranted to examine more closely the physiological mechanisms that lead to improvements in performance following intensified training and also to establish the time course over which any performance benefits are lost.

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CHAPTER 7.
GENERAL DISCUSSION

7.1 DISCUSSION & MAJOR FINDINGS

The purpose of this body of research was to determine the reliability of a variable gradient performance test, describe the physiological correlates of variable gradient cycling performance and the pacing pattern during variable gradient cycling, and determine the effects of a short intensified block of training on physiological adaptation and variable gradient cycling performance. The results show that cycling performance can be reliably measured using a computer simulation of a 20-km variable gradient course. Performance from the variable gradient cycling test was strongly correlated to PPO, $\dot{V}O_{2max}$, OBLA and VT; however the strength of correlations increased when the same variables were expressed relative to body mass. To complete the 20-km variable gradient test, cyclists distribute exercise intensity in a variable-parabolic pattern so that, in addition to a fast start and end-spurt, exercise intensity fluctuates throughout the test in response to changes in gradient. Variable gradient cycling performance improved substantially following a brief block of intensified training. The improvement in performance was associated with positive adaptation in several physiological variables; however the precise physiological adaptation underpinning performance enhancements remains unclear.

The first study in this series evaluated the reliability of a computer-simulated, 20-km variable gradient cycling time-trial. The unique aspect of this study was the inclusion of frequent gradient variation throughout the 20-km trial so that cyclists encountered segments of positive and negative gradients. When trials were separated by less than 14 days, completion time and mean power output were highly reliable measures of cycling performance. Additionally, when separated based on ability, fastest cyclists were more reliable than the slowest cyclists, particularly in the short term. However, reliability for all cyclists declined when more than 14 days elapsed between trials and was similar for both groups after 28 days. A similar decline in reliability with increasing time between trials has been reported previously.[1] Importantly, the results indicate the need for habituation prior to commencing experimental trials, and again when time between experimental trials is greater than 14 days. Nevertheless, results also indicate the inclusion of gradient variation in a cycling performance trial does not negatively impact on the ability to detect small, yet meaningful changes in performance.

Study two examined the physiological correlates of variable gradient cycling performance. The physiological correlates of other forms of cycling, namely constant gradient self-paced time-trials,[2-5] and flat researcher paced stochastic time-trials[6] have been well described by previous research. However, in all instances, the performance test used in those studies was somewhat unlike field cycling which takes place on public roadways where gradient frequently changes. Importantly, the current study indicated variable gradient cycling performance is strongly correlated with PPO, $\dot{V}O_{2max}$, OBLA, VT and GE. However, the strength of those correlations increased when the physiological variables were expressed relative to body mass. Even though the test course included numerous downhill sections where a greater body mass is beneficial to performance, the results indicate cyclists need to maximise their power output and oxygen uptake relative to body mass to optimise variable gradient cycling performance. Additionally, differences between the strength of correlations observed in the current study and those reported in previous investigations suggests comparison between such tests and physiological variables underestimates the importance of some variables for field cycling.

The third study in the overall body of work explored the spontaneous pattern of exercise intensity during a variable gradient cycling test. Despite the inclusion of large and frequent variations in gradient, a fast start and end-spurt, characteristics of a parabolic distribution of work, were observed during the variable gradient cycling test. Previous studies also report a parabolic distribution of exercise intensity during constant gradient cycling performance over medium to long distances.[7-9] However, in the current study large variations in power output were evident between consecutive segments throughout the trial in response to changes in gradient between segments. Interestingly, the pacing pattern observed in the current study presents as a mixture of the parabolic and variable patterns described previously.[10] The pattern of power output distribution observed in competitive cyclists during the cycling time-trial suggest distance and gradient interact to determine the pacing response during variable gradient cycling. Importantly, when viewed in combination with results of study two, it is evident variable gradient cycling has distinctly different performance characteristics and physiological determinants when compared to self-paced and experimenter paced constant grade cycling. Therefore, one of the primary overall recommendations from this dissertation, is cycling tests should include some form of variation in external environmental resistance to adequately mimic field cycling performance and improve the ecological validity of performance testing

The final and major study of this thesis assessed the efficacy of a short block of intensified training to induce physiological adaptation and improve cycling performance. Previous investigations reported performance improvement and beneficial physiological adaptation when HIT is integrated into periodised programs for 4-6 weeks.[11-13] More recently, others have reported large improvements in performance when HIT is implemented in a highly concentrated block and followed by three weeks of LSD training.[14,15] In the current study, participants completed seven consecutive days of highly concentrated short or long sprint HIT.

Following one week of recovery, there were large improvements in cycling performance and physiological variables in the long HIT group. At the same time point, cycling performance for the short sprint group was slightly worse than pre-training, which suggests a lingering fatigue effect despite a week of recovery. However, after an additional week of recovery, there were substantial improvements in performance for cyclists in both groups when compared to pre-training measures and a control group. The improvements in performance were accompanied by enhancement in aerobic physiological variables, particularly GE and OBLA. Importantly, results indicate short blocks (one week) of intensified HIT can induce large beneficial gains in performance and physiology to a similar magnitude of that reported for 6-8 week training interventions. However, in light of the ongoing performance decrement for the short training group, cyclists should select the long sprint form of the training intervention or allow a greater recovery period before competition if using the shorter form of training.

7.2 PRACTICAL APPLICATIONS

The major findings discussed above have the following practical applications for cyclists, coaches and sport scientists in preparation for competition:

- A novel, computer-simulated variable gradient cycling time-trial can be used to detect small, yet worthwhile changes in cycling performance.
- Coaches, cyclists and sport scientists should include additional habituation trials when the time between experimental trials exceeds 14 days. However, if time or other circumstances do not permit, faster more experienced cyclists can commence experimental trials without habituation.

- These data highlight the physiological variables that underpin hilly cycling performance and indicates cyclists targeting hilly events need to produce high power relative to body mass and have a high relative $\dot{V}O_{2max}$.
- Coaches and sports scientists should consider ways to optimise body mass when preparing cyclists for hilly competitive events.
- When assessing performance and physiology sport scientists should evaluate and report results as absolute and relative values to better predict performance potential in hilly events.
- 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 hilly.
- Ventilatory threshold and OBLA expressed as a percentage of PPO (fractional utilisation) were poorly correlated with performance and were 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 hilly events.
- The variable-parabolic pacing pattern observed in the current study indicates performance testing of cyclists should include some variation in environmental resistance to remain specific to competitive events.
- Although power output varied in response to changes in gradient, a parabolic pacing pattern was still evident which suggests energy distribution during endurance cycling events is dominated by an anticipatory control system.

- Sport scientists and coaches can use the results of study three to inform pacing strategy selection and target possible coaching interventions to improve the pacing response to hilly cycling.
- Heart rate is not sensitive enough to describe the frequent changes in power output during variable gradient cycling and may therefore under or overestimate exercise intensity and training load.
- Short blocks of intensified training can be used to evoke substantial physiological adaptation and performance improvement in cyclists preparing for competition.
- Sport scientists, coaches and cyclists should ensure there is adequate time for recovery prior to competition if using the short duration sprints. If sufficient recovery time is not available (minimum 2 weeks), only longer duration sprint intervals should be used to ensure performance is not compromised by ongoing fatigue.
- Coaches, cyclists and sport scientists should use care when prescribing short blocks of intensified training paying particular attention to signs and symptoms of ongoing fatigue and potential non-functional overreaching.

7.3 FUTURE DIRECTIONS

The results from this series of studies discussed, above present a number of opportunities to integrate the concepts and findings described into future projects regarding testing and training of competitive cyclists. While the first study described the reliability of a computer-simulated, variable gradient performance test, only one specific course profile was tested. Road cycling is a sport that takes place on public roadways and as such, competitive cyclists encounter a variety of courses throughout a racing season. Therefore, future studies could establish the reliability of other variable gradient course profiles to determine the broader effect of gradient variation on the reliability of cycling time-trial performance tests. The first study also reported decay in the reliability of the variable gradient test with increasing time between trials. Maintenance of test reliability is imperative during experimental trials when it is important to be able to detect small but worthwhile differences in performance. However, the precise cause of the decline in reliability observed here and in previous investigations[1] remains largely unknown. Therefore, future studies could determine the contribution of changes in fitness, learning or de-learning to change in test reliability. Additionally, other studies could determine how frequently cyclists need to complete a performance test to mitigate possible fitness and learning effects and subsequently maintain reliability.

Recently, the concepts of critical power[16-18] and functional threshold power[19] have become popular to determine training zones and describe the load of specific training sessions. The protocols for establishing CP and FTP call for a consistent effort of 3-20 minutes.[18,19] However, the results reported in studies two and three indicate the physiological determinants and pacing response are different for variable gradient cycling time-trials compared to constant gradient time-trials. Additionally, others have reported differences in the physiological response to constant and variable exercise intensities.[20] Importantly, results suggest the need for variation in external environmental resistance during cycling performance tests. Therefore, future studies could investigate the efficacy of CP and FTP derived from a variable gradient or variable resistance performance test.

The pacing pattern observed during variable gradient cycling also presents a number of questions for future research. Importantly, future studies should investigate the effect of pacing coaching to ease the fast start to determine the effect on ensuing pacing response and subsequently overall performance. Additionally, the physiological and perceptual responses to exercise were not measured in the current project. Therefore, future studies could include such measures to further describe the characteristics of variable gradient cycling. Other limitations related to the technical specifications of the cycling ergometer used in the study also present research opportunities. Specifically, studies should investigate the effects of matching external cooling to cycling speed and reducing or removing the power output required to propel the cyclist during downhill segments on the pacing response during variable gradient cycling.

While the results of study four highlighted the performance benefits of short term, highly concentrated, intensified training, as the first investigation of such training it also presents a number of areas for further investigation. In particular, the differences in the fatigue response between the two training groups and the rate at which physiological and performance improvements decay following intensified training warrant further investigation. Additionally, future research could use targeted, more invasive, testing of the skeletal muscle of the lower limb to elucidate the precise mechanisms associated with the gross physiological adaptation observed in the current study. Lastly, investigations of similar, yet slightly longer, training interventions have reported perturbations in the immunological and psychological response to intensified training.[21] Therefore, future research should determine the effects of shorter periods of intensified training, similar to the intervention used in the current study, on markers of immune function and well-being. Ultimately, such analysis will help determine when and how often short blocks of intensified training should be implemented throughout a competitive season to optimise performance while reducing the risk of inducing non-functional overreaching.

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APPENDICES

APPENDIX A. ETHICS APPROVAL STUDIES 1-4

Approval

Human Research Ethics Committee

University of Ballarat
Learn to succeed

Principal Researcher:	Brendan O'Brien
Other/Student Researcher/s:	Bradley Clark
School/Section:	Health Sciences
Project Number:	A11-111
Project Title:	New testing and training methodologies for road cycling
For the period:	9/1/2012 to 28/6/2014

Please quote the Project No. in all correspondence regarding this application.

REPORTS TO HREC:

An annual report for this project must be submitted to the Ethics Officer on:

9 January 2013

9 January 2014

http://guerin.ballarat.edu.au/ard/ubresearch/hdrs/ethics/humanethics/docs/annual_report.doc

A final report for this project must be submitted to the Ethics Officer on:

28 July 2014

http://guerin.ballarat.edu.au/ard/ubresearch/hdrs/ethics/humanethics/docs/final_report.doc

Ethics Officer

9 January 2012

Please see attached ‘Conditions of Approval’.

CONDITIONS OF APPROVAL

1. The project must be conducted in accordance with the approved application, including any conditions and amendments that have been approved. You must comply with all of the conditions imposed by the HREC, and any subsequent conditions that the HREC may require.

2. You must report immediately anything which might affect ethical acceptance of your project, including:

   - Adverse effects on participants;
   - Significant unforeseen events;
   - Other matters that might affect continued ethical acceptability of the project.

3. Where approval has been given subject to the submission of copies of documents such as letters of support or approvals from third parties, these must be provided to the Ethics Office before the research may commence at each relevant location.

4. Proposed changes or amendments to the research must be applied for, using a ‘Request for Amendments’ form, and approved by the HREC before these may be implemented.

5. If an extension is required beyond the approved end date of the project, a ‘Request for Extension’ should be submitted, allowing sufficient time for its consideration by the committee. Extensions cannot be granted retrospectively.

6. If changes are to be made to the project’s personnel, a ‘Changes to Personnel’ form should be submitted for approval.

7. An ‘Annual Report’ must be provided by the due date specified each year for the project to have continuing approval.

8. A ‘Final Report’ must be provided at the conclusion of the project.

9. If, for any reason, the project does not proceed or is discontinued, you must advise the committee in writing, using a ‘Final Report’ form.

10. You must advise the HREC immediately, in writing, if any complaint is made about the conduct of the project.

11. You must notify the Ethics Office of any changes in contact details including address, phone number and email address.

12. The HREC may conduct random audits and / or require additional reports concerning the research project.

Failure to comply with the *National Statement on Ethical Conduct in Human Research* (2007) and with the conditions of approval will result in suspension or withdrawal of approval.

Final Project Report

Human Research Ethics Committee

1) Project Details:

Project No:	A11-111
Project Name:	New testing and training methodologies for road cycling

2) Principal Researcher Details:

Full Name:	Brendan O'Brien
School/Section:	School of Health Sciences
Phone:	5327 9677
Fax:	N/A
Email:	b.obrien@federation.edu.au

3) Project Status:

Please indicate the current status of the project:	
☒ Data collection complete **Completion date: 28/05/2014**	☐ Abandoned **Please give reason:**

4) Special Conditions:

If this project was approved subject to conditions, were these met?		
☒ N/A	☐ Yes	☐ No * **NB: If 'no', please provide an explanation:**

5) Changes to project:

Were any amendments made to the originally approved project?	
☐ No	

	☒ Yes *** NB: Please provide details:** An application to amend the approval for this project to include an additional investigation of the changes to blood and immunology parameters was approved by the ethics officer on the 17th December 2013. However due to difficulties arising in the collection method of some measures and subsequent time restraints of the student research, this aspect of the project wasn't completed.

6) Storage of Data:

Please indicate where the data collected during the course of this project is stored:
Hard copies of collected data (data collection sheets, training questionnaires etc.) are being stored in a secure filing cabinet in the office of the principal researcher. Electronic data are being stored on a password secured computer owned by the student researcher in a password protected folder.

7) Research Participants:

Were there any events that had an adverse effect on the research participants?	
☒ No	☐ Yes *** NB: Please provide details:**

8) Summary of Results:

8.1. Please provide a short summary of the results of the project (no attachments please):
Power output and performance time measured during a computer simulated 20-km variable gradient cycling test were reliable, however reliability diminished with increasing time between trials. Performance in variable gradient time-trial correlated strongly with absolute measures of physiological variables; however the strength of correlations increased when variables were measured relative to body mass. There were large differences in power output and cadence between consecutive 1-km segments during a variable gradient time-trial due to an interaction effect between elapsed distance and road gradient. Performance in the variable gradient time-trial improved substantially following a brief period of overload training. Performance improvement corresponded with adaptation in important physiological determinants of cycling performance.

8.2. Were the aims of the project (as stated in the application for approval) achieved? Please provide details.
The majority of the principle aims of the research project were achieved via four separate investigations. The first investigation established the reliability of a novel cycling time-trial performance test which was subsequently used in studies 2,3 and 4 to determine the physiological correlates of performance, describe the pacing response to variable gradient cycling and determine the effects of a brief period of high volume, high intensity training on performance. The aim of determining the effects of more frequent training during a short block of high volume, high intensity training was not achieved due to a delay in data collection as a result of equipment

malfunction and slower than anticipated participant recruitment through the initial phases of data collection.

9) Feedback:

The HREC welcomes any feedback on:

- **difficulties experienced with carrying out the research project; or**
- **appropriate suggestions which might lead to improvements in ethical clearance and monitoring of research.**

10) Signature/s:

Principal Researcher:	…………………………….. Print name:	**Date:**	
Other/Student Researchers:	.Brad Clark….. Print name: Brad Clark	**Date:**	18/08/2014
	……………………………. Print name:	**Date:**	

Please return to the Ethics Officer, Mt. Helen campus, as soon as possible.