The role of pacing in sub-maximal and maximal intensity exercise: impacts of environmental and protocol manipulations.

by

Patrick James Lander

A thesis submitted in partial fulfilment of the
requirements of Leeds Metropolitan University
for the degree of Doctor of Philosophy.

Carnegie Faculty
Leeds Metropolitan University

June 2011

Abstract

The purpose of this thesis was to investigate the role of pacing in the development of fatigue through four studies which examined the impact of environmental and protocol manipulations, and evaluated the role of an ability to fluctuate pace during exercise at sub-maximal and maximal intensities. The role of self-pacing in exercise protocols represents a distinct contrast to the use of enforced-pace exercise common in many conventional scientific protocols, and thus required the development of novel methodologies, relevant to current sporting practices, which were shown to demonstrate validity and reliability using a range of contemporary measures.

Chapters 1-3 of this thesis provided a rationale for the studies, a review of relevant literature, and an overview of the scientific methodologies common to the studies.

The study in Chapter 4 reported the findings of an investigation comparing 1) self-paced and 2) enforced-pace exercise at matched intensities. This study demonstrated that self-paced exercise poses a reduced metabolic challenge when compared to matched-intensity enforced-pace exercise. The study findings suggest that the ability to voluntarily fluctuate power output in accordance with transient sensations of fatigue may represent an important physiological mechanism used during self-paced exercise to defend homeostasis.

The study in Chapter 5 reported the test-retest reliability of a self-paced perceptually regulated time-trial by comparing power output responses within- and between-groups of aerobically-matched participants. Using a range of reliability measures this study showed that all participants were able to reliably reproduce the same power output over 5000m at a fixed rate of perceived exertion (RPE 15) providing evidence of the reliability of a sub-maximal time-trial protocol based on a fixed RPE score both within-groups and between independently sampled groups.

Chapter 6 reported a study which investigated the effects of intervals of radiant warming and thermoneutral conditions on pacing during a sub-maximal perceptually regulated exercise test. Participants completed 5000m rowing trials in 1) warmed, 2) non-warmed, or 3) interval-warmed conditions. Dynamic analysis of results showed a significant reduction in power during the first warming bout in the interval warmed condition, which was unobserved in the second period of warming. The ability to complete each exercise bout with similar average power and performance time, despite significant changes to pacing within the trial demonstrated evidence of a multi-level pacing plan with the capacity to alter effort during a bout in response to thermal challenges, but without impact to overall performance within a trial.

The final study in Chapter 7 reported the design of a novel perceptually regulated test of maximal aerobic power. The study compared physiological and performance responses to repeated 1) self-paced perceptually regulated maximal exercise tests and 2) conventional incremental maximal exercise tests. Similar peak power outputs and $\dot{V}O_{2peak}$ were observed in the self-paced and conventional, enforced pace exercise tests ($p>0.05$). The findings of this study validated a reliable self-paced maximal exercise test ($\dot{V}O_{2peak}$ CV<1%; icc 0.999) that presents a protocol which can be applied across multiple modalities, furthermore the dynamic analysis of the performance responses in this novel protocol provided evidence of energy-sparing pacing behaviours unobservable using conventional measures.

This thesis has shown the importance of self-pacing in exercise through outcomes which cannot be demonstrated when the pace of an exercise bout is externally enforced. The imposition of an enforced pace results in an increased physiological demand in response to a mode of performance that is unrelated to current sporting practices. The positive impact of self-pacing on performance and physiological variables demonstrated in this thesis suggests that the ability to vary pace, under the influence of a model of complex metabolic control, is fundamental to optimal performance, and the incorporation of self-paced protocols in exercise testing is vital to the continued development of models of fatigue.

Candidates Declaration

I confirm that the thesis is my own work; and that all published or other sources of material consulted have been acknowledged in notes to the text or the bibliography. I confirm that the thesis has not been submitted for a comparable academic award.

Patrick James Lander

Acknowledgements

I would like to take this opportunity to thank all those who contributed to the completion of this thesis.

To the participants;	without whose time and effort this research would not have been possible.
To my supervisors;	Dr Andrew Edwards, Dr Ron Butterly, and Dr Lee Ingle who have guided me and my work towards the fulfilment of this thesis.
To my employers;	The Universal College Of Learning in New Zealand who provided funding for facilities, resources and the time of laboratory assistant Rakai Timutimu.

And finally

To my family and friends;	whose patience and support have known no limits throughout this thesis, in particular; to my Father; six sevens are forty two and to Renata; thank you for all you do for me.

Contents Page

The following table provides a list of the contents of this thesis.

List of Figures

The following table provides a list of the figures used within this thesis.

List of Tables

The following table provides a list of the tables used within this thesis.

List of Appendices

The following table provides a list of the documents appended to this thesis.

List of Abbreviations

The following table provides a list of the common abbreviations used within this thesis.

Abbreviation	Description	Unit of measurement
$\dot{V}O_{2peak}$	Volume of oxygen taken up per minute at peak exertion	$L \cdot min^{-1}$ or $ml \cdot kg^{-1} \cdot min^{-1}$
$\dot{V}O_{2max}$	Volume of oxygen taken up per minute at maximum exertion	$L \cdot min^{-1}$ or $ml \cdot kg^{-1} \cdot min^{-1}$
$\dot{V}O_2$	Volume of oxygen taken up per minute	$L \cdot min^{-1}$ or $ml \cdot kg^{-1} \cdot min^{-1}$
PO	Power Output	W
HR	Heart Rate	$b \cdot min^{-1}$
BLa	Blood Lactate	$mmol \cdot L^{-1}$
RPE	Rate of Perceived Exertion	
ttv	Time trial variability	
T_c	Core temperature	˚C
T_{sk}	Skin temperature	˚C
T_{oes}	Oesophageal temperature	˚C
sEMG	Surface electromyography	mV
MVC	Maximum Voluntary Contraction	%
DF	Drag Factor	$N \cdot m \cdot s^{-1}$
CGM	Central Governor Model	
CNS	Central Nervous System	
rms	Root mean square	mV
icc	Intra-class correlation coefficient	
LoA	Limits of Agreement	
CI	Confidence Intervals	
CV	Coefficient of Variation	%
r	Pearson product moment correlation	
p	Probability	
O_2	Oxygen	
CO_2	Carbon dioxide	
N_2	Nitrogen	
ATP	Adenosine Tri-Phosphate	

s	Seconds	seconds
min	Minutes	minutes
hr	Hours	hours
m	Metres	metres
ml	Millilitres	
W	Watts	
˚C	Temperature in celsius	
mV	Millivolts	
$L \cdot min^{-1}$	Litres per kilogram per minute	
$ml \cdot kg^{-1} \cdot min^{-1}$	Millilitres per kilogram per minute	
$mmol \cdot L^{-1}$	Millimole per litre	
$N \cdot m \cdot s^{-1}$	Newton metres per second	
SEM	Standard Error of Measurement	
SD	Standard Deviation	
ACSM	American College of Sports Medicine	
BASES	British Association of Sport and Exercise Sciences	
≈	Approximately	
$p<0.05$	Statistical probability of an outcome	
$> \geq$	Greater than, Greater than or equal to	
$< \leq$	Less than, Less than or equal to	

Maximal: Pertaining to the highest possible level.

Fatigue: The inability to maintain an expected power output.

Self-paced exercise: Exercise in which the participant has the ability to alter intensity in response to their perception of effort.

Enforced-pace exercise: Exercise in which the participant must maintain a fixed intensity regardless of the perception of effort.

Complex metabolic control: A model of fatigue which incorporates feedback from metabolic systems in order to avoid the catastrophic failure of any one physiological system.

Chapter One

General Introduction

Chapter One

1.1 General Introduction

The aim of this thesis is to examine the relative impacts of self-paced and enforced-paced exercise on the signs/sensations of fatigue. Furthermore, it will investigate whether or not the facilitation of self-pacing may alleviate such sensations, thereby providing evidence of an influential central mechanism over performance.

Until comparatively recently the study of pacing in exercise had been the subject of relatively few research articles (Foster et al., 1994, Foster et al., 1993), and the majority of exercise measures were conducted using enforced pacing strategies (Brooks et al., 1996b, Jeukendrup et al., 1996), in which participants performance was measured by their ability to maintain a power output equivalent to their maximal effort until exhaustion. The ability to maintain a maximal effort was traditionally viewed as a peripherally limited factor (Kirkendall, 1990), but models of centrally limiting control have also been proposed (Newsholme et al., 1987). The developmental nature of science often requires a modern re-evaluation of techniques, and thus this thesis will investigate the role of pacing and fatigue from a contemporary perspective in order to further the understanding of this previously overlooked area of exercise physiology.

Fatigue has notably been defined as the inability to maintain an expected power output (Hultman and Sjoholm, 1986, Kirkendall, 1990). Pacing within an exercise bout could thus be suggested to be a process or mechanism, which occurs in order to avoid the occurrence of an inability to maintain an expected power output. It may be considered that to understand pacing, the literature must first distinguish how fatigue is brought about and whether limitations are peripherally or centrally invoked. However, it could equally be argued, that investigation into the practices, such as pacing, which enable the avoidance of fatigue, may provide valuable insight into the topic of fatigue itself.

One model of fatigue, known as complex metabolic control, considers the development of fatigue to be based upon a complex interaction of peripheral and central metabolic factors. It may be distinguished from the isolated peripheral and central models of fatigue through its incorporation of feedback from peripheral factors which are interpreted centrally to avoid a catastrophic failure of physiological systems (Ulmer, 1996, Noakes et al., 2004). The incorporation of peripheral and central influences on performance makes complex metabolic control an attractive platform from which to investigate the role of pacing when compared with other models of fatigue, and has led to a current interest in the role of pacing and the use of self-paced exercise in research protocols. A more detailed review of the differing epistemologies of models of fatigue may be found in Chapter 2.2, whilst a critical review of the contemporary interest in pacing may be found in Chapter 2.5.

Much of the research into the effects of fatigue has been conducted using trials to exhaustion at enforced paces of exercise (Brooks et al., 1996b), such protocols are rarely replicated in sporting performance, in which performers are much more likely to have a knowledge of an exercise endpoint and are therefore able to apply a pacing strategy to their performance. Moreover, they do not allow for participant control, which may lead to motivational issues and withdrawal from an exercise bout as the only alternative through which the participant can modulate effort (Schabort et al., 1998). Self-paced time-trials have greater parity with the exercise requirements of sporting performances due to their ability to freely fluctuate pace when required, and may be adapted for application in a range of research environments. The use of time-trial protocols and time-to-exhaustion protocols is discussed in Chapter 2.8.

Perceptions of effort may vary during an exercise bout, thus the rate of perceived exertion scale (RPE), which has been previously described as a measure that encapsulates the sum of all sensations of physical exertion (Faulkner and Eston, 2007) has been used in self-paced exercise investigations (Eston et al., 2008, Mauger et al., 2010a, Tucker et al., 2006a). Ratings of perceived exertion are thought to consist of the integrated feedback of physiological and psychological mechanisms, which may be assigned a value between 6 and 20 (Borg, 1970). RPE scales have previously been shown to be reliable and valid in a range of exercise environments details of which are reviewed in Chapter 2.6.

The influence of a complex metabolic controller relies upon the assimilation of feedback from a range of metabolic measures and incorporated anticipation of an effort yet to come. Support for such a system may be presented in light of numerous laboratory studies which have failed to identify a single metabolic variable or combination of variables which can definitively explain fatigue (Edwards and Noakes, 2009).

With the development of theories, comes new equipment, and the development of fast-response technologies, now commonly used in sports science laboratories, make it feasible to examine the concept of pacing and fatigue in more dynamic experimental conditions than was previously practical (Sparling et al., 1993). Physiological markers of fatigue such as indicators of muscle recruitment and temperature regulation, previously unobserved due to the rates of data capture required, may now be measured dynamically and related to the perception of effort and pacing during exercise which may provide further understanding of the development of fatigue and thus the role of pacing within it.

During the development of this thesis the investigation of pacing and fatigue has drawn interest from other researchers such as Mauger (2010a, 2010b) , Micklewright (2010), and Schlader (2010a, 2010b), however the initial aims of this series of studies remain un-addressed by the research literature.

1.2 Purpose of the thesis

This project will investigate the role pacing in the development fatigue.

1.3 Aims of the thesis

The aims of thesis are:

To examine the relative impacts of self-paced and enforced-pace exercise on markers of fatigue.

To investigate the influence of environmental variables such as radiant warming on self-paced exercise.

To identify reliable methods of scientific observation which have relevance to current sporting practices.

The purpose and the aims of this thesis were achieved through four studies, each study has been written up separately, but the collective findings of all studies are brought together in a summary discussion in Chapter 8 of this thesis.

Study 1: A comparison of self-paced and enforced-pace exercise at a matched-intensity.

Study 2: The test-retest reliability of power output in self-paced exercise: within-group and between-group observations.

Study 3: A comparison of self-paced exercise in response to intervals of radiant warming and constant thermoneutral conditions.

Study 4: A comparison of self-paced and enforced-pace exercise protocols on the assessment of maximal oxygen uptake.

Chapter Two

Review of Literature

Chapter Two

Review of Literature

The following review of literature presents a critical review of the central themes of this thesis. It will introduce the concept of fatigue and give background to the common perspectives of fatigue, it will then develop to introduce markers of fatigue, and discuss the concept of pacing before identifying other aspects of the research literature pertinent to this thesis.

2.1 Fatigue

The word 'fatigue' comes from the 17th century Latin word *fatigare* meaning 'tire out'. In modern society its use can refer to a wide variety of situations which could include military clothing, the breaking point of materials, or perhaps most commonly; extreme tiredness resulting from mental or physical exertion (Pearsall, 1999). In the realm of sport science the term fatigue is equally not without its duplicates; for an academic from the field of psychology it may mean transient feelings of tiredness, for a biomechanist it may refer to a reduction in force, and for the exercise physiologist, fatigue has been traditionally defined as the inability to maintain an expected power output (Hultman and Sjoholm, 1986, Kirkendall, 1990); this may be attributed to failings of the cardiovascular, central nervous, or muscular systems or any combination of therein. The context of the use of the term fatigue has been discussed by Abbiss and Laursen (2007) who advise that in the interests of clear dissemination of information, the context in which the term fatigue is used be clearly defined. To those ends the following review of literature will start by describing and discussing the concept of fatigue from a physiological perspective, considering the field from the three most common models of fatigue; the traditional model, the central model, and the complex model.

2.2 Models of fatigue

2.2.1 Traditional model of fatigue

Some of the earliest work to influence the field of exercise physiology is that of A. V. Hill (Hill et al., 1924a, Hill, 1932) who investigated muscular exercise, oxygen uptake and lactic acid. Hill's work from 1924 was some of the first to describe a model of fatigue that we recognise today, and yet despite the intervening 80 years, the interaction of exercise, oxygen and blood lactate, particularly at maximal levels of effort are still sources of great debate (Bassett, 2009, Calbet and Lundby, 2009, Cheung and Flouris, 2009, Foster and Lucia, 2009, Gonzalez-Alonso and Mortensen, 2009, Kemi, 2009, Marcora, 2009, Shephard, 2009a, Noakes and Marino, 2009b, Ekblom, 2009a). A traditional view of fatigue can be traced back to Hill's measurements of $\dot{V}O_2$ at maximum (Hill et al., 1924a) in which Hill described an oxygen uptake constant as "remaining constant because it cannot go any higher owing to limitations of the circulatory and respiratory systems". These studies are credited with shaping the way of future research (Bassett, 2002), which in some cases then took over 60 years to provide support for concepts that Hill had first envisaged (Sharp et al., 1986).

A traditional perspective of fatigue predicts that fatigue will occur due to a failure in the cardiovascular system which prevents oxygen getting to an area of need; or by a failure in the contraction coupling cycle which brings about fatigue through an inability to remove the byproducts of Adenosine Triphosphate (ATP) resynthesis (Korge, 1995), or by a combination of these factors.

In a cardiovascular model of fatigue, performance could thus be limited by any one of the following processes:

the ability to extract oxygen from the atmosphere and move it into the blood stream,
the ability to move oxygen from the blood stream to the working muscles,
the ability of the muscle to use the oxygen provided.

In healthy individuals, the ability to extract oxygen from the air and move it into the blood stream is the function of the respiratory system, which at sea level, provides red blood cells with approximately 98% saturation, more than enough to sustain sub-maximal exercise. At altitude, oxygen saturation is reduced, but this decrement is still less likely to inhibit the performance of a healthy individual than the ability to move oxygen to the area of need. As such, any failing in this model comes from the delivery of oxygen to the muscle, or its utilisation at the muscle rather than the delivery of oxygen to the circulation (Brooks et al., 1996a).

The movement of oxygen around the vascular system is primarily governed by the heart's ability to pump blood. In times of need the heart is able to increase heart rate and/or stroke volume in order to increase the volume of blood ejected from the heart, which is also known as cardiac output. Cardiac output is however limited, and whilst endurance training is known to increase its capacity it is clear if all other aspects of exertion were not limited, fatigue could be brought about by the inability of heart rate and stroke volume of increase on an infinite scale. Cardiac output can therefore be considered to be one factor which may bring about fatigue (Brooks et al., 1996a).

The ability of the muscle to use the oxygen provided pertains to the efficiency of the contraction of skeletal muscle, much of which was described in work on the sliding filament theory of muscular contraction by Huxley and colleagues in 1954 (Huxley and Hanson, 1954, Huxley and Niedergerke, 1954). As fatigue develops humans are known to reduce muscular power output, which suggests some effect is being exerted upon the contraction coupling cycle. This observation should be combined with a biochemical knowledge that an increase in muscle lactate impairs the body's ability to resynthesise ATP and therefore the ability to maintain power output.

It is commonly thought that the failure of the contraction coupling cycle is primarily due to an inability to supply energy substrate at a rate fast enough to meet demand. However this is a misconception, as the inability for supply to meet demand (which moves humans from an indeterminately sustainable aerobic energy source into an environment whereby ATP must be synthesised using anaerobic means) is more likely to be due to an accumulation of selective metabolic byproducts, which cause a down-regulation of the enzyme required to resynthesise ATP (Korge, 1995). This process results in an increased reliance on anaerobic energy production and an accumulation of hydrogen ions, reducing the pH of the muscle and inhibiting the enzyme phosphofructokinase (Robergs et al., 2004). In turn this stops the conversion of fructokinase-6-phosphate into fructose 1,6-biphosphate, (Nevill and Greenhaff, 1999) thereby effectively halting the cascade of energy until the demand for ATP reduces, the practical application of which is for the athlete to decrease the use of energy and thus power output, either by reducing intensity of exertion or by ceasing the exercise altogether.

An additional factor which may be of influence in the failure of the contraction coupling cycle is the reduction of intramuscular calcium following prolonged periods of contraction. Calcium is one of a number of neurotransmitters involved during muscular contraction but evidence suggests that a reduction in its release may negatively affect the contraction coupling cycle (Green, 1997). This is perhaps more pertinent when considered alongside the knowledge that the delayed return of calcium to the sarcoplasmic reticulum can increase muscle relaxation time (Hill et al., 2001). Furthermore, that during excitation of muscle tissue intramuscular calcium has been suggested to be taken up by the mitochondria consequently impairing mitochondrial function (Green, 1997) and in addition, that an increase in mitochondrial $Ca^{2}+$ is known to reduce the phosphorylation abilities of the mitochondria (Brooks et al., 1996b). Collectively these factors present a strong argument for a peripherally based development of fatigue due to some failure in the contraction coupling cycle.

The conclusions of many traditional models of fatigue hold that changes in metabolites in the chain of reactions from stimulation into action potential and into muscular contraction are what bring about a reduction in force at the muscle which is commonly termed ‘fatigue’.

In contrast to the traditional, peripheral based model, some scientists (Meeusen et al., 2006, Newsholme et al., 1987) have argued that fatigue occurs not at the end of the chain, but at the initiation, with a reduced neural output that brings about a reduction in the messages sent to the muscles and, as a consequence, reducing the force production of the muscle, the product of which is still termed fatigue, however the way in which this is suggested to occur is very different.

2.2.2 Central model of fatigue

The concept that fatigue may occur due to a reduction in the central drive rather than the peripheral feedback of physiological systems has a strong element of logic to it. A popular hypothesis proposed in support of the concept of central fatigue is that, as exercise progresses the ratio of neurotransmitters associated with tiredness increases and this impairs the brain’s central drive and consequentially its ability to recruit motor units (Meeusen et al., 2006). This theory conveniently suggests a solution to the complication of why neural activation might increase when power decreases in the final stages of fatigue (as has been previously observed (Crenshaw et al., 1997)) but is still somewhat based on the peripheral feedback of systems, as in order to increase the production of neurotransmitters, the brain would require afferent feedback from the muscles to acknowledge that insufficient motor units were being recruited. The consequence of this system would be the further reduction of motor unit recruitment and the inhibition of muscle force production (St Clair Gibson and Noakes, 2004). Central fatigue theorists have suggested that the increases in serotonin levels in the brain induced by exercise may bring about fatigue (Newsholme et al., 1987). The neurotransmitter serotonin is thought to have a role in the regulation of mood, sleep, appetite, and emotion, and so its role in fatigue is indeed plausible, however despite numerous investigations evidence for the role of serotonin in fatigue during exercise is still lacking (Meeusen et al., 2006).

Early work on the reduction of neural drive, which soon became known as the central fatigue theory, was initially accredited to Acworth et al., (1986) but is perhaps better recognised through its developments by authors such as Newsholme et al., (1987) and Meeusen and De Meirleir (1995). Much of the development of this theory has now discounted serotonin as a singular factor in the development of fatigue during exercise. Moreover, it is likely that a complex interaction of substances such as dopamine, adenosine and ammonia (NH_3) are involved. In a 2006 review of Central fatigue Meeusen concluded that:

> "It is likely that the interaction of cerebral metabolic, thermodynamic and hormonal responses during prolonged exercise will determine the delicate communication between the brain and the periphery. Fatigue is therefore likely to be an integrated phenomenon with complex interaction among central and peripheral factors" (Meeusen et al., 2006) p904.

The idea of fatigue being either a central or a peripheral phenomenon is therefore increasingly less appealing. Much of the previous research into fatigue has taken a reductionist approach, which involves the isolation of factors in order to investigate and quantify their effect. However the reality of fatigue is that it presents as a dynamic multifaceted concept, and therefore does not lend itself well to a deductive investigation which has the potential to rule out factors which may be of great significance in a more complex view of fatigue. Furthermore, the proposition of authors working from a central perspective, such as Meeusen, that fatigue may be an integrated phenomenon clearly coincides with suggestions from authors from a peripheral perspective such as Hargreaves, who, despite a lifelong bias toward a peripheral model has written that:

> "In the absence of significant changes in peripheral biomarkers of fatigue following impaired exercise in hot environmental conditions he must consider a more complex regulatory process" (Hargreaves, 2008) p1542.

A regulatory process which incorporates feedback from both peripheral and central factors would indeed be complex, and would require such a mechanism to selectively respond or reject physiological feedback based upon pre-determined factors. As fatigue may be brought about by the failure of more than one physiological system, a complex model of fatigue must be sufficiently dynamic in order to respond to changes in feedback which may unacceptably hasten the onset of exhaustion.

2.2.3 Complex model of fatigue

The concept of a complex model of fatigue is often attributed to Professor Tim Noakes and his 1996 address to the American College of Sports Medicine's Annual Conference, however any credit for the development of the concept should be equally attributed to a group of authors; including Lambert et al. (2005), St Clair Gibson et al. (2001b), and Ulmer (1996). Indeed the suggestion of a central controller may be considered an aspect of the original work on models of fatigue by Professor A.V. Hill (Noakes, 2008a).

Initial descriptions of a complex model of fatigue describe a process of fatigue managed by a central governor which acts as an assimilator of signals from biological mechanisms in the body that governs the body's ability to create motor impulses, thus reducing muscle force and preventing the catastrophic failure of systems (Ulmer, 1996, St Clair Gibson et al., 2001b). The concept originally described as the central governor model has since been progressed individually and collectively by authors such as Lambert et al. (2005), Tucker (2009) and St Clair Gibson et al. (2006) which supports the description of the model as a complex system integration of biological feedback and feedforward mechanisms (St Clair Gibson and Noakes, 2004).

The model of complex metabolic control was described in a series of papers published in the British Journal of Sports Medicine (Noakes et al., 2004, Noakes and St Clair Gibson, 2004, St Clair Gibson and Noakes, 2004, Lambert et al., 2005, Noakes et al., 2005). The model incorporates a number of core concepts, central to these are the suggestion that a complex metabolic controller will assimilate biological feedback and manage performance in order to avoid a catastrophic failure of systems. In contrast to peripheral or central models of fatigue it is proposed by this model, that feedback from peripheral physiological sources is combined with a central anticipation of the effort required to complete a bout of exercise, which culminates in the increase or decrease of effort in order to complete the bout without the catastrophic failure of physiological systems or an unacceptable disturbance to homeostasis.

Evidence in support of this model is derived from situations in which physiological responses do not match those predicted by any individual peripheral model. One notable example of this may be found in the investigation of exercise during the heat. It is known that performers will fatigue and terminate exercise in advance of core temperatures likely to cause damage to cells (Brooks et al., 1971, Gonzalez-Alonso et al., 1999). In itself this suggests exercising individuals are able to predict a disturbance in homeostasis and initiate a change in the behavioural response, prior to a catastrophic failure of systems, be that through decreasing exercise intensity or aborting altogether. In this situation, a peripheral model would predict the continuity of exercise at a similar intensity until a catastrophic failure of the thermoregulatory system, whilst a central model would fail to incorporate the increases in temperature and thus also continue to innervate a similar exercise intensity. According to a central model of complex control the regulation of exercise intensity (power output) is a behavioural response to both feedback information from peripheral receptors and feedforward (anticipatory) mechanisms which regulate exercise intensity to avoid the development of bodily harm (Lambert et al., 2005, St Clair Gibson and Noakes, 2004). Additionally this model also addresses the perception of sensations of fatigue, which serve little purpose if performance is governed by either peripheral or central mechanisms, yet in common sporting practices the perceptions of fatigue play an influential role in exercise intensity and endurance.

The sensations of fatigue and fluctuations in power output during a performance may therefore be an important feature of a regulatory process, based on information from various peripheral systems (e.g. muscle, respiratory, metabolic receptors) within a complex metabolic control system. Multiple studies have suggested that discreet alterations in distribution of power output (pace) are evidence of a regulatory process to maintain a reserve of motor units and thus avoid catastrophic fatigue (St Clair Gibson et al., 2001b, St Clair Gibson et al., 2001a, Noakes et al., 2005). Thus the influence of pace may be fundamental to the investigation of fatigue.

Abbiss and Laursen (2005) have previously attempted to explain a number of mechanisms of fatigue in relation to endurance cycling performance. Using nine different models of fatigue including models based on neuromuscular fatigue, thermoregulatory fatigue and psychological fatigue, the authors systematically explained each model using referenced articles of interest and relevance to cycling. Clearly a conclusion as to which is the ‘best’ physiological model to suit all analysis of fatigue would have been preferable, but given that such a concept has been the source of much debate for at least ten years, it was also unlikely.

The singular review of multiple theories of fatigue by Abbiss and Laursen (2005) serves to highlight commonalities in models of fatigue which extend beyond the central governor model to demonstrate the relevance of peripheral mechanisms of fatigue to a complex model of metabolic control (Lambert et al., 2005, St Clair Gibson and Noakes, 2004). The peripherally based metabolism of lactate has traditional been described as a mechanism of fatigue in response to the high levels of lactate accumulation recorded at the cessation of high intensity exercise, and improvements in buffering capacity as a consequence of training, which have been considered to highlight lactate as a factor fundamental to fatigue. However as research has enhanced the understanding of lactate metabolism (Robergs et al., 2004), its role in fatigue has become less well defined; whilst the increased acidosis brought about increases in lactate accumulation may inhibit the further degradation of ATP, the acidosis itself may maintain cell membrane excitability in the presence of high extracellular potassium ions (Pedersen et al., 2004) thus allowing the continued propagation of neural impulses. Furthermore, the increased H^+ ions stimulating pain receptors, previous considered to impair performance (Bogdanis et al., 1994) may actually represent a signalling mechanism to create a feedforward mechanism of peripheral control. (Lambert et al., 2005).

As a finalised model to explain the development of fatigue, lactate metabolism may be shown to be flawed, yet in certain circumstances its application is entirely appropriate and herein lies the progression beyond a central governor toward a model of complex metabolic control, underpinned by the observation that, to-date, no single factor which brings about fatigue in all situations has been identified (Lambert et al., 2005, Edwards and Noakes, 2009). The complex model of fatigue may therefore be considered a model which incorporates influences of central control; factors such as motivation, experience or a central processor, and also incorporates concepts of peripheral control; factors such as body temperature or circulating levels of blood lactate.
The complex interaction of these models is demonstrated in figure 2.1; an adapted version of the model developed by Abbiss and Laursen (2005).

The integration of concepts of peripheral control which signal the potential for upcoming fatigue may be particularly relevant in the role of thermal fatigue.
A discussion of the role of core and skin temperatures as peripheral mechanisms of control, signalling mechanisms, or physiological markers of fatigue follows in section 2.3.

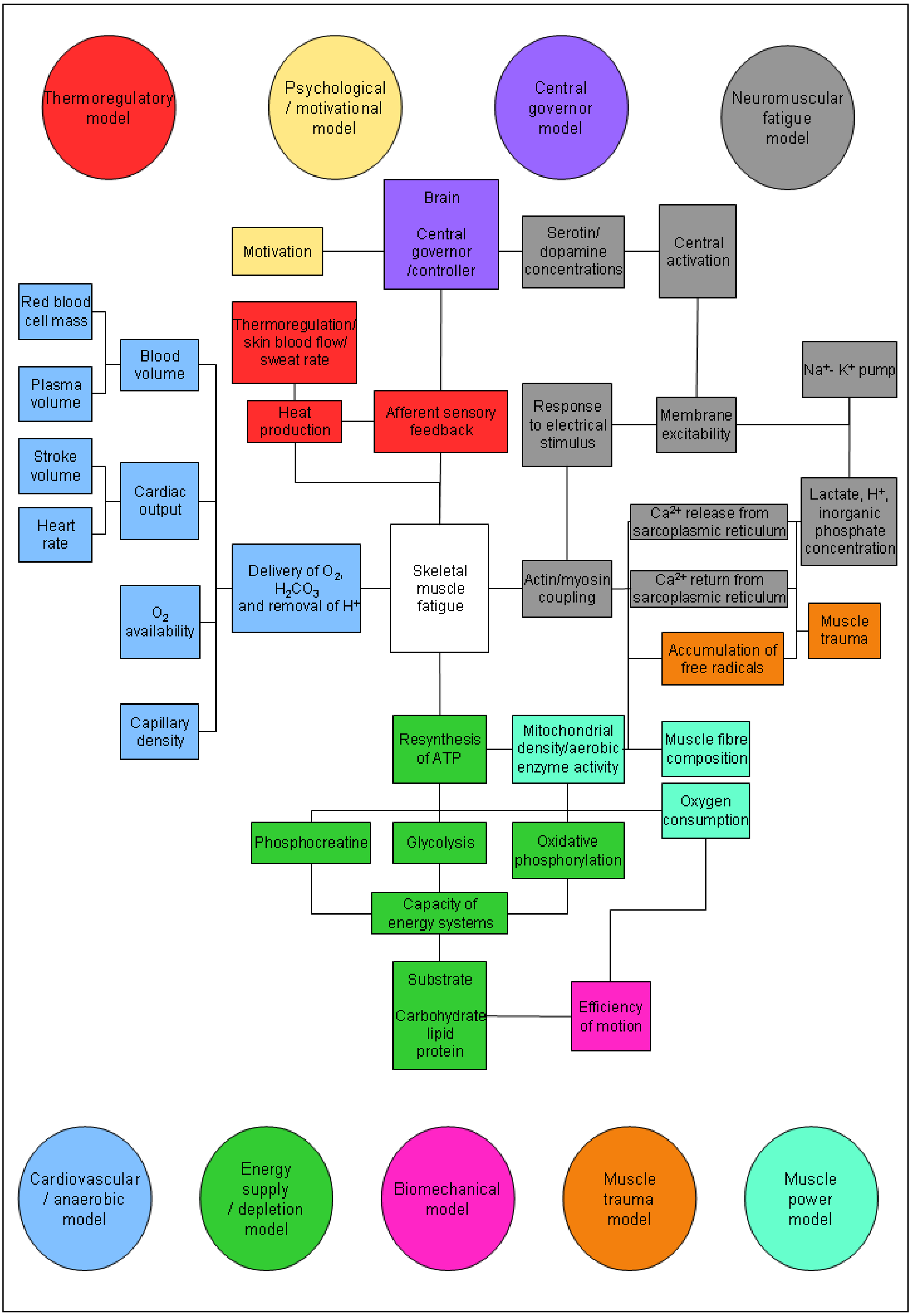


Figure 2.1 Complex systems model of fatigue; the interaction of developed fatigue models.

Adapted from (Abbiss and Laursen, 2005)

Whilst succinctly demonstrating the integration of multiple models of fatigue into on larger complex model Abbiss and Laursen also identify that many of the models of fatigue that have previously addressed the concept did so using a linear methodology, from the start of exercise toward a catastrophic failure. This approach does not allow for the interaction of effects, such as hydration status, experience, and transient changes in effort perception, which is a scenario much more likely in the investigation of fatigue. The suggestion of an interaction of effects provides support to the earlier conclusions of Hargreaves and Meeusen (Hargreaves, 2008, Meeusen et al., 2006) which referred to fatigue as an integrated phenomenon with complex interaction among central and peripheral factors. Abbiss and Laursen (2005) add strength to these suggestions of an integrated system by reporting that that researchers often fail to address alterations in muscle power mechanics and therefore view peripheral fatigue as the (integrated) combination of both neuromuscular failure and biochemical changes at the level of the muscle.

The idea of complex control of metabolic fatigue is not without its critics (Hopkins, 2009, Shephard, 2009b, Weir et al., 2006), some of whom are now calling for colleagues to ‘retire’ investigation into complex metabolic control on the grounds of 13 years of research which has failed to prove that a central governor exists.
In a review entitled ‘Is fatigue all in your head? A critical review of the central governor model’ Weir et al., suggested that central governor model (CGM) does not adequately explain fatigue in tasks that require very high forces and or power outputs for relatively brief periods (Weir et al., 2006). The authors compared and contrasted peripheral fatigue and aspects of the CGM creating the position that, whilst they could agree with some aspects of CGM, it was suggested that a model of fatigue based on task dependency may also be used to explain the findings core to the CGM. The article also discussed perceived flaws in the interpretation of electromyography, maximum voluntary contractions (MVC) and with results from the Wingate anaerobic test (WAT). The authors suggested that a central complex metabolic controller, and more specifically a pacing strategy, is not capable of explaining the maintenance of power output in MVC and WAT exercise bouts. Instead they posited that the muscle gives feedback to the Central Nervous System (CNS) rather than the CNS governing or pacing the muscle.
Noakes (2006) responded to the challenge to the theory of CGM by clarifying the model as a complex integration of metabolic systems as described by all five of the BJSM articles, but specifically toward the article surrounding the integration of systems and the concept of teleoanticipation (Ulmer, 1996), which proposes that an individual has some understanding of the effort gone and the effort yet to come. Herein lies the

flaw of many of the rebuttals of CGM (Hopkins, 2009, Shephard, 2009b, Weir et al., 2006) which fail to consider the model as incorporating an integration of systems, or perhaps more mistakenly consider the CGM as a physical space in the brain where all decisions about exercise are made. Critics argue that researchers' inability to identify the location of this central governor is therefore evidence that it does not exist. Proponents of the model however retort this accusation, by suggesting that by focusing on the detail of physiological responses these academics miss the bigger picture (Marino, 2010) the elephant in the room, as Noakes indeed alludes to (Noakes et al., 2005). He himself points out that "we cannot force Dr… to see what he does not want to see" (Noakes and Marino, 2009a).

It is clear that fatigue is a multifaceted phenomenon and to consider it as anything other than a complex interaction of system appears flawed. The muscular, central nervous, and cardiovascular systems appear not to work in isolation, thus in order to consider what fatigues a whole human being we must consider fatigue from a viewpoint which allows the investigation of a number of physiological systems and their consequential markers of fatigue.

A physiological marker of fatigue common to traditional, central and complex models of fatigue is that of a set point core temperature at which participants will reduce exercise intensity or cease exercising altogether. Whether that core temperature is a singular value of 40˚C (Nielsen et al., 1993) or a more likely better considered as an interthreshold range is still unclear (Cooper, 2002, Mekjavic and Eiken, 2006), however given its incorporation in a number of models of fatigue, core temperature appears to be a marker of physiological fatigue worthy of further investigation. A further marker of fatigue previously used to identify the fatigued state of skeletal muscle is that of electromyographical stimulation, which has been used to conclude whether contractions from fatigued muscle can be superseded by electrical stimulation(Enoka, 1995, St Clair Gibson et al., 2001a).

2.3 Physiological markers of fatigue

The following section of this review will consider thermoregulatory and electromyographic markers of the process of fatigue which are of particular relevance to this study, as both variables have previously identified as being of interest in the investigation of fatigue (Noakes et al., 2005).

2.3.1 Core Temperature (T_c)

It is well known that exercise in the heat is more likely to bring about fatigue sooner than in a comparable bout of exercise in a thermoneutral environment (Galloway and Maughan, 1995, Gonzalez-Alonso et al., 1999, Tucker et al., 2004). Humans are homeotherms and as such attempt to maintain a temperature independent of their environment. The fixity of the (human) internal environment is the condition for free life (Bernard, 1878), and thus in any environment which may cool or heat that internal environment, the defence of core temperature is critical.

During exercise the sum of the biological processes occurring causes an increase in core temperature, indeed it is suggested that up to 75% of the energy released in order to exercise is released as heat, due to skeletal muscle's relatively low mechanical efficiencies (Astrand et al., 2003, Hagerman, 1984). This rise from in-vivo heat brings about a sweating response in order to defend core temperature (Ekblom et al., 1971), for above 41˚C the interior of cells is known to deteriorate (Brooks et al., 1971). It is not surprising therefore, that the body's thermoregulatory mechanisms are primarily in place to protect against overheating (Maughan et al., 1996).

The temperature regulation centre of the body is the hypothalamus, and any measures of core temperature are taken to be representative of changes in the temperature at the hypothalamus. There is disagreement as to the precise average core temperature of a human at rest with figures from between 35 and 41˚C (Astrand et al., 2003, Sawka and Wenger, 1988); 36.6-37.1˚C, (Marieb, 2005); and 37 $\pm$ 1˚C (McArdle et al., 2001) however these figures are generally consistent with the early work conducted by Carl Wunderlich in 1861 who is credited as first quantifying a mean core temperature of healthy adults (Mackowiak et al., 1992).

Since core temperature is rarely measured at the hypothalamus itself, at least during exercise, researchers have had to identify alternative locations for measurement of core temperature. Contemporary research seems to favour the measurement of core temperature at the oesophagus, which appears to provide the most appropriate measure of deep body tissue temperature (Mairiaux et al., 1983, Sawka and Wenger, 1988, Sparling et al., 1993, Gant et al., 2006). The development of short range telemetry to monitor core temperature; comprised of a silicon-coated ingestible transmitter and portable receiver, has made thermal physiological investigation far more dynamic and far less invasive. The first published use of this CorTemp© system was by Sparling and colleagues (1993) in which they compared the efficacy of the ingestible thermistor with scores from a rectal temperature in subjects exercising at different intensities, durations, and in different modalities. Since then, use of thermometer pills in exercise investigation has become common place (Challis and Kolb, 2010, Domitrovich et al., 2006) and replaced many of the previously uncomfortable and unreliable measures of core temperature.

Thermometer pill ingestion times as short as 30-45min prior to measurement have been proposed (Domitrovich et al., 2006), however the pill has also been shown to exhibit a blunted response when compared with other measures of core temperature (Gregson et al., 2006). Furthermore, such short ingestion times may cause readings from the pill to be influenced by the ingestion of hot or cold fluids (Sparling et al., 1993), thus longer ingestion times are more likely to elicit a balanced measure of temperature. O'Brien and coworkers (O'Brien et al., 1998) have suggested that a 2-3 hour ingestion period is insufficient to adequately advance the pill along the digestive system, preferring to use an ingestion of 12 hours prior to exercise. Whilst this time frame demonstrated strong correlations with other measures of T_c these authors also failed to identify a signal from the pills on 3 occasions which could be suggested to be a consequence of the pill passing further along the digestive tract in some participants than others within the 12 hour window. Edwards and Clark (2006) have previously used a 4 hour ingestion when observing thermoregulatory changes in soccer match play, whilst Gant et al., (2006) have shown ingestion times of 10 hours to be sufficient in order to observe reliable recordings from this system. Thus an optimal window for ingestion and reliable use of the thermometer pill appears to be within 5-10 hours of exercise commencement.

In exercise of a mild to moderate intensity, such as that required to elicit a $\dot{V}O_2$ of 1.0 $L \cdot min^{-1}$, core temperature could rise by approximately 1˚C every 15min without adequate heat dissipation (Kenney, 1998), however this rise can increase to a rate of 1˚C per min during the initial moments of high intensity exercise (Gleeson, 1998). Clearly these rates of increase in temperature cannot be tolerated by the body for long, such rises would cause catastrophic failure of the contractile enzymes and put subjects into hyperthermic states of exercise termination within 15 to 20min of commencement (Gleeson, 1998). Thus during any exercise humans must initiate an appropriate strategy to effect the dispersion of metabolic heat.

Sub-maximal exercise which can provide sufficient cooling within an evaporative capacity, tends to provide the investigator with a relatively stable core temperature (Saltin and Hermansen, 1966). However, as exercise duration continues, or as intensity increases the body's capacity to remove the metabolic heat created by exercise diminishes and exhaustion ensues (Cheung and Sleivert, 2004). Gleeson (1998) argued that during exercise at a constant work rate, heat production increases in a square wave fashion, and it is therefore important to realise that problems of hyperthermia and heat injuries are not restricted to prolonged exercise in a hot environment rather, that they are a reflection of the body's heat production, so that even exercise in cool conditions can cause a substantial rise in body temperature. This acceptance of the increase in temperature during exercise stems from studies as early as 1938 (Nielsen, 1938) which showed that body temperature was regulated at a higher level during exercise than at rest (Saltin and Hermansen, 1966).

Hyperthermia is known to have a profound effect on cerebral activity, muscle activation, and perceived exertion during exercise, thus the monitoring of core temperature is important in the study of fatigue. Whilst it is currently unclear how an elevated body temperature contributes to the development of fatigue it seems possible that a critical core temperature may serve as a protective mechanism to prevent damage to the body by bringing about premature fatigue in a hot environment and thereby limiting further heat production (Meeusen et al., 2006).

The concept of a critical core temperature was first proposed by Nielsen et al., (1993) following an investigation into heat acclimation; the authors found that despite increases in exercise capacity following heat acclimation, fatigue occurred at similar oesophageal temperatures of around 40˚C (T_{oes}=39.7 $\pm$ 0.15˚C). This finding was supported by the work of Gonzalez Alonso et al., (1999) who observed exhaustion in cyclists at T_{oes} of 40.1-40.3˚C following prolonged exercise in environments with differing rates of heat storage. These studies collectively promulgated a belief that humans would automatically fatigue when core temperatures reached 40˚C.
The concept of a critical core temperature of 40˚C was challenged by Byrne et al., (2006) who tracked core temperatures in runners of a half marathon in Singapore, where the environment was 26˚C Wet Bulb Globe Temperature (WBGT) and 87% humidity, and showed that 18 runners (100% of their sample) completed the course with a T_c >39˚C, 56% of the sample completed the race with T_c >40˚C, and 11% of the sample completed the race with a T_c of >41˚C and all without symptoms of heat illness. In response to scepticism from other authors (McLellan, 2007) surrounding accuracy of these T_c measurements Byrne (2007) justifies the methodology and cites a 1977 paper (Maron et al.), which reports core temperatures of 41.9˚C, which is the highest asymptomatic T_c currently recorded during exercise.

Further challenge to the concept of a critical core temperature of 40˚C as an influence on exercise has recently come from Ely et al., (2009) in a study which compares 8km running performance in indoor (cool) and outdoor (warm) conditions. These authors argue for the use of rectal measurements of core temperature despite previous work demonstrating that rectal temperatures show blunted responses to changes in core temperature (Sawka and Wenger, 1988) and a reduced sensitivity to changes in T_c due to localised blood flow in active skeletal muscle of the gluteal group (Kenney, 1998, Nielsen and Nielsen, 1962). Although flawed in its methodology the work of Ely et al., (2009), does present further evidence of a limitation of core temperatures at approximately 41˚C, and given the variance that can be innate to most measures of temperature, the concept of a critical core temperature is not yet without a conclusive opposition, particularly as many authors now accept that this might be one physiological measure which forms part of a complex defence of fatigue (Cheung and Sleivert, 2004, Tucker et al., 2006c, Tucker, 2009).

2.3.2 Skin Temperature (T_{sk})

As previously identified, changes in core temperature are linked to altered physiological responses in order to maintain thermal homeostasis. The thermal comfort of an individual is however, strongly linked with behavioural thermoregulation (Bulcao et al., 2000), and that behaviour is as likely to be influenced by skin temperature as by core temperature (Frank et al., 1999). In a study designed to quantify the relative contribution (or weighting) of core and cutaneous responses Frank et al., found a 1:1 contribution of T_c:T_{sk} for thermal comfort. The weighting was altered when vasomotor changes were assessed (3:1) and different again when assessing the contributions in relation to metabolic heat production (3.6:1). These data suggest that T_{sk} has a greater contribution to thermal comfort than to autonomic thermoregulatory responses. As T_{sk} is influenced more rapidly by changes in a thermal environment, the increased weighting of T_{sk} serves to initiate changes in behaviour before the activation of the more metabolically demanding responses that maintain body temperature. The balanced contribution of 1:1 (T_c:T_{sk}) is in contrast to earlier work by Wyss and colleagues (1974) who found core to skin ratios of 20:1 in sweating humans, data which may have contributed to a perceived reduction in the importance of skin temperature in exercise. Although greater understanding of the relationship between skin and core temperature is welcomed, it could be argued that the findings of Frank et al., and Wyss et al., which were developed using heated mattresses and warmed intravenous fluids, are less applicable when applied to an exercising situation due to the inability of participants to convectively cool during exercise.

In a study by Saunders et al., (2005) investigating the effect of wind on heat dissipation during exercise, the authors elegantly demonstrated that body cooling may be limited more by the environment than by the individual's physiological processes. By varying wind speed during a laboratory based cycling exercise test, Saunders was able to demonstrate that in lab based studies with wind speeds of less than those seen in the equivalent outdoor exercise, that it was the environment, rather than the individual, that impaired heat removal. When applied to the work of Frank et al., and Wyss et al., the finding from the Saunders work could be suggested to cast doubt on the efficacy of protocols using techniques which reduce the skins natural opportunities for heat loss, and although the logic of the skin as a first line defence in order to maintain body temperature in humans still holds true, the relative contribution of skin and core temperatures from studies which do not allow opportunity for natural heat loss may be less relevant.

A further study to investigate the skin and core temperature responses to heating and cooling by Huizenga and colleagues (2004) has demonstrated clear relationships between skin heating and core cooling using air sleeves to heat specific areas of the body. They found quicker core response changes when heating areas of the pelvis and the chest than when heating the head, hand or face. In a resting environment, the authors were able to calculate a reduction in core temp 7min after the application of skin warming. They do not quantify response times of other body areas but offer the detail contained in Figure 2.1 to demonstrate the response of core temperature to the various local exposures of skin warming, notable in this Figure is the inverse relationship between T_c and T_{sk}, particularly apparent when the face and chest are warmed.

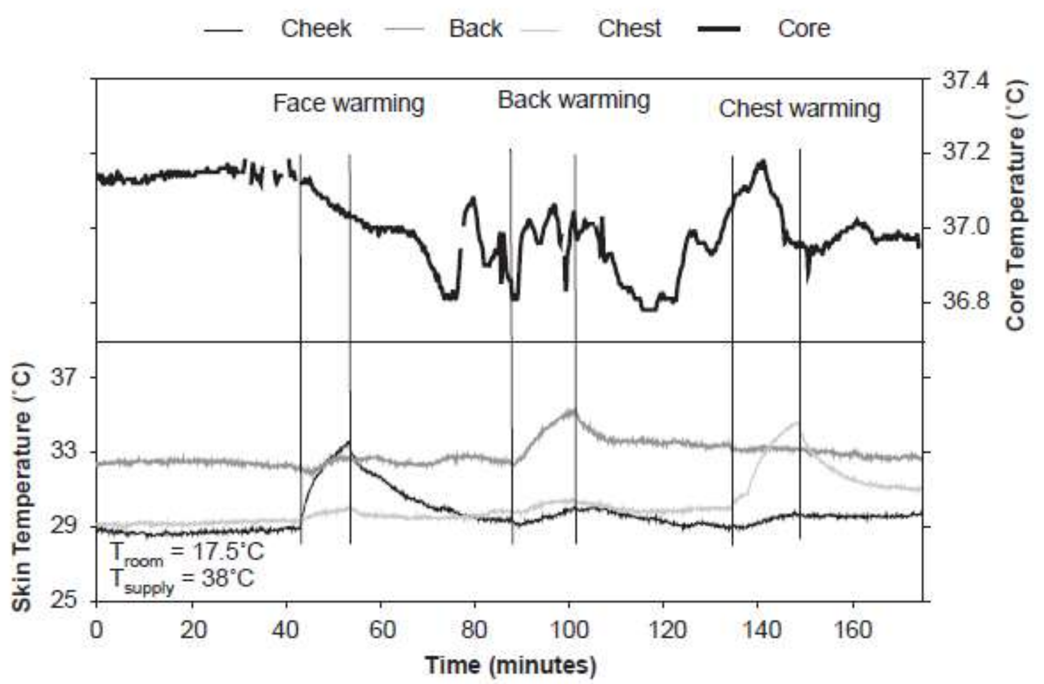


Fig. 11. Core and local skin temperatures during local warming applied to a cold body.

Figure 2.2 Core and local skin temperatures during localised warming of a resting individual warmed using manoeuvrable air sleeves.
Adapted from (Huizenga et al., 2004)

The idea of skin temperature as integrally linked to core temperature is also supported by work from Flouris and Cheung (2009) who have shown that skin temperature and core temperature respond synergistically in order to maintain thermoneutrality. These authors used a liquid conditioning garment capable of heating and cooling participants, which is obviously subject to the environmental flaw previously discussed, but is worthy of inclusion here as the investigation also included a 10min exercise regime (previously identified as resulting in a heat gain of 137 Watts) in which the authors saw participants actively selecting to cool their suit as core temperature increased in exercise thereby demonstrating a mathematical equalization of skin and core temperatures which actually resulted in a heat gain of -1.3W during exercise.

In order to avoid the influence of localised heating and cooling (as described by Houdas and Ring, 1982), a mean of skin temperature can be used to represent the sum effects of heating and cooling on the whole body. Such a measure must take into account not only the surface area of a subject, but also the altered responses which may be seen in different areas of the body depending on local climate, exercise modality, and individual inter-subject differences.
Early formulas devised to measure mean skin temperature were based on measurements from 7 sites (Hardy and Dubois, 1938). In order to improve practicality, subsequent authors have attempted to minimise the number of measurement sites needed (Astrand et al., 2003). The formula of Ramanathan (1964) based on 4 sites of measurement is commonly used to-date (Marsh and Sleivert, 1999, Tucker et al., 2006c).

T_{sk} ,˚C = 0.3 (chest + upper arm) + 0.2 (Thigh + Calf)   Ramanathan (1964)

The four sites identified in this formula are selected as areas over active muscles, on relatively exposed surfaces, and in important portions of the body that can influence temperature changes in the skin (Ramanathan, 1964). Using this calculation the areas of measurement are divided in terms of whole limbs and surface area weightings are applied accordingly to provide researchers with a valid measure of mean skin temperature for comparison with other thermal physiological variables. Whilst the Ramanathan formula for mean skin temperature does not take into account localised changes in heating, it can be considered a measure of changes in skin temperature during whole body exercise and is recommended as a user-friendly reliable measure of mean skin temperature (Mitchell and Wyndham, 1969)

Recent work by Schlader et al.,(2010a, 2010b) has asserted that skin temperature may represent a thermal controller of exercise following studies which progressively heat or cool participants during exercise. In a 60min cycling bout Schlader et al., (2010a) found that greater work was completed in the trial which went from cold to hot when compared to the trial which went from hot to cold. In support of previous work by these authors (2010b) Schlader concluded that skin temperature plays an important role in the choice of exercise intensity upon exercise commencement.

Whilst the relationship between thermoregulation and fatigue has yet to be identified; the influence of skin temperature on the defence of core temperature and the concomitant changes in exercise behaviour makes both these variables of current interest in the investigation of physiological markers of fatigue.

2.3.3 Electromyography (EMG)

Electromyography (EMG) is a measurement tool used to identify the recruitment of motor units in skeletal muscle (Jurell, 1998). More specifically it is the electrical representation of the neuromuscular activity of a contracting muscle (De Luca, 2002). This measurement method can be applied using needle electrodes by piercing the skin in order to isolate individual muscle fibres, but is more commonly used as surface EMG, in which electrode pads are placed on the skin approximately 1 cm apart, in a line parallel with the muscle fibres, and away from the tendinous insertion or the innervation zone of the muscle (De Luca, 1997). The consequent recording of raw EMG can then be treated using a range of filters in order to eliminate signal noise and allow the correct interpretation of the EMG signal. In an article on the use of surface electromyography (sEMG) De Luca (2002) discussed the role of electrode placement, filters and treatment of EMG signals, recommending the use of the root mean squared method in order to quantify EMG signal. The root-mean-squared method provides a measure of the power of an sEMG signal, which can be used by researchers to demonstrate a clear physical meaning, which is not the case with other methods of EMG interpretation such as averaged rectified values or integrated rectified signals that measure the area under a signal curve or provide a uni-polar view of muscle activation. The root-mean-squared method of sEMG normalisation is therefore the preferred method of analysis for most applications (Burden and Bartlett, 1999, De Luca, 2002, Nowicky et al., 2005) .

Reporting of an EMG signal is often normalised in comparison to a maximum voluntary contraction. Recent experiments evaluating methods of EMG normalisation concluded that the use of isometric and isokinetic contraction to normalise EMG were better able to detect changes in the magnitude of force applied to the biceps brachii than using dynamic methods (Burden and Bartlett, 1999). However the use of any normalisation procedure must be questioned when applied to dynamic multiple muscle movements such as those included in rowing ergometry. In an article comparing the impact of ergometer design Nowicky et al., were unsuccessful in their attempts to normalise the dynamic sEMG activity to a standard isometric MVC, as more peak muscle sEMG was observed during rowing than during the isolated MVC's themselves (Nowicky et al., 2005).

The role of EMG in fatigue is eloquently tested in a paper by St Clair Gibson et al., in which the authors contrasted the role of EMG in models of central and peripheral fatigue (St Clair Gibson et al., 2001b). Their investigation found that electrical activity of the vastus lateralis muscle declined in parallel with power output decreases but that less than 20% of the available muscle was recruited at any time during a 100km time-trial.

The opposing arguments in the investigation of EMG are that;

1: In fatigue EMG should increase as more motor units are needed to be activated due to reductions in muscle contractile function, through either excessive accumulation of metabolic acidosis or the depletion of intramuscular fuels which inhibit the ability to maintain force (Hulleman et al., 2007, Kirkendall, 1990). Or that

2: EMG should decrease as the centrally regulated system reduces the efferent command to muscles thus reducing muscle tension.(Enoka and Stuart, 1992, St Clair Gibson and Noakes, 2004)

The finding of parallel reductions in force and EMG activity, despite the use of only 20% of MVC is in conflict with both of these traditional viewpoints, and suggests the presence of a mechanism which may bring about fatigue due to factors other than muscular activity. The additional observation that following fatiguing exercise contractions of greater percentages of MVC can be produced by artificial stimulations (Bigland-Ritchie et al., 1986, Enoka, 1995, St Clair Gibson et al., 2001a) points toward the measurement of EMG as an important marker in the investigation of fatigue. However the use of varied methods of analysis and a lack of agreement on the directional magnitude of EMG in the development of fatigue contributes to conflicting evidence surrounding the role of EMG in fatigue.

2.4 Concept of a maximal exertion

Inherent to the study of fatigue is the concept of maximal exertion. The concept of a maximal voluntary contraction has already been rejected in studies involving dynamic multiple muscle movements, however maximal exertion is not just related to voluntary contractions, rather, it may better described as whole body exercise of the highest possible level. The assessment of maximal oxygen uptake is perhaps the most common measure of exercise physiology (Howley et al., 1995). The form of a $\dot{V}O_{2max}$ assessment used to test physically capable individuals will most often comprise of a ramped exercise protocol which requires athletes to work to an ever increasing enforced exercise intensity, in an exercise bout to which they do not know the endpoint, until fatigue. The assumed linear relationship between increases in power output and $\dot{V}O_2$ makes sense in a peripheral model of fatigue, in which it is predicted that humans will fatigue and stop exercise after a given period of time or at a given intensity, because of an inability to get oxygen to the working muscle. However if, as has been argued, fatigue is part of a complex interaction of systems then the $\dot{V}O_{2max}$ test only assesses an individual's ability to continue in the face of ever increasing resistance. Proponents of complex metabolic control point out that theoretically, at the end of 'maximal exercise', when energy sources are depleted, that humans should be suffering from rigor mortis (Noakes, 2008b, St Clair Gibson and Noakes, 2004). Since this is rarely the case, the body must have some mechanism by which it regulates 'maximal' exertion in order to avoid catastrophic failure of the organism.

It is beyond the scope of this review to discuss the strengths and weaknesses of the different exercise tests designed to predict $\dot{V}O_{2max}$ from sub-maximal scores, the interested reader is directed elsewhere (Bentley et al., 2007, Hawley et al., 1994, Howley et al., 1995, McArdle et al., 2001). Rather it is the aim of this section of review to introduce the measurement of $\dot{V}O_{2max}$ in conjunction with the models of fatigue described earlier.

2.4.1 Measures of $\dot{V}O_{2max}$

The British Association of Sport and Exercise Science (BASES) criteria for the assessment of maximal oxygen uptake require a test to satisfy any number of six criteria in order to acknowledge that $\dot{V}O_{2max}$ has been achieved (Bird and Davison, 1997). Their protocol for the measurement of $\dot{V}O_{2max}$ is a continuous protocol aiming to exhaust a participant in between 9-15min which requires participants to start at a pace that produces blood lactate concentrations of approximately 2 $mmol \cdot L^{-1}$ and an increase in exercise intensity every 1-2min, until volitional exhaustion.

The six criteria set by BASES are

1. a plateau in the oxygen uptake/exercise intensity relationship. Defined as an increase in oxygen uptake of less than $2ml \cdot kg^{-1} \cdot min^{-1}$ or 3% with an increase in exercise intensity.
2. A final respiratory exchange ratio of 1.15 or above.
3. A final heart rate within 10 $b \cdot min^{-1}$ of the age related maximum.
4. A post-exercise (4-5min) blood lactate concentration of 8 $mmol \cdot L^{-1}$.
5. Subjective fatigue and volitional exhaustion.
6. A rating of perceived exertion of 19-20 on the Borg scale or equivalent.

(Bird and Davison, 1997)

It is commonly considered among exercise physiologists that a plateau in $\dot{V}O_2$ uptake will be observed in an incremental exercise challenge which concludes in a maximal effort. It is believed that for a brief period, the aerobic energy systems are capable of sustaining exercise at a maximal intensity, after which participants will have to rely more on anaerobic energy production and thus a drop in $\dot{V}O_2$ should be observed signifying the end of the test. The ability to observe a plateau in $\dot{V}O_{2max}$ testing is contentious; work by Day et al., (2003) using continuous gas samples, found that a plateau-like response in oxygen uptake was only evident in 12 of 71 subjects (17%). However work by Snell et al., (2007) and following commentary by Howley (2007) has described participants as clearly capable of demonstrating an identifiable $\dot{V}O_2$ plateau.

Day and colleagues (2003), compared a constant load and incremental exercise trial and found no difference in $\dot{V}O_{2peak}$ and $\dot{V}O_{2max}$ plateau as calculated by the plotting of $\dot{V}O_2$ vs. work rate, suggesting that a $\dot{V}O_{2peak}$ is likely to be a valid index of $\dot{V}O_{2max}$. The term $\dot{V}O_{2peak}$ has been previously used by authors unable to observe a plateau (Bird and Davison, 1997) and therefore justify that they had measured $\dot{V}O_2$ at maximum. However if only 17% of participants reach a plateau, and therefore reach the score defined as maximum, it could be argued that $\dot{V}O_{2peak}$ is a more appropriate description than that of maximum. Indeed, if maximum implies the maximal limit of the human body then surely the measurement of this score can only be superseded by an exertion beyond the limits of the human body. This brings into question the terminology of the original measure.

The term supra-maximal is used by Snell and colleagues (2007) who, in an effort to demonstrate that a $\dot{V}O_2$ plateau can be observed, conducted a series of $\dot{V}O_{2max}$ tests on 52 participants, which were followed the day after by a supra-maximal test at an 8% gradient designed to fatigue the participants in 2 to 4min. No difference was observed between the $\dot{V}O_{2max}$ scores seen at plateau and the $\dot{V}O_2$ scores in the supra-maximal exercise, and thus it was concluded that incremental exercise tests do maximise oxygen uptake, and moreover, that a plateau in oxygen uptake can be observed in both male and female subjects of a trained status.

A most notable difference between the work of Day et al., and Snell et al., can be found in their respective methods of gas sampling. Whilst the Day study uses breath-by-breath sampling of respired air at the rate of $1ml \cdot s^{-1}$, the work by Snell et al., sampled gas for 40s within each 2min stage. It could be argued that the increased sample rate used in breath-by-breath analysis creates more data of greater precision, thereby masking a plateau which would be observed were fewer samples to be taken as is the case in the use of Douglas bag techniques. Conversely it has been argued that the higher sampling rate provides a better opportunity to observe a $\dot{V}O_2$ plateau (Astorino et al., 2005). Research on the topic of $\dot{V}O_2$ sample rates in plateau observation is scarce, but in order to conclude the physiological debate over the observation of an oxygen uptake plateau at $\dot{V}O_{2max}$, a consensus must first be reached on the methodology used to identify this extensively utilised measure.

The supra-maximal testing of athletes following the final stage of $\dot{V}O_{2max}$ testing has been termed a verification phase, and provides a new measure through which investigators can confirm the observation of a 'true' $\dot{V}O_{2max}$. Midgley et al., have described a supra-maximal protocol in order to measure and confirm $\dot{V}O_{2max}$ in a single laboratory visit, this is achieved by conducting an incremental $\dot{V}O_{2max}$ test, followed by a rest period standardised by both time and responses to motivational criteria, then conducting a verification phase of approximately 4.5min which culminates at an exercise intensity 1 stage in advance of that which the previous test ended on (Midgley et al., 2009). This protocol with a proposed set of standardised criteria was designed in response to the varied adoption of secondary criteria in the identification of maximal oxygen uptake.

To-date only a small number of studies have utilised the process of verification to clarify the observation of maximal $\dot{V}O_2$ without the use of any of the traditional criteria associated with its measurement (Midgley and Carroll, 2009), however concern surrounding the use of secondary criteria to confirm $\dot{V}O_{2max}$ has previously been reported. In a study attempting to clarify the validity of secondary criteria associated with the attainment of $\dot{V}O_{2max}$ Poole et al., (2008) were able to identify that subjects could achieve secondary 'maximal criteria' at $\dot{V}O_2$ values of much less than those eventually confirmed as maximal (Poole et al., 2008). In one case a $\dot{V}O_2$ of only 73% of maximum was sufficient to achieve secondary criteria. Thus the verification phase developed by Midgley and Carroll may present a suitable alternative to the traditional use of secondary criteria in maximal exercise tests when used in conjunction with an exercise endpoint known to participants at the start of the exercise bout.

The commentary by Howley (2007) on the need for a $\dot{V}O_{2max}$ plateau has since been followed by reviews from Levine (2008) and more recently, and controversially, by Noakes (2008b). Each author has suggested that the mechanisms behind a true $\dot{V}O_{2max}$ are uncertain, but Noakes went further by suggesting that because the majority of the traditional ramp tests (Rossiter et al., 2006, Winter, 2006) do not allow an athlete to self-pace or indeed know an endpoint, such tests can never "evaluate athletic potential or understand the biological basis of superior athletic performance." (Noakes, 2008b) p554. Indeed if fatigue is controlled by a complex interaction of metabolic systems it is incongruous that these would be best maximised in a test in which the athletes have so little control.

The point as to whether maximal oxygen uptake is/is not limited by a central nervous system governor has recently been the source of much debate with authors arguing both for and against (Ekblom, 2009b, Noakes and Marino, 2009b, Ekblom, 2009a, Shephard, 2009a, Noakes and Marino, 2009a). Whilst much literature was quoted, both sides of the debate ultimately concluded that they were correct, leaving readers non-the-wiser as to whether maximal oxygen uptake is/is not limited by a central nervous system governor.

In the same way that the nature of the majority of laboratory trials and their relevance to sporting performance has previously been questioned (Saunders et al., 2005), so too must the nature of enforced-pace exercise trials in a field where the majority of current sporting practices rely on a self-paced exercise bout. A complex model of fatigue and its implications on the pacing of a bout of exercise requires exercise physiology to step back and conduct a modern re-evaluation of many of its practices (Noakes, 1997, Tucker and Noakes, 2009)

2.5 Pacing

The proper pacing of a bout of exercise is critical to optimal individual performance, be that in training or an Olympic final. Conversely, improper pacing can easily influence an exercise bout and lead to failure and distress. At the highest level of physical effort, pacing is critical to performance in order to use all available energy stores, but not so soon as to bring on fatigue which might impair performance. To most, pacing would seem an obvious area for scientific examination but up until 1993 the investigation of athletes pacing behaviour during competition received little attention (Foster et al., 1993).

2.5.1 Origins of the study of pacing

Pacing strategy in an athletic event is widely acknowledged to have been first investigated by Foster and colleagues (Foster et al., 1993) however its origins can probably be traced back to as early as 600BC in Aesop's fable about the Hare and the Tortoise (Temple and Temple, 1998). The initial work of Foster et al., investigated changes in velocity during 2km cycling time-trials and proposed five pacing strategies for middle distance events, strategies which still form the basis of research literature today (Aisbett et al., 2009). Using evidence from the 2km trials Foster suggested that athletes pre select a pacing strategy prior to an exercise bout and then commence exercise with a start strategy ranging from an 'all-out' start to 'slow' start, furthermore early works suggested that this strategy then influenced the nature of power output throughout the rest of the bout.

In a recent article, Aisbett et al., (2009) investigated the effects of two of Foster's five pacing strategies on 5min cycle time-trial performance. They concluded that an all-out start (where athletes reached 235% Mean Aerobic Power (MAP) in the first 6s then reduced to an average of 100% MAP for the first minute of the trial) produced superior middle distance cycling performance when compared with a fast start (in which athletes worked at a steady 127% MAP throughout the first minute of the trial). They concluded that the improvement seen in an all-out start may have been brought about by a faster oxygen uptake response rather than the mere reduction in time. In contrast Hettinga et al., (2011) recently found that optimising the pacing strategy of speedskaters by increasing their pace in the early stages of exercise was actually detrimental to the exercise bout and increased performance time. Aisbett and colleagues are not the first researchers to consider pacing of an exercise bout to be about more than just the efficient use of energy stores. In a recently published critical review of the physiological regulation of pacing strategy Tucker and Noakes (2009) reference authors who also regard the rate of heat storage and body temperature as integral to the study of pacing (Marino et al., 2004, Tucker et al., 2004).

2.5.2 Contemporary interest in pacing

The topic of pacing is currently enjoying a rise in popularity, with groups in Australia and South Africa both publishing reviews in the area. Abbiss and Laursen (2008) recently reviewed pacing strategies during athletic competition adding to Foster's five original strategies by describing negative, positive, parabolic, and variable pacing strategies, and also adding to the literature a better definition of pacing strategy as "how an athlete distributes work and energy throughout an exercise task" (Abbiss and Laursen, 2008) p239. They concluded that optimal pacing strategies for bouts of various durations are dictated by an athlete's ability to resist fatigue, which may be affected by one or more factors including energy availability and heat storage. Once again it appears that a sound understanding of the mechanisms of fatigue and pacing are synergistically linked.

Tucker and Noakes (2009) have recently published both a review of pacing and a model of pacing strategy (Tucker, 2009) which incorporates the interrelated factors of fatigue discussed by Abbiss and Laursen (2005). In contrast to Foster, who suggested that pace is decided prior to exercise performance, Tucker (2006c) has argued that it is decided in the first 4min of exercise, and later that pace may be reset or recalculated based on perception of fatigue throughout an exercise duration (Tucker, 2009). The flow diagram in Figure 2.2 attempts to explain the way in which pace may be influenced during exercise by perceptions of fatigue:

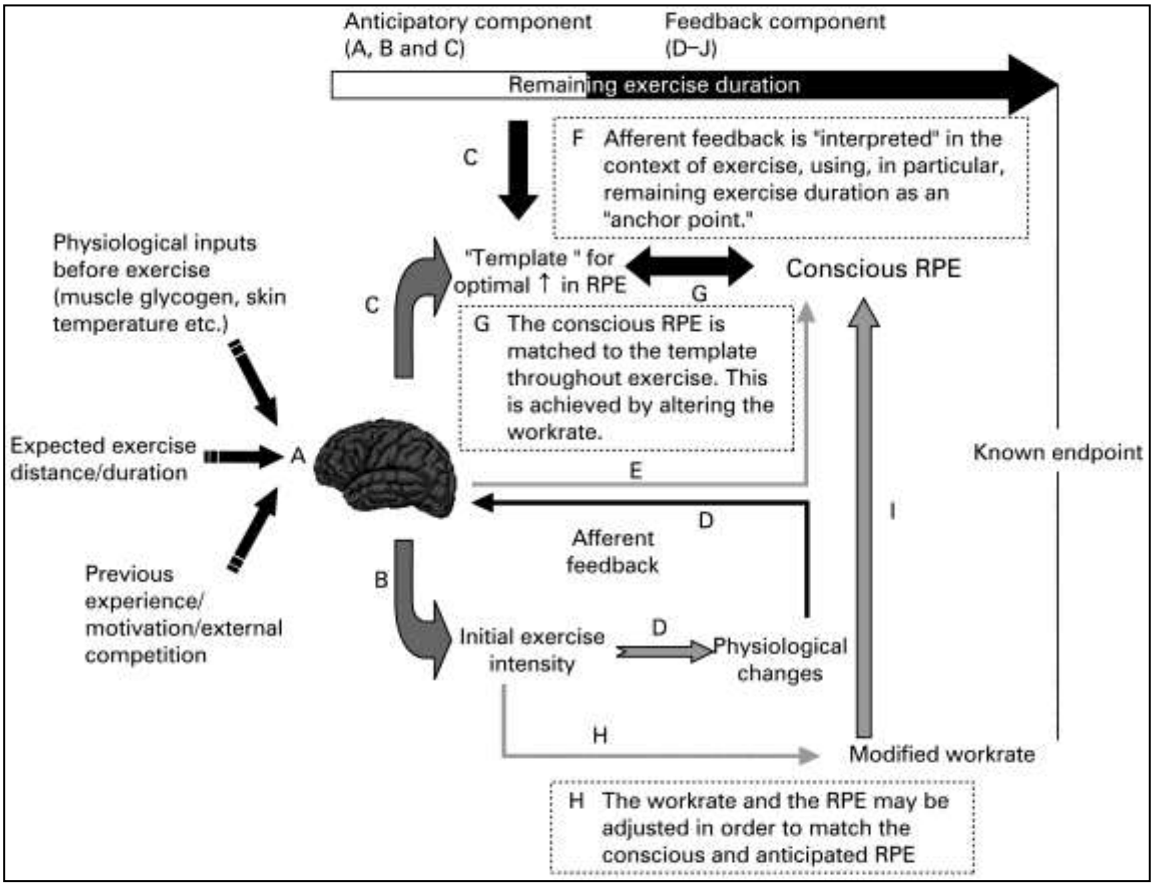


Figure 2.3 Flow diagram showing the proposed model for the anticipatory regulation of exercise performance during self-paced exercise.

Black shading denotes input to the brain, Grey shading denotes output or efferent processes.

Adapted from (Tucker, 2009)

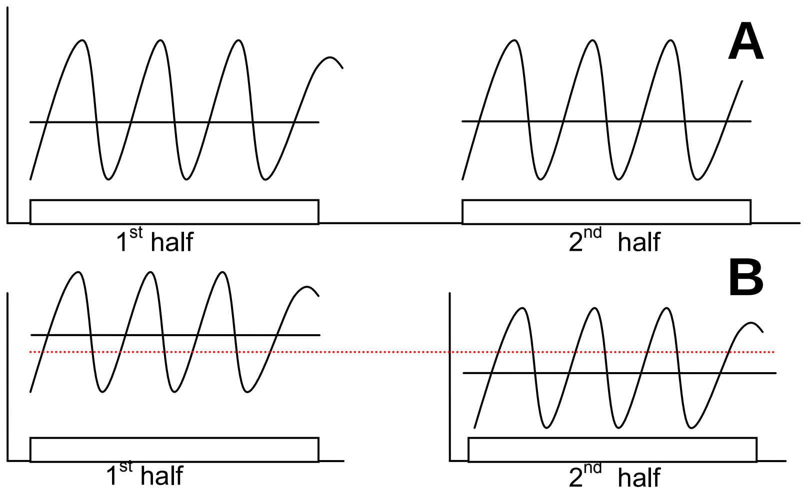
According to Tucker's model, the initial pace of a bout of exercise is influenced by current physiological inputs that may reflect the effect of recent exercise bouts and/or environmental conditions. This current physiological status will be combined with a perception of the expected duration and the previous experience of such a bout to create an overall pacing plan or template for the bout. Once exercise has commenced, this plan can then be adapted during the exercise bout. In this model, initial physiological changes at the onset of exercise are fed back to the brain which matches these against the template and anticipated perception of effort. This information is interpreted, and the work rate is then modified in order to match the template and avoid unacceptable disturbances to homeostasis prior to the known exercise endpoint. Underlying this model is the concept that pacing employs previous experience, a concept which is similar to the early work of Foster et al., (1994). However this model progresses the understanding by attempting to explain the drive to alter performance, through transient perceptions of fatigue. Whilst it is well known that performers alter power output throughout a bout of exercise according to perceptions of fatigue, until recently models through which these changes were brought about were not available. Indeed such models are only accessible if fatigue is considered as a complex interaction of metabolic factors.

Evidence in support of purposeful adaptations of effort during a bout of exercise has been previously presented through the observation of the variations of effort during an exercise bout. McLellan et al., (1995) has demonstrated biological variation to be an important feature in sub-maximal exercise. These authors observed coefficients of variation ranging from 2.8% to 31.4% in time-to-exhaustion in 5 repeated cycle-based time-trials. The study went on to identify that the low variation group exercised at a significantly higher percentage of $\dot{V}O_{2max}$ than that of the high variation group, however the study never looked at variation within each time-trial, and how that might affect the time-trial performance. This separation of biological variation could be considered to represent those who prioritised performance time over effort and therefore exhibited high biological variation by exercising to an enforced pace, in contrast to those who prioritised effort over performance time who may be suggested to have exercise at a self-paced intensity and demonstrated low biological variation.

Data from the Tucker et al, (2006a) identified non-random fluctuations in power output during a 40 km cycle time-trial. Whilst fluctuations in performance have often been observed, this study was one of the first to show demonstrable evidence of patterns which have been proposed to be the behavioural response to disturbance in homeostasis. By recording dynamic power output and applying a mathematical procedure known as Fourier analysis, which looks for waves patterns within data, Tucker et al., were able to identify non-random fluctuations in the power output of cyclists completing the all-out time-trial. These fluctuations may have been previously dismissed as recording noise, however when considered alongside a model of fatigue which incorporates feedback from multiple physiological mechanisms, some variability in a performance response ought to be expected.

In the consideration of a contemporary perspective of pacing, the intra-trial fluctuations of power output seen in self-paced exercise bouts are unlikely to be simply due to random misjudgements of pace. Rather it is probable that these fluctuations of power output are important behavioural responses during exercise at times when homeostasis is challenged (St Clair Gibson et al., 2006, Tucker et al., 2006a).

Building on the supposition that changes in pacing reflect the need for a biological mechanism to avoid a catastrophic failure of systems, Edwards and Noakes (2009) have proposed a model of multi-level pacing plans with specific reference to elite soccer. This model incorporates the concept of a predefined pacing plan, with one in which biological feedback induces performance responses which may increase or decrease effort during a bout of exercise. The macro- and meso-pacing plans proposed by Edwards and Noakes are suggested to allow players to defend set points of homeostatic imbalance, whilst a micro pacing strategy is also employed in order to respond to dynamic changes in a game. Collectively these plans allow players to complete a full match and still avoid the failure of any single physiological mechanism, through a dynamic up and down-regulation of effort, this concept is described graphically in Figure 2.3. Evidence for this proposal is presented in light of the absence of core temperatures sufficiently critical to cause the immediate cessation of exercise, and in response to the failure of numerous previous studies to identify a single metabolic factor linked to the development of fatigue in self-paced exercise (Lambert et al., 2005).



Panel A represents a schematic view of the 'meta' pacing strategy pre-set by each individual player at the commencement of the match. The horizontal line represents exercise-homeostasis (subconscious level of tolerable physical discomfort) the player anticipates experiencing during the game. The oscillations represent the dynamic (micro) pacing strategy to release energy and sustainable effort in relation to the long term objectives. Panel B represents the meso-pacing plans (1st and 2nd halves of the match) with differential levels of subconscious regulatory points between halves of the match. The second half level is subconsciously down-regulated from the first half although the mean of the two (dotted line) broadly equates to the pre-match expectations of the player.

Figure 2.4 Multi-level pacing plan showing the proposed model of macro-, meso- and micro-pacing strategies employed in the first half and second half of a soccer match (Edwards and Noakes, 2009).

In the diagram by Edwards and Noakes it should be noted that both halves end with an increase in effort. This increase has been referred to as an end-spurt and is common in self-paced activities. An end-spurt in self-paced performance was observed by Catalano (1973) who monitored the repetitive tapping of a telegraph key and found that subjects increased their effort at around 90% of task completion. The work of Catalano also identified not only that end-spurts may be scalar to the length of time spent on a task, but also that the increase in effort within the spurt may be proportional to the total decrement in effort (Catalano, 1974a). The presence of an end-spurt or increase in effort has been used to justify the suggestion that time-trial exercise bouts are not truly maximal (Hinckson and Hopkins, 2005a). However the persistent appearance of an increase in effort toward the end of a self-paced exertion (Billaut et al., 2010, Catalano, 1974a, Tucker et al., 2006b) may be better described as confirmation of scalar rather than absolute pacing in maximal trials (St Clair Gibson et al., 2006).

Much of the recent work in pacing studies uses a scale of ratings of perceived exertion in order to quantify perceptions of effort and pacing during an exercise bout. The scale of Rating of Perceived Exertion will therefore now be introduced.

2.6 Use of RPE

2.6.1 Origins of RPE

The rate of perceived exertion scale was conceived by Gunnar Borg in the 1960's and first published in its entirety in 1970 (Borg, 1970). Since then Borg and others have developed additional scales for use with different populations (Grant et al., 2002, Eston et al., 2008, Noble et al., 1983, Borg, 1998), and those scales have themselves been adapted (Eston et al., 2009) in order to meet the needs of investigators requiring a subjective scalar rating.

Perceived exertion is said to reflect the sum of all sensations of physical exertion (Faulkner and Eston, 2007) and is thought to consist of the integrated feedback of physiological and psychological mechanisms, to which Borg assigned a value between 6 and 20. The scale was designed for use with physiological functions such as heart rate and oxygen consumption such that at an RPE of 6 an individual would exhibit a heart rate of approximately 60 b$\cdot$min^{-1}, whilst an RPE of 20 would elicit a heart rate of 200 b$\cdot$min^{-1}. The values are corresponded with a verbal anchor that goes from 'No exertion at all' at 6 to 'Maximal exertion' at an RPE of 20. The verbal anchors were changed slightly in a later edition of Borg's work, (1998) however the 6-20 scale has remained the same and is accepted as a reliable measurement tool by many researchers and organisations including the ACSM (2005).

The summation of all sensations of physical exertion may be seen as both a strength and a weakness of a scale of perceived exertion. Whilst a rating of perceived exertion may provide researchers with a quantitative score to indicate how hard participants perceive they are working, recent research has suggested that this uni-dimensional value fails to take into consideration emotional and cognitive factors (Micklewright and St Clair Gibson, 2010) which may influence participant's ratings of perceived exertion, creating a difference between perceived exertion, and the experience of exercise. To-date the RPE scale remains an accepted reliable and valid measurement tool in the assessment of psychobiological aspects of exertion, in the absence of a suitable multi-dimensional scale of fatigue the use of ratings of perceived exertion to quantify participant's perception of effort remains an appropriate measurement tool, albeit to be used with caution.

2.6.2 Use of RPE in different exercise environments

Borg and Ohlsson demonstrated test-retest reliability of the RPE scale with runners completing an 800m track run on 3 occasions. Heart rate correlations across the three trials varied from r=0.64 to 0.89, the highest correlation was seen between trials 2 and 3, with the lowest between trials 1 and 3. This pattern was repeated in the reliability of RPE scores which varied from r=0.69 to 0.87, suggesting that RPE was as good a measurement tool as heart rate for repeated trials of exercise intensity (Borg and Ohlsson, 1975). The use of the RPE scale has since been validated in a number of exercise modes including cycling (Skinner et al., 1973), walking and running (Robertson, 1982), swimming (Ueda and Kurokawa, 1995), stepping (Walker et al., 1996) and rowing (Marriott and Lamb, 1996).

An interesting study by Kang and colleagues (2003) used a Rating of Perceived Exertion scale to compare exercise at 50% of $\dot{V}O_{2max}$ and 70% of $\dot{V}O_{2max}$ using alternative exercise modes. In a multiple crossover design participants completed a graded exercise test on a treadmill (TM) and on a cycle (C) giving RPE indications after every minute (estimation phase). On subsequent visits subjects were asked to perform 20min of exercise at 50% or 70% $\dot{V}O_{2max}$ of their cycle or treadmill score on either a treadmill or cycle ergometer (production phase). This design allowed researchers to test the efficacy of assessing performance based on an alternative mode of exercise to the original measurement. Moreover, it allowed researchers to compare the effect of exercising to a rate of perceived exertion across different exercise modes. The authors found no differences in the estimation and production of both HR and $\dot{V}O_2$ when compared across similar exercise modes (TM/TM and C/C) demonstrating that rates of perceived exertion can be confidently used to produce exercise of up to 20min at both 50% and 70% of $\dot{V}O_{2max}$ in exercise of a similar modality. However, when using the TM estimation target in the C production trial the researchers found that $\dot{V}O_2$ was consistently lower at both 50% and 70% of $\dot{V}O_{2max}$. This was supported by a consistently higher $\dot{V}O_2$ in the TM production trial which used the C estimation target. Perhaps the most pertinent finding from this work was that, when the individual scores were adjusted to represent % of a max value there was a notable trend to suggest that when estimation trial scores are taken from a different exercise modality scores using for similar ratings of perceived exertion appear at least comparable.

Table 2.1 Physiological measures estimated and reproduced during intra-modal exercise at 50% and 70% $\dot{V}O_{2max}$.

Conditions		Mode specific % $\dot{V}O_{2max}$			
	est/prod	5min	10min	15min	20min
50% $\dot{V}O_{2max}$	TM/C	50	50	51	52
	C/TM	53	53	54	55
70% $\dot{V}O_{2max}$	TM/C	65	66	68	69
	C/TM	72	73	72	74
	Mode specific % HR_{max}				
50% $\dot{V}O_{2max}$	TM/C	70	71	71	73
	C/TM	68	70	69	71
70% $\dot{V}O_{2max}$	TM/C	80	81	84	85
	C/TM	83	83	86	87

(Adapted from Kang et al., 2003) est, estimation trial; prod, production trial; TM, treadmill; C, cycle.

In a remarkably similar study to that of Kang et al., (2003), Dunbar and colleagues (1992), some years earlier demonstrated similar findings when attempting to reproduce RPE scores using cycle and treadmill ergometry, with the notable exception that Dunbar et al., identified a significant reduction on the $\dot{V}O_2$ and heart rate responses in the production trial of the treadmill-treadmill exercise at 70% $\dot{V}O_{2max}$, which was not observed in any other comparison.

In response to this unanticipated observation Dunbar et al., acknowledged flaws in their matching of modality between estimation and production trials. In the estimation trial, the use of the Bruce protocol had involved athletes working on a treadmill at gradients which precipitated the participant to walk, however in the production trial a fixed gradient of 0% was used and participants where asked to produce the estimated RPE's by increasing treadmill speed. This study raises questions regarding the reliability of exercise regulation based on perceived exertion, however it could be argued that these questions are due to methodological inconsistencies rather than inconsistencies of exercise with the RPE scale. The Dunbar study did demonstrate participants' abilities to accurately reproduce performances in cycle-to-cycle, in cycle-to-treadmill, and in treadmill-to-cycle trials, thus it may be that the ability to accurately reproduce the quality and consistency of a perceived exertion may be much easier for a participant in a more stable physical environment such as cycling or alternatively rowing.

2.6.3 Reproducibility of RPE

In rowing, RPE was shown by Marriott and Lamb (1996) to be a valid measure of physiological strain and, especially at higher levels, a way of regulating the intensity of rowing ergometry. In this study nine competitive male rowers were recruited to participate in a study involving an estimation trial and a production trial. In the estimation trial subjects were asked to complete a discontinuous incremental exercise test increasing exertion by 40W per 3min stage, within which $\dot{V}O_2$, HR, and RPE were recorded. Stages were separated by a 15s recovery, after which subjects were asked to continue the incremental process until reaching a voluntary maximum. On a different day subjects were asked to produce the appropriate wattage to match RPE scores of 15, 11, 17, 13, and 19 respectively, over a similar 3min stage.
Marriott and Lamb found that subjects were able to reproduce similar heart rates in the estimation and production trials at RPE's of 15, 17 and 19 demonstrating a correlation coefficient across the 2 trials of r=0.95, much higher than that previously seen during a similar cycling ergometry experiment (Skinner et al., 1973). The differences in power output between the estimation and production trials were not as close as those of heart rate, but this is perhaps a reflection of the irregular order in which the exercise intensities were requested in the production trial, rather than the rower's ability to associate power outputs with RPE. Despite this, there were no significant differences between estimation and production at RPE 17 and an r value of 0.87 still demonstrated a significant correlation between RPE and power output in the production trial. A fundamental flaw in this study, which impacts on the interpretation of the power output data, comes from a difference in the data recording strategies employed in the trials. In each trial a 3min stage was used in order to allow for a steady state heart rate to be achieved. Heart rate was only recorded in the last 15s of each 3min stage. Power output, however, was reported as mean power output across the 3min stage, meaning it would be less likely to have demonstrated a steady state during the data collection phase and thus is therefore likely to include much more variability in the recorded scores.

In a later study on the reliability of ratings of perceived exertion in a treadmill based exercise test, Lamb and colleagues used limits of agreement to assess the reliability of RPE (Lamb et al., 1999). This study demonstrated that strong limits of agreement (LoA) at lower levels of exertion had the potential to mask lower levels of agreement in the latter stages of a maximal exercise. Using a 4 stage incremental exercise test Lamb et al., maintained treadmill spread but increased incline with every stage whilst recording RPE and heart rate. This protocol demonstrated LoA's of 0.88-2.02 RPE units in stage 1 (mean RPE 10.05), which increased to -0.13-2.94 RPE units in stage 4 (mean RPE 15.45) suggesting that lower intensities would demonstrate better agreement than at the higher end of their range of intensities. Trends in LoA were mirrored by corresponding changes in intra-class correlation coefficients and Pearson product moment correlations such that r values of 0.81 were found in stage 1 which reduced to 0.60 in stage 4. The most notable finding from this study was that, in contrast with the 1996 paper, this study found the reliability of RPE to have a converse relationship with exercise intensity, albeit over a much smaller range of intensities (RPE 10.05-15.45), and using a different exercise modality.

In a study involving thirty Physical Education students Garcin et al., (2003) showed that RPE can demonstrate a test-retest coefficient of 0.94-1.0 during incremental exercise tests on a running track over exercise intensities from RPE 7.5-18.8. The investigation consisted of an incremental exercise to determine maximal aerobic velocity (MAV) followed by either 1) an identical incremental exercise test, 2) a run to exhaustion at 90% MAV, or 3) a run to exhaustion at 100% MAV. Time-to-exhaustion was ≈10mins at 90% MAV and ≈6min at 100% MAV. Similar test-retest scores were observed for RPE and heart rate in all three conditions concluding that HR and RPE scales are reliable during both constant load and progressive exercise tests until exhaustion.

The concept of RPE has recently been challenged due to its, influence from both emotional and cognitive aspects of individuals' focus (Micklewright and St Clair Gibson, 2010), however in the absence of a suitable reliable alternative, RPE scales may be considered a reliable method of quantifying exertion, as previously shown in a number of exercise media, including rowing ergometry. The particular use of this mode of exertion will now be discussed.

2.7 Use of rowing ergometry

2.7.1 Equivalent mode of exercise

In the field of pacing and fatigue much of the previous sports science laboratory work has been conducted using treadmills or cycle ergometry. These ergometers recreate movements familiar to most athletes and thereby allow participants to exercise in a relatively static environment whilst researchers move around them collecting measures and adjusting variables. Although recreating a very different movement to that of cycling, rowing ergometers have been found to replicate relatively similar maximal exercise performance results (Wiener et al., 1995), and in the absence of equivalent data, rowing ergometer test scores are often compared with similar measures taken in running and riding studies (Cosgrove et al., 1999, Celik et al., 2005). The rarity of data on rowing is surprising given its role as one of the most physically demanding endurance type sports (Hagerman, 1984, Marriott and Lamb, 1996).

A notable disadvantage of using treadmills (and to a lesser extent, cycle ergometry) in pacing research, is that in order to change the pace of an exercise bout, a participant must first perceive a need to change that pace, then initiate a conscious effort in order to speed up or slow down, be that by signalling, or by pushing a button to speed up or slow down the ergometer or by changing cadence or gear on a cycle ergometer. In any of these scenarios the participant has to respond to the pace as prescribed by the apparatus rather than them being able initiate changes in pace to which the ergometer then responds. This relationship is less prescriptive when using a rowing ergometer, in which participants are able to initiate change in not only the pace of the work done, by increasing strokes per minute, but also through the quantity force utilised in each stroke as measured by the power output. The efficiency of movement in rowing when compared with cycling has been investigated by authors interested in oxygen uptake kinetics, who have described a small but significantly higher work rate and higher power per stroke in rowing when compared to matched cycling ergometer exercise (Ingham et al., 2007). Furthermore the $\dot{V}O_2$ kinetics of rowing exercise have been found to be similar to that of cycling exercise at the same moderate and heavy intensities in subjects who are not specifically trained for either mode of exercise (Roberts et al., 2005). Perhaps the best endorsement for the use of this exercise modality in the investigation of pacing has been presented by Marriot and Lamb (1996) who noted that:

> "Power outputs cannot be fixed by the experimenter, as with a treadmill, but are subject controlled" p 268.

As such the rowing ergometer presents a mode of exercise that has parity with that of running and cycling studies but which also allows the participant to initiate, not respond, to changes in pace.

The most common race distance in rowing is 2000m however this equates to only 6.5min of exercise (Ingham et al., 2002, Kennedy and Bell, 2003) and in order to match the 20min or more of performance times seen in similar pacing cycling studies, a distance of 5000m may be considered more appropriate. This distance is used in the 'Head of the River' races which are often conducted at the start of the season.

2.7.2 Physiology of indoor rowing

On-water rowing is clearly different from that of rowing an ergometer. Weather, balance, and co-ordination with other participants are not aspects that ordinarily affect performance on an ergometer, and it is for these reasons that the ergometers are commonly used in the training and testing of rowers (Maestu et al., 2005, Kramer et al., 1994). Whilst the comparison of ergometer scores with on-water performances may be controversial (Macfarlane et al., 1997), studies such as those of Lamb (1989) have concluded that despite some differences in the arm motion, the leg and the trunk kinematic variables are similar across the on-water and off-water conditions. Data from authors such as Craven et al., (1993) has also demonstrated that ergometer use can allow accurate measurements of the physiological changes produced by work done in each ergometer stroke. Thus the physiological responses of indoor and on-water rowing are often used interchangeably to describe the physiological profiles of rowers (Mahony et al., 1999).

The rowing movement pattern has been estimated to use between 43% and 70% of muscle mass (Secher, 1993, Steinacker, 1993) and the activation of almost every major muscle group in the body (Panjkota and Music, 2005). Steinacker (1993) estimated that, of the skeletal muscle engaged in rowing, approximately 70% is of a slow twitch structure, although this can vary across rowing abilities. Given the endurance nature of the sport it's unsurprising that $\dot{V}O_{2max}$ can be used as a strong predictor of sporting performance (Secher, 1993, Steinacker, 1993), however because the sport is non-weight-bearing the relative $\dot{V}O_{2max}$ is lower than that seen in other sports. Prior to specified training, Kennedy and Bell (2003) reported that club rowers were capable of 2000m in 458.1 $\pm$ 30.7s and exhibited baseline $\dot{V}O_{2max}$ scores of 46.1 $\pm$ 7.1 $ml{\cdot}kg^{-1}min^{-1}$ (3.6 $\pm$ 0.5 $l{\cdot}min^{-1}$) and Max HR of 191.6 $\pm$ 8.8 $b.min^{-1}$. In another study (Ingham et al., 2007) similar participants were capable of 2000m in 394s with $\dot{V}O_{2peak}$ scores of 55.6 $\pm$ 1.2 $ml{\cdot}kg^{-1}min^{-1}$ (4.9 $\pm$ 0.1 $l{\cdot}min^{-1}$), HR peak 193 $\pm$ 2 $b{\cdot}min^{-1}$ and 314.5 $\pm$ 7.7 Watts at $\dot{V}O_{2peak}$ further details of physiological responses to 2000m time-trials can be found in Table 2.2. Whilst these maximal values may appear low in comparison to other sports, previous authors have identified that $\dot{V}O_{2max}$ can be reduced by between 10-29% in rowing exercise, dependent on protocol, when compared with equivalent treadmill $\dot{V}O_{2max}$ scores (Jensen and Katch, 1991, Bassett et al., 1984).

Table 2.2 Physiological measures and 2000m time-trial performance recorded during incremental exercise of club-level rowers.

$\dot{V}O_{2peak}$ ($l \cdot min^{-1}$)	4.9 ± 0.1
W$\dot{V}O_{2peak}$ (W)	314.5 ± 7.7
HRpeak ($b \cdot min^{-1}$)	193 ± 2
WLT (W)	224 ± 6
W4mM (W)	272 ± 9
LT% $\dot{V}O_{2peak}$	78.1 ± 1.9
BLa peak (mM)	8.1 ± 0.3
2000m ($m \cdot s^{-1}$)	5.07 ± 0.12

W$\dot{V}O_{2peak}$; wattage at $\dot{V}O_{2peak}$, WLT; wattage at lactate threshold, W4mM; wattage at 4 mmol blood lactate, LT% $\dot{V}O_{2peak}$; percentage of $\dot{V}O_{2peak}$ at with lactate threshold occurred.(Adapted from Ingham et al., 2007).

For a more detailed description of the physiology of rowers, interested readers are directed toward the work of Shephard (1998), Secher (1983) and Steinacker (1993).

The popularity of indoor rowing ergometers with both rowers and exercise enthusiasts has led to the development of indoor rowing as a sport in its own right (Kennedy and Bell, 2003) with races being described as early as 1980, and a World Indoor Rowing Championship held every year in Boston Massachusetts hosted by Concept 2 ergometers, manufacturers of the most popular brand of rowing ergometer.

2.7.3 Reliability of Concept 2 ergometers

Patent was applied for the Model A Concept 2 ergometer in 1981 (Dreissigacker et al., 1981, Bernstein et al., 2002) . Since then the brand has gone on to be the most widely used wind resistance braked ergometer (Cosgrove et al., 1999), and the most popular ergometer found in UK rowing clubs (Nowicky et al., 2005). A notable competitor to the Concept 2 brand is the Rowperfect ergometer which was used by Bernstein et al., (2002) in an attempt to compare the use of fixed head and floating head ergometers in order to investigate the potential of fixed head ergometers to contribute to the increased injury rates seen in rowers completing land based training (Budgett and Fuller, 1989). The fixed head machine (a similar design to the Concept 2) was found to create a greater mean force per stroke and longer stroke than the floating head machine, however this alone was insufficient to conclude whether the different design was likely to influence the injury rate of its users. The supposition that the Concept 2 design may cause more injuries than the Rowperfect ergometer was also refuted by a study from Nowicky (2005), which used sEMG data to compare the hip and trunk muscle activity on Rowperfect and Concept systems. The investigators found no differences between the sEMG responses from the two systems. Thus muscle activation when using the Concept 2 ergometer is no different from that of its major competitor, furthermore the Concept 2 ergometer is capable of producing a greater mean force per stroke.

The Concept 2 brand is (to-date) currently selling its 4th generation of rowing ergometer, the Model D, whilst the previously mentioned studies have described comparisons across brands, the question of the reliability of model generations has been the subject of only one study (Vogler et al., 2007). These authors found no significant difference in the responses of power output, oxygen consumption, rowing economy, heart rate, blood lactate concentration, stroke rate and rating of perceived exertion following the maximal and sub-maximal testing of national level rowers on two generations of ergometer. The lactate threshold at LT_1, (the intensity at which BLa began to increase above resting levels) was found to be significantly higher in the newer model, however the practical significance of a difference of 0.2 $mmol \cdot L^{-1}$ is doubted by the authors, and deemed to more of a representation of real world effects on the measurements than a potential difference in the two ergometer models.

Performance on the Concept 2 ergometer has been described as inherently stable and repeatable, with a test-retest co-efficient of r=0.96 (0.87-0.99) when assessing trained rowers over 2000m (Schabort et al., 1999). When comparing this reliability with data collected from other cycling and running, Schabort calculated coefficients of variation of approximating 1.8-2.0% (Hickey et al., 1992) to 3.0% (Jeukendrup et al., 1996) in cycling time-trials and 2.7% in their own running trials (Schabort et al., 1998). The authors concluded that tests on the Concept 2 were more reliable than those in 60min cycling and running exercise trials, and at least as good as any cycle exercise trials of comparable length on a Kingcycle, or trials on a Cybex MET100. The reliability of this data is supported by Soper and Hume (2004) who observed an intra-class correlation coefficient of 0.99 (0.95-1.0) in performance time following a test-retest evaluation of 15 national rowers performance over 2000m. When the trial length was shortened to 500m, the reliability of the performance time reduced to 0.93 (0.8-0.0.98), although the reliability of the power output remained strong (0.99-1.0). Whilst the reliability of performance time was clearly better the greater the trial time, the authors also cited the previously described data from Schabort (1999) which suggested that a 7min rowing bout may be more reliable than a 60min cycling bout due to its ecological validity and relevance to that of a normal competitive sporting event.

Table 2.3 Mean performance time and power output and reliability of measures during 500m and 2000m rowing ergometer races.

	Performance Time (min:s)	Power Output (W)
500m Mean	1:34 ± 0:01	418.1 ± 7.4
Change in mean	-0.2% (-2.0-1.6)	0.8% (-1.0-2.7)
%SEM	1.0 (0.8-1.1)	2.8% (2.3-3.4)
icc	0.93 (0.80-0.98)	0.99 (0.99-1.0)
2000m Mean	6:58 ± 0:05	312.4 ± 0.5
Change in mean	0.03% (-0.6-1.2)	0.02% (-1.9-1.5)
%SEM	0.7 (0.4-1.5)	1.3 (0.8-2.9)
icc	0.99 (0.95-1.0)	0.99 (0.98-1.0)

Percent standard errors of the mean (%SEMs) intra-class correlation coefficients (icc) and ranges in parentheses. (Adapted from Soper and Hume, 2004).

In summary, the use of the Concept 2 ergometer in exercise bouts equivalent to normal race distances with sufficient familiarisation appears a valid and reliable methodology with which to study the effects of an appropriate variable on the physiological responses to exercise. Such a protocol has a previously identified high reliability (Schabort et al., 1999) and has parity with tests of a similar intensity on cycle ergometers (Wiener et al., 1995). Moreover, the mode of rowing may be a better medium than that of cycling or running with which to study pacing as power outputs cannot be fixed by the experimenter, but are participant controlled (Marriott and Lamb, 1996).

2.8 Design of studies involving pacing

2.8.1 Time-to-exhaustion protocols

It is commonplace, in experiments of exercise physiology, for the changes in a variable to be measured whilst a subject works toward an unknown endpoint of exhaustion. Sporting parallels to such physical challenges are rare, or at least undesired. Yet in order to be sure an athlete has 'maximised' their performance, exercise to exhaustion, or more properly termed volitional fatigue, has become a popular model of investigation. The use of time-to-exhaustion tests has been previously questioned by authors due to the nature of their test re-test reliability (Jeukendrup et al., 1996, Jeukendrup and Currell, 2005). Hinckson and Hopkins (2005a, 2005b) have asserted the opinion that the measurement of performance in time-to-exhaustion trials and subsequent conversion to percent change in performance in time-trials (using their suggested method of conversion) is better than the measurement of change in performance in time-trials alone because of the previously observed spurt in performance toward the end of a time-trial which suggests to them that the subject could have tried harder throughout the trial.

In the field of pacing however, it is very difficult to argue that an exercise test which aims to report changes in pace on the way toward an unknown endpoint of volitional fatigue adds a great deal to the scientific understanding of exercise. Indeed despite recommending an alternative measure Hinckson and Hopkins have acknowledged the benefits of time-trial experiments in the study of pacing (Hinckson and Hopkins, 2005b).

2.8.2 Time-trial protocols

Producing a successful individual pacing strategy is an inherent part of real life performance and should therefore be an inherent part of any performance test (Atkinson and Nevill, 2005, Jeukendrup and Currell, 2005). Time-trial experiments are now commonplace in the study of pacing (Mauger et al., 2009, Townshend et al., 2010, Mauger et al., 2010b, Hettinga et al., 2006a). The work of Tucker et al., (2006a) identified non-random fluctuations in power output during a self-paced time-trial and proposed that these non-random fluctuations may be part of a signalling mechanism through which the body regulates effort. As described earlier there is a suggestion that perceived exertion, which is said to reflect the sum of all sensations of physical exertion (Faulkner and Eston, 2007), may be part of a complex model that can up- and down-regulate effort in order to avoid fatigue (Tucker, 2009). These factors cannot be observed in time-to-exhaustion experiments, nor are they observable in exercise bouts of an external fixed intensity or constant load. Thus in studies involving pacing, and particularly the dynamic changes in physiological variables, the use of time-trial designs is much more valid than that of time-to-exhaustion.

Given the current parity between developments in the understanding of pace and complex models of fatigue the time seems right for a re-evaluation of the concepts of pacing and fatigue which considers a complex interaction of metabolic markers throughout exercise tests relevant to current sporting practices.

Chapter Three

General Methodologies

Chapter Three

General Methodologies

The nature of the studies described in this thesis required the use of similar equipment, calibration, and protocols. Each Chapter will incorporate a separate section on study methodologies, however in order to avoid repetition the following Chapter describes the procedures used in data collection which were similar in nature in each of the following studies.

3.1 Ethic approval

Ethical approval for all studies was received from the local ethics committee, the Central Regional Ethics Committee of New Zealand, from the employing institution Research Sub-committee, at UCOL Institute of Technology and from the Faculty Research Ethics Committee at Leeds Metropolitan University.
Further details of ethical approval may be found in Appendix 1.0.

3.2 Participant recruitment

All participants were recruited from the UCOL Institute of Technology student population. In all studies healthy, well-trained male participants were recruited, were informed of the procedures in advance, and agreed to take part in each study by providing specific informed consent prior to any data collection. In each study participants were recreational gymnasium users accustomed to using rowing ergometers, but novice rowers. Novice rowers were recruited in order to avoid the influence of experience or preconceptions on any study requirements. All participants were asked to maintain their habitual exercise routines during the course of the study but refrain from any additional organised physical activity. All exercise trials (within each study) were held at the same time of the day to avoid diurnal variations in body temperature, and were each separated by approximately one week. All participants consumed a beverage of water 2 hours before the start of each test (5 $ml \cdot kg^{-1} \cdot$body mass) to ensure comparable euhydration between participants and trials (Montain and Coyle, 1992).
Examples of the information provided to participants may be found in Appendix 2.0.

3.3 Familiarisation for studies

All participants were screened prior to participation in the studies; this involved an introduction to the equipment and investigators, followed by written and verbal explanation of the protocols. Participants were then asked to complete a pre-test questionnaire which included the measurement of stature and body mass. During a two-week familiarisation period participants took part in a familiarisation process which introduced participants to the use of ratings of perceived exertion and the replication of effort in accordance with RPE anchors. On each visit participants completed a four stage incremental exercise protocol whilst stroke-to-stroke power output was instantaneously monitored. The familiarisation process was facilitated by a qualified rowing coach who provided participants with technical advice on the use of the rowing ergometer and culminated in the participants' ability to successfully replicate a four stage incremental exercise protocol. The initial stage required participants to work for 4min at RPE 11 (Light), each subsequent stage increased in intensity and decreased in time (3min: RPE 13 (Moderate), 2min: RPE 15 (Hard), 1min: RPE 19 (Very Very Hard)). Any participants who did not pass the pre-test questionnaire or that could not demonstrate consistent technique in using the rowing ergometer were excluded from the study for safety reasons.
Examples of the information provided to participants and the pre-test questionnaires utilised may be found in Appendix 2.0.

3.4 Equipment

3.4.1 Oxygen uptake, heart rate and power output measurement

Oxygen uptake ($\dot{V}O_2$) was continuously recorded breath-by-breath via a commercially available portable metabolic test system ($\dot{V}O_2$) (Cortex MetaMax 3B, Cortex Biophysik, Leipzig, Germany). The system was calibrated before, and verified after each test with standard calibration gases (15% O_2 5% CO_2 balance N_2). Volume expired was measured by a volume measuring turbine which was calibrated with a 3L syringe (Hans Rudolph, Kansas City, MO, USA).

Whole blood capillary samples (BLa) were drawn from the finger tip prior to exercise and at the immediate cessation of exercise performances for the analysis of blood lactate concentration (Lactate Pro, Akray Inc, Kyoto, Japan). Heart rates (HR) were continuously recorded (S610i, Polar, Kempele, Finland) throughout all exercise tests.

Stroke-to-stroke power output (PO) from the Concept 2 rowing ergometer (Model D: Concept 2, Tauranga, New Zealand) was assessed using the RowPro v2.006 software (Digital Rowing, Boston, MA, USA) in conjunction with the Concept 2 interface.

After each trial, power output was exported to Microsoft Excel v11 (Microsoft, Redmond, WA, USA) for further analysis.

In all conditions the air resistance of the ergometer flywheel was standardised by using the damper lever to apply a pre-determined drag factor (130 10^{-6} $N \cdot m \cdot s^{2}$) (Smith, 2000, Dudhia, 2008).

3.4.2 Measurement of thermoregulatory factors

These methods were used in studies one and three only.
Core temperature (T_c) was measured via telemetry from the intestine using a silicon-coated thermometer pill (CorTemp2000, HQ, Palmetto, Florida, USA) which was swallowed by all participants 5-8 h before exercise to ensure that it would be beyond the stomach and insensible to swallowed hot or cold liquids (Sparling et al., 1993). A four-stage temperature calibration of the pills against a certified mercury thermometer in a water bath at temperatures ranging from 34°C to 40°C was conducted prior to pill ingestion. In accordance with earlier work, a linear regression equation was then used to adjust pill measurements (Edwards and Clark, 2006).

Skin temperatures (T_{sk}) were measured at four sites using stainless steel surface skin thermistors (Grant Logistics, Cambridge, UK). Temperatures were recorded continuously throughout trials using a data logger (SQ400 Squirrel Data logger, Grant Logistics, Cambridge UK). Mean body skin temperature was calculated using the formula previously described by Ramanathan (1964) and others (Marsh and Sleivert, 1999, Mitchell and Wyndham, 1969). The Ramanathan formula is derived from four sites identified as areas over active muscles, on relatively exposed surfaces, and in important portions of the body that can influence temperature changes in the skin (Bicep, Chest, Thigh, Calf) (Ramanathan, 1964). Using this calculation the areas of measurement are divided in terms of whole limbs, appropriate surface area weightings are then applied to provide researchers with a valid measure of mean skin temperature for comparison with other thermal physiological variables.
Measurements were taken of T_c and T_{sk} continuously throughout the trials in order to assess dynamic responses within each exercise bout.

3.4.3 Measurement of surface electromyography (sEMG)

These methods were used in studies one and three only.

Surface electrodes (Medi-Trace 230 Foam Electrode, Kendall Healthcare, Mansfield, MA, USA) were placed 20mm apart on the belly of the bicep brachii and vastus lateralis muscles and a reference electrode was placed on the lateral aspect of the styloid process of the radius (Basmajian and De Luca, 1985, De Luca, 2002). Bicep brachii and vastus lateralis were chosen as representatives of upper and lower body muscle activation and have been previously used in rowing exercise by other investigators (Maestu et al., 2005, Panjkota and Music, 2005).

The skin surface was cleaned and shaved prior to electrode application in order to avoid interference and to increase adhesion; all electrodes were additionally fastened with medical adhesive tape. As rowing involves bilateral activation of the muscles (Nowicky et al., 2005) recordings were only taken from one side of the body (right). Scores were not standardised against a standard isometric maximal voluntary contraction (MVC) as the dynamic nature of the movement pattern involved in rowing has been previously shown to elicit higher peak muscle sEMG in rowing than in the manoeuvre used to produce isolated maximal voluntary contractions (Burden et al., 2003, Nowicky et al., 2005). In addition, the plane of movement in rowing is difficult to replicate in MVC conditions, and pilot study evaluations did not support the use of such a technique.

sEMG was recorded during the final 100m of each 1000m period using the Power Lab data acquisition system (Power Lab AD Instruments, NSW, Australia). Raw scores were digitally filtered (Band pass filter; 20Hz to 480Hz), digitised (1kHz sampling rate) and stored (Chart 5 v5.5.5, AD Instruments, NSW, Australia). Each stroke was visually identified and quantified using the root mean square (rms) method and the mean of three strokes at the end of each 1000m interval was then batched for the purposes of statistical comparisons across trials. Processing the EMG signal using the root-mean-squared method provides a measure of the power of an sEMG signal which demonstrates a clear physical meaning, something other methods such as average rectified value or integrated rectified signal cannot do. As such the rms measure is preferred for most sEMG applications (De Luca, 2002) and has been previously used in rowing studies (Nowicky et al., 2005).

Manufacturers specifications of the equipment used in this thesis may be found in Appendix 3.0.

3.5 Reliability of measures

3.5.1 Use of RPE

The 15 point Borg scale for rating perceived exertion (6-20) was used in warm up and main trials as a measure of exercise intensity in each of the following studies.
Since its proposal, concern has been raised over the reliability of subjective ratings of perceived exertion. In response to these Borg and Ohlsson demonstrated test-retest reliability of the RPE scale with runners completing an 800m track run on 3 occasions, heart rate correlation across the three trials varied from 0.64 to 0.89, the highest correlation was seen between trials 2 and 3, with the lowest between trials 1 and 3. This pattern was repeated in the reliability of RPE scores which varied from 0.69 to 0.87, suggesting that RPE was as good, if not a better, measurement tool for repeated trials of exercise intensity (Borg and Ohlsson, 1975). Later studies from other laboratories have confirmed the early work by Borg. Indeed a study by Garcin et al., (2003) showed that RPE can demonstrate a test-retest correlation coefficient of 0.94-1.0 during incremental exercise tests on a running track, indicating that, if anything, Borg's early calculations of the reliability of RPE underestimated the strength of the reliability. In support of this Marriot and Lamb (1996) have previously demonstrated the reliability of the use of RPE in rowing ergometry finding that the 15 point RPE scale can be used to prescribe exercise intensities with a test-retest correlation coefficient of 0.95 at RPE's of 15 and greater.
As such the use of RPE in warm up and main trials has been previously demonstrated as reliable across different exercise mediums including that of rowing ergometry.

3.5.2 Use of ergometer

The Concept 2 ergometer is the most widely used wind-resistance braked ergometer (Cosgrove et al., 1999) and the most popular ergometer found in UK rowing clubs (Nowicky et al., 2005). Performance on the Concept 2 ergometer has been described as inherently stable and repeatable, with a test-retest coefficient of 0.96 (95% confidence limits of 0.87-0.99) when assessing trained rowers over 2000m (Schabort et al., 1999). Whilst the same model of ergometer was used in all studies it is worthy of note that the model-to-model testing of Concept 2 ergometers has previously demonstrated no significant differences in the responses of power output, oxygen consumption, heart rate, blood lactate concentration, and rating of perceived exertion following the maximal and sub-maximal testing of national level rowers on two generations of ergometer (Vogler et al., 2007).

3.6 Calibration of equipment

3.6.1 Calibration of expired air measurements

The Cortex Metamax 3B has been previously described a reliable instrument for exercise testing in sports and medical research (Meyer et al., 2001). Prior to each exercise trial the Cortex Metamax portable online gas analysis system was calibrated using Cortex Metasoft software version 3.9.7(Cortex Biophysik, Leipzig, Germany). Following activation, the Cortex Metamax required a period of approximately 5min to ‘warm up’ and perform a series of self checks after which the system could be calibrated. At the start of each calibration barometric pressure was measured using a calibrated handheld device (Greisinger 2300, Regenstauf, Germany) an offset value was then transferred to the Metamax. The digital volume transducer was then calibrated using a 3L syringe (Hans Rudolph, Kansas City, MO, USA) which required a total of 5 inspirations and 5 expirations. Gain factors for 1.0 $\pm$ 0.1 were considered acceptable and once complete these values were transferred to the Metamax. Gas fractions were calibrated first using ambient air and then repeated using a certified mixture of 15% O_2 and 5% CO_2 balance N_2 (BOC Gases, Auckland New Zealand), these values were then also transferred to the Metamax. Prior to recording data the Metamax required a further sample of ambient air and was then ready to commence data collection. This calibration procedure was completed in approximately 30min, prior to every trial and verified after every trial.

3.6.2 Calibration of power output measurements

Prior to each warm up the drag factor on the rowing ergometer was measured. Drag factor is a measure of the how quickly the flywheel decelerates based on the volume of air which passes through the flywheel housing and can be influenced by changes in air pressure, temperature, and humidity. Consequently, the ergometer was calibrated to a drag factor of 130 10^{-6} $N{\cdot}m{\cdot}s^2$ prior to any data recording. A drag factor of 130 10^{-6} $N{\cdot}m{\cdot}s^2$ is recommended by Concept 2 (Fletcher, 2010) and Smith (2000) in order to best represent the feel of a boat on the water and to ensure consistency of the ergometer resistance. Drag factor can be measured by selecting *More Options* from the main menu of the ergometer’s performance monitor then selecting *Display Drag Factor.* It is then adjusted by moving the lever on the fan to create the appropriate amount of air flow and thus resistance. This calibration procedure ensured that participants were working against the same resistance regardless of changes in air pressure or humidity. This calibration process took approximately 5min to complete and was conducted prior to every trial.

3.6.3 Calibration of core temperature measurements

Calibration of core temperature thermometer pills is conducted by the manufacturers (HQ Inc, Palmetto, Florida, USA) prior to their distribution and each sensor pill is supplied with an identification number and a calibration code. Previous authors have identified variance in these calibrations (Sparling et al., 1993, Kolka et al., 1993) and the use of linear regression equations in order to calibrate individual pill scores with certified mercury thermometers is now considered essential (Challis and Kolb, 2010, Byrne and Lim, 2007). Therefore, prior to distribution to each participant, each sensor pill was calibrated against a certified mercury thermometer using 4 water baths at temperatures ranging from 34˚C to 40˚C. A linear regression equation was then used to calculate a correction factor for each individual core temperature sensor. Following calibration, sensor pills were distributed to the participants for ingestion 5-8 hours prior to the trial, in order to ensure the pill had passed the stomach where it might be sensitive to the temperature of any fluid consumption, and to avoid the potential of voiding the sensor prior to the trial (Edwards and Clark, 2006, Goodman et al., 2009, Lee et al., 2000). The calibration procedure for this measure was approximately 10min per sensor pill and conducted on each pill prior to their distribution to participants.

3.6.4 Calibration of blood lactate measurements

The Lactate Pro portable analyser (Lactate Pro, Akray Inc, Kyoto, Japan) has been previously shown to be a reliable and valid measurement tool for use in the assessment of blood lactate in normal, hot, and humid environments (Mc Naughton et al., 2002, Pyne et al., 2000). The calibration of the Lactate Pro involved the insertion of a (yellow) Check Strip which provided a reading of between 2.1-2.8 $mmol \cdot L^{-1}$ followed by the insertion of a 2nd (green) Calibration Strip which used a calibration curve appropriate to the test strips (Shimojo et al., 1993). The Lactate Pro required 5 microlitres of blood and can provide a blood lactate measure of between 0.8 and 23.3 $mmol \cdot L^{-1}$. All blood samples were taken from finger prick incisions of the right hand (Accu-Chek Softclix, Roche Diagnostics, Auckland, New Zealand). The same Lactate Pro analyser was used throughout the study and was calibrated prior to every trial.

Blood Lactate measurements were taken prior to warm up and immediately post exercise. Blood lactate concentration has previously been shown to rise to a peak concentration 4-6 min post a maximal exercise test lasting a mean of 487$\pm$58s (Gass et al., 1981), however following longer duration exercise bouts, blood lactate sampling post-exercise has been suggested to reflect the type of activity immediately preceding sample, thus delays in sampling could lead to a reduction in reported values (Bangsbo et al., 1991). Blood lacate sampling with the Lactate Pro analyser has been reliably demonstrated with swimmers, cyclists and rowers (Pyne et al., 2000, Beneke et al., 2001) and recommended in protocols by Sport and Exercise New Zealand (Sleivert, 2003, Smith, 2000)

3.7 Data analysis

Where possible outcome measures were recorded at least every 30s in order to observe dynamic changes in variables. When appropriate, data were transformed into 30s measures in order to reduce data noise and create comparable measurement intervals; these measures were then time-aligned and batched in 30s means for statistical comparison.

Graphical representations in Chapter 4 express data per unit of time, whilst Chapters 5, 6 and 7 express data as a percentage trial in order to better represent physiological and performance responses of participants without the impact of differences in time to completion.

Examples of the manual recording sheets utilised may be found in Appendix 4.0.

3.8 Statistical analysis

The statistical software packages SPSS (version 11.0-17.0, SPSS, Chicago, IL, USA) and GraphPad Prism (version 4, GraphPad Software Inc, La Jolla, CA, USA) were used for statistical analysis. Parametric results were statistically compared using tests as appropriate, most commonly one-way repeated measures analyses of variance (ANOVA) with post-hoc Tukey tests. Other comparisons were made using Student's *t*-tests. Non-parametric data were assessed using Friedman's analysis of variance and Mann-Whitney U tests. Reliability measures were assessed using Pearson product moment correlations, Intra-class correlation coefficients, 95% Limits of agreement and Coefficients of variation as appropriate. Probability values of less than 0.05 were considered significant. All results are expressed in means ± SD.

Chapter Four

Comparison of self-paced and enforced-pace exercise at a matched-intensity.

Chapter Four

Comparison of self-paced and enforced-pace exercise at a matched-intensity.

4.0 Abstract

The purpose of this study was to compare the physiological responses to a 5000m rowing exercise bout in which the participants were either 1) able to voluntarily fluctuate power output (self-paced; SP) whilst exercising at a fixed rate of perceived exertion, or 2) were required to maintain a matched-intensity (externally-paced EXT) constant power output. Nine male participants (age; 29 ± 6 years, $\dot{V}O_{2peak}$; 52 ± 3 ml·kg^{-1}·min^{-1}) performed four exercise trials ($\dot{V}O_{2peak}$, 5000m rowing at RPE 15 (SubRPE), at an enforced matched-intensity constant power output (SubEXT), and to disguise the importance of the sub-maximal trials, 5000m as a maximal time-trial (MaxTT). In the SubEXT trial participants were deceived to believe that the enforced intensity was based on ventilatory threshold in order to avoid participants matching pace to their previous SubRPE trial. Environmental temperature was standardised across all trials (18˚C, 35-45% humidity). Performance time, mean $\dot{V}O_2$ and power output were not significantly different in the sub-maximal trials (PT: SubRPE; 1300 ± 78s, vs. SubEXT; 1298 ± 67s. $\dot{V}O_2$; 37 ± 5ml·kg^{-1}·min^{-1}, vs. 36 ± 6ml·kg^{-1}·min^{-1}. PO: 162 ± 7W vs. 161 ± 27W; $p>0.05$). However; mean core temperature, post-test blood lactate, and muscular activity in vastus lateralis and bicep brachii were all significantly higher in SubEXT when compared to SubRPE ($p<0.05$-0.01). The variability in power output during SubRPE was significantly higher than SubEXT suggesting that the ability to fluctuate power during the self-paced exercise brought about a reduction in the physiological demand of an otherwise similar exertion. Dynamic analysis of self-paced exercise has previously identified non-random fluctuations in power output (Tucker et al., 2006a). It is likely that these fluctuations represent an important physiological mechanism used during exercise to defend homeostasis in accordance with transient sensations of fatigue.

4.1 Introduction

The ability to accurately self-pace an exercise bout is an important feature of race and time-trial performances (Abbiss and Laursen, 2008, Foster et al., 1994, St Clair Gibson and Noakes, 2004). Self-paced exercise bouts are known to demonstrate considerable intra-trial fluctuations of power output (Tucker et al., 2006a), and it is unlikely that this is simply due to random misjudgements of pace. It is probable that these fluctuations of power output are important behavioural responses during exercise at times when homeostasis is challenged (St Clair Gibson et al., 2006). However, the importance of this observation requires researchers to consider the brain as a (central) feature of pacing and the development of fatigue.

Until recently (St Clair Gibson et al., 2001b, St Clair Gibson et al., 2001a, Noakes et al., 2005), it had commonly been viewed that exercise of maximal intensity progressively induced a decrease in force production towards a terminal endpoint of fatigue at which the immediate cessation of exercise was a necessary consequence (e.g. Hulleman et al., 2007). This theory has often been used to attribute fatigue to impaired peripheral muscle contractile function, through either excessive accumulation of metabolic acidosis or the depletion of intramuscular fuels (Kirkendall, 1990). However, such peripheral fatigue cannot easily explain all observations during endurance exercise (Lambert et al., 2005), in particular those where performance improves in the end stages of a self-paced exercise bout (Catalano, 1973, Catalano, 1974b, Catalano, 1974a).

Contemporary research studies have suggested that, in contrast, discreet alterations in pace are mediated through central neural control, by which muscle recruitment is manipulated as part of a regulatory process to maintain a reserve of motor units and thus avoid catastrophic fatigue (St Clair Gibson et al., 2001b, St Clair Gibson et al., 2001a, Noakes et al., 2005). According to this model of central complex metabolic control, the regulation of exercise intensity (power output) is a behavioural response to both feedback information from peripheral receptors and feedforward (anticipatory) mechanisms which regulate exercise intensity to avoid the development of bodily harm (Lambert et al., 2005, St Clair Gibson and Noakes, 2004). Consequently, fluctuations in power output during exercise may be an important feature of a regulatory process, based on information from various peripheral systems (e.g. muscle, respiratory, metabolic receptors) within a complex metabolic control system.

Previous work has shown biological variation to be an important feature in sub-maximal exercise (McLellan et al., 1995). However relatively few studies have thoroughly examined both the dynamic physiological and thermoregulatory responses to exercise in relation to the concept of pacing (Abbiss and Laursen, 2008, Foster et al., 1994, Tucker et al., 2006a). With the development of fast-response technologies it is now feasible to examine the concept of pacing in more dynamic experimental conditions than was previously practical. For example, it is possible that thermoregulatory factors such as core and skin temperatures are dynamically related to the perception of effort during exercise through which alterations in pacing are linked to temperature regulation and/or muscle recruitment patterns. Nevertheless, there currently remains a lack of empirical data in which dynamic responses have been evaluated.

This investigation proposes that the inter-relationship between conscious perceptions of effort (RPE) and subconscious metabolic control (mediating muscle recruitment) will result in physiologically meaningful non-random fluctuations of power output (Tucker et al., 2006a) in self-paced exercise, while enforced-pace matched-intensity exercise will result in adverse physiological responses.

In the field of pacing and fatigue much of the previous sport science laboratory work has been conducted using treadmills or cycle ergometry. Although producing a very different movement to that of cycling, rowing ergometers have been found to replicate relatively similar maximal exercise performance results (Wiener et al., 1995), and often in the absence of equivalent data, rowing test scores are often compared with similar measures taken in running and riding studies (Cosgrove et al., 1999, Celik et al., 2005). Because the power output developed by each rowing stroke during a bout can be easily influenced by dynamic sensations of fatigue, it is therefore highly sensitive to fluctuations in power and pacing during an exercise bout.

4.2 Purpose of the study

The purpose of this study was to compare physiological responses to a 5000m rowing exercise bout at a matched-intensity in which the participants were either able to voluntarily fluctuate power output (self-paced) while performing exercise at a fixed rating of perceived exertion (RPE), or were required to maintain a matched-intensity (enforced) constant power output.

4.3 Aims of the study

To compare physiological responses in self-paced exercise and enforced-pace matched-intensity exercise over 5000m of rowing exercise.

To investigate the inter-relationship between conscious ratings of effort (RPE) and power output in self-paced and enforced-pace matched-intensity exercise over 5000m of rowing exercise.

To investigate the physiologically meaningful non-random fluctuations of power output in self-paced exercise and enforced-pace matched-intensity exercise.

4.4 Methodology

4.4.1 Participants

Nine healthy, well-trained male participants agreed to take part in this study (Table 4.1). All were informed of the procedures in advance and informed consent was provided prior to any data collection. The study was approved by the Central Regional Ethics Committee of New Zealand and the Faculty Research Ethics Committee at Leeds Metropolitan University. All participants were recreational gymnasium users and each received technical advice from a qualified rowing coach on using the rowing ergometer during a two-week familiarisation period.

Table 4.1 Anthropometric and cardiovascular characteristics of study participants.

	Participant Characteristics				
	Height (m)	Weight (kg)	Age (years)	$\dot{V}O_{2peak}$ ($ml\cdot kg^{-1}\cdot min^{-1}$)	HR at $\dot{V}O_{2peak}$ ($b\cdot min^{-1}$)
Mean ± SD	1.77 ± 0.06	77.10 ± 8.11	29 ± 6	52 ± 3	185 ± 8

4.4.2 Participant Screening and Familiarisation

Participant screening and Familiarisation followed the pattern described in Chapter 3 General Methods.

In brief: All participants were screened prior to participating in the study, this involved an introduction to the equipment followed by written and verbal explanation of the protocols. Participants were asked to complete a pre-test questionnaire and asked to participate in a familiarisation process consisting of a four stage incremental protocol. In each familiarisation session participants received technical advice from a qualified rowing coach on the use of the rowing ergometer. Any participants that did not pass the pre-test questionnaire or that could not demonstrate consistent technique in using the rowing ergometer were excluded from the study.

4.4.3 Preliminary testing

At the beginning of the study all participants performed a standardised familiarisation trial which consisted of a four stage incremental protocol which was subsequently used as a standardised priming exercise in each of the trials and is described in detail in Chapter 3 General Methods.

In all conditions the air resistance of the ergometer flywheel was standardised by using the damper lever to apply a pre-determined drag factor (130 10^{-6} $N \cdot m \cdot s^2$) (Smith, 2000, Dudhia, 2008).

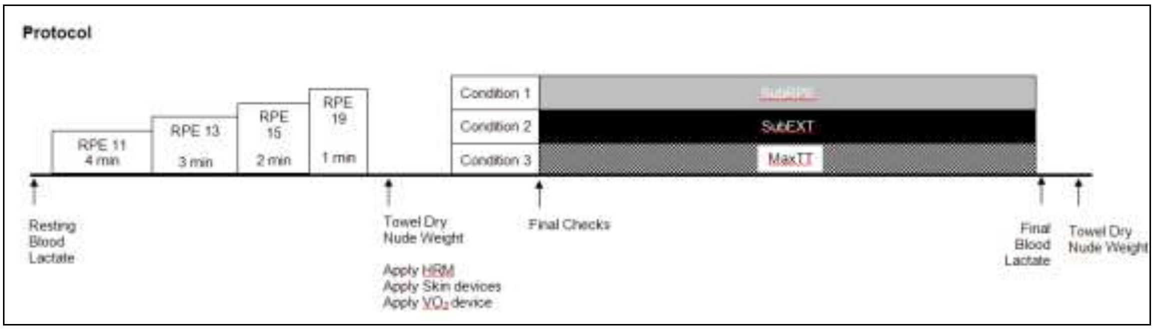
On a separate and subsequent occasion all participants performed an incremental exercise test to volitional exhaustion on a Concept 2 rowing ergometer (Model D: Concept 2, Tauranga, NZ) for the determination of peak aerobic power ($\dot{V}O_{2peak}$). Oxygen uptake (Cortex MetaMax 3B, Cortex Biophysik, Leipzig, Germany) and power output (RowPro v2.006 software. Digital Rowing, Boston, MA, USA) were continuously monitored stroke-to-stroke. Power output was visible via the Concept 2 display unit at all times. Initial exercise intensity was set at 150 Watts for 3min then increased by 25 Watts each subsequent minute until volition exhaustion, or an inability to maintain the required power output was reached. This protocol has previously described by Smith (2000) and is used in assessments by Rowing New Zealand.

4.4.4 Experimental procedures

Each participant completed three 5000m rowing trials in three different experimental conditions in an individualised order. Condition one (SubRPE) required the participants to complete 5000m at an enforced constant rating of perceived exertion (RPE: 15 – Hard). Condition two (SubEXT) required the participants to perform 5000m at an enforced constant power output equivalent to the mean power output attained in the SubRPE condition. No visual feedback was provided in the SubRPE condition to ensure participants self-paced, whilst only stroke-to-stroke power output was visible during the SubEXT condition and participants received continual verbal reinforcement to ensure the required power output was attained. A further experimental condition (MaxTT) was included to disguise the importance of the two sub-maximal conditions and to compare intensity of efforts, whilst also facilitating an element of randomisation in the test sequence. In the MaxTT condition, participants were instructed to perform 5000m as fast as possible whilst stroke-to-stroke power output was visible at all times. A diagrammatic representation of the protocol may be found in Figure 4.1.

In the SubEXT condition, participants were deceived to believe that the required exercise intensity was based on an enforced power output equivalent to that of ventilatory threshold attained in the baseline $\dot{V}O_{2max}$ test. This deception was conducted in an attempt to avoid participants realising that the two sub-maximal efforts in the three test series were matched for mean intensity and thus pacing the SubEXT trial on their previous SubRPE efforts.

The exercise trials were held at the same time of the day on each of the three occasions to avoid diurnal variations in body temperature, and were each separated by approximately one week. The participants were instructed to refrain from additional organised physical activity during the testing period and to maintain habitual exercise routines. The laboratory temperature was standardised at 18˚C across all tests while relative humidity remained consistent (35-45%). All participants consumed a beverage of water 2 hours before the start of the test (5 $ml \cdot kg^{-1}$ body mass) to ensure comparable euhydration between participants and trials (Montain and Coyle, 1992).



Condition 1; SubRPE, 5000m at RPE 15, self-paced, stroke-to-stroke PO unknown. Condition 2; SubEXT, 5000m at RPE 15 work matched to C1, enforced-pace, stroke-to-stroke PO known. Condition 3; MaxTT, 5000m at Maximal effort, stroke-to-stroke PO known.

Figure 4.1 Diagrammatic representation of the warm-up and protocol in three experimental conditions.

4.4.5 Oxygen uptake, heart rate and power output measurement

Oxygen uptake, heart rate and power output measurements followed the pattern described in Chapter 3 General Methods.

In brief: Oxygen uptake was continuously recorded breath-by-breath ($\dot{V}O_2$) (Cortex MetaMax 3B, Cortex Biophysik, Leipzig, Germany). Whole blood capillary samples (BLa) were drawn from the finger tip prior to exercise and at the immediate cessation of time-trial performances for the analysis of blood lactate concentration (Lactate Pro, Akray Inc, Kyoto, Japan). Heart rates (HR) were continuously recorded (S610i, Polar, Kempele, Finland). Stroke-to-stroke power output (PO) was assessed using the RowPro v2.006 software (Digital Rowing, Boston, MA, USA) in conjunction with the Concept 2 interface.

4.4.6 Measurement of thermoregulatory factors

Thermoregulatory measurements followed the pattern described in Chapter 3 General Methods.

In brief: Core temperature (T_c) was measured via telemetry from the intestine using a silicon-coated thermometer pill (CorTemp2000, HQ, Palmetto, Florida, USA) which was swallowed by all participants 5-8 hours before exercise. Skin temperatures (T_{sk}) were measured at four sites using stainless steel surface skin thermistors (Grant Logistics, Cambridge, UK). Temperatures were recorded continuously throughout the trial using a data logger (SQ400 Squirrel Data logger, Grant Logistics, Cambridge UK). Mean body skin temperature was calculated using the formula previously described by

Ramanathan (1964) and others (Marsh and Sleivert, 1999, Mitchell and Wyndham, 1969).

4.4.7 Measurement of surface EMG

Surface EMG (sEMG) measurements followed the pattern described in Chapter 3 General Methods.

In brief: Surface electrodes (Medi-Trace 230 Foam Electrode, Kendall Healthcare, Mansfield, MA, USA) were placed 20mm apart on the belly of the bicep brachii and vastus lateralis muscles and a reference electrode was placed on the lateral aspect of the styloid process of the radius (Basmajian and De Luca, 1985, De Luca, 2002). Measurements were taken from the right side of the body only and maxim voluntary contraction measures were not taken as previous research (Nowicky et al., 2005) and pilot study evaluations did not support its use. sEMG from vastus lateralis (VL) and bicep brachii (BB) was recorded during the final 100m of each 1000m period using the Power Lab data acquisition system (Power Lab AD Instruments, NSW, Australia). Raw scores were digitally filtered (Band pass filter; 20Hz to 480Hz), digitised (1kHz sampling rate) and stored (Chart 5 v5.5.5, AD Instruments, NSW, Australia). Each stroke was visually identified and quantified using the root mean square (rms) method and the mean of three strokes at the end of each 1000m interval across the three trials was then batched for the purposes of statistical comparisons.

Figure 4.2 Physical representation of the experimental environment.

4.4.8 Calibration procedures

Calibration procedures followed the pattern described in Chapter 3 General Methods an additional brief description of these processes is provided.

4.4.9 Expired Air Measurements

Prior to each exercise trial the Cortex Metamax on-line gas analysis system was calibrated using Cortex Metasoft software version 3.9.7(Cortex Biophysik, Leipzig, Germany). Gas fractions were calibrated using room air and then repeated using a certified mixture of 15% O_2 and 5% CO_2 stored with a N_2 balance (BOC Gases, Auckland New Zealand). The digital volume transducer was then calibrated a 3L syringe (Hans Rudolph, Kansas City, MO, USA) and these values were then transferred to the Metamax.

4.4.10 Power output Measurements

Prior to each warm up the drag factor on the rowing ergometer (Concept 2, Tauranga, New Zealand) was measured and calibrated to a drag factor of 130 10^{-6} $N{\cdot}m{\cdot}s^2$. (Dudhia, 2008, Smith, 2000).

4.4.11 Core Temperature Measurements

In addition to the calibration of thermometer pills conducted by the manufacturers (HQ Inc, Palmetto, Florida, USA), prior to their distribution to each participant each sensor pill was also calibrated against a certified mercury thermometer using 4 water baths at temperatures ranging from 34˚C to 40˚C. Participants were instructed to ingest the pills no more than 8 and no less than 5 hours prior to the trial to avoid the risk of excretion or the influence of swallowed fluids on pill temperature.

4.4.12 Blood Lactate Measurements

The calibration of the Lactate Pro portable analyser (Lactate Pro, Akray Inc, Kyoto, Japan) involved the insertion of a (yellow) Check Strip followed by the insertion of a 2nd (green) Calibration Strip which used a calibration curve appropriate to the test strips (Shimojo et al., 1993). All blood samples were taken from finger prick incisions of the right hand (Accu-Chek Softclix, Roche Diagnostics, Auckland, New Zealand). The same Lactate Pro analyser was used throughout the study and was calibrated prior to every trial.

4.4.13 Data analysis

Dynamic variations attributable to pacing were assessed by the measurement of oxygen uptake, heart rate and power output which were recorded individually and transformed into 30s measures in order to reduce data noise and create comparable measurement intervals; these measures were then time-aligned and batched in 30s means for statistical comparison.

A simple and effective means of determining time domain variability is to calculate the standard deviation (SD) of each data point (i.e. each 30s time-aligned interval) as a series. Since variance is mathematically equal to the total power of spectral analysis, the SD of the data series reflects all the cyclic components responsible for variability in the period of recording, in this case the time-trial. This method of analysis is frequently used in the study of heart rate variability (Achten and Jeukendrup, 2003, Aubert et al., 2003). The standard deviation of the standard deviation of each data series was therefore used to provide an overall comparative measure of dynamic time-trial variability (ttv) between test conditions using the following outcome measurements: Oxygen uptake ($\dot{V}O_{2ttv}$), Heart rate (HR_{ttv}) and Power output (PO_{ttv}).

4.4.14 Statistical analysis

The statistical software package SPSS (version 11.0, SPSS, Chicago, IL, USA) was used for all statistical analysis. Parametric results were statistically compared using one-way repeated measures analyses of variance (ANOVA) and post-hoc Tukey tests of Honest Significant Differences as appropriate. Other comparisons were made using paired Student's *t*-tests. Probability values of less than 0.05 were considered significant. All results are expressed in means ± SD.

4.5 Results

The fastest mean 5000m performance time was observed in the MaxTT condition and this was shorter in duration than both SubRPE ($p<0.01$) and SubEXT ($p<0.01$) (Table 4.2). There was no difference in the performance times of the two sub-maximal matched-intensity trials (SubRPE and SubEXT). Mean performance characteristics of $\dot{V}O_2$, HR, and power output were not different between both sub-maximal conditions but these were all significantly elevated in MaxTT (Tables 2 & 3).

Table 4.2 Mean responses of performance time and power output in three experimental conditions.

	Performance outcome measurements		
	Performance Time	Power Output	
	(s)	(W)	(ttv)
SubRPE	1300.11 ± 77.53 ‡	162 ± 27 ‡	18 ± 4 † ‡
SubEXT	1298.67 ± 71.59 ‡	161 ± 27 ‡	12 ± 4 * ‡
MaxTT	1219.33 ± 53.92 * †	194 ± 27	30 ± 14 * †

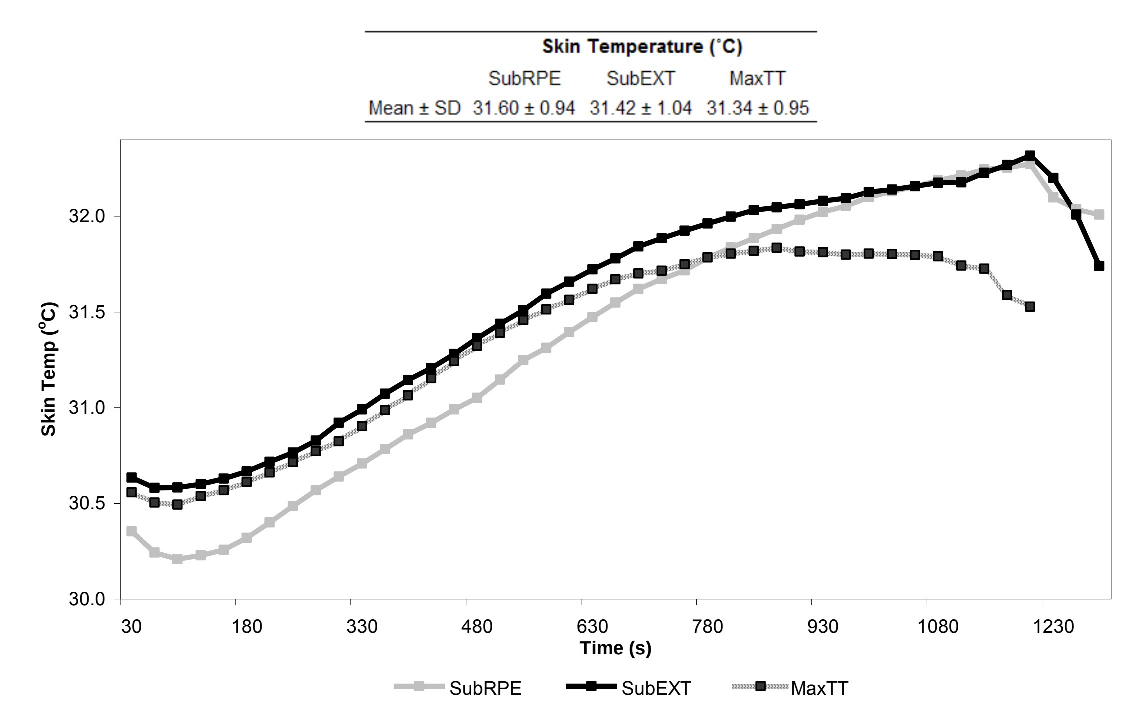
Significantly different from; SubRPE $p < 0.01$ * ; SubEXT $p < 0.01$ † ; MaxTT $p < 0.01$ ‡.

Table 4.3 Mean responses of oxygen uptake and heart rate in three experimental conditions.

	Physiological (oxygen uptake and heart rate) responses			
	Oxygen Uptake		Heart Rate	
	($ml \cdot kg^{-1} \cdot min^{-1}$)	(ttv)	($b \cdot min^{-1}$)	(ttv)
SubRPE	37 ± 5 ‡	5 ± 1 ‡	156 ± 15 ‡	11 ± 1
SubEXT	36 ± 6 ‡	4 ± 1	153 ± 17 ‡	13 ± 2
MaxTT	43 ± 4	5 ± 1 *	172 ± 12	12 ± 2

Significantly different from; SubRPE $p < 0.01$ * ; SubEXT $p < 0.01$ † ; MaxTT $p < 0.01$ ‡.

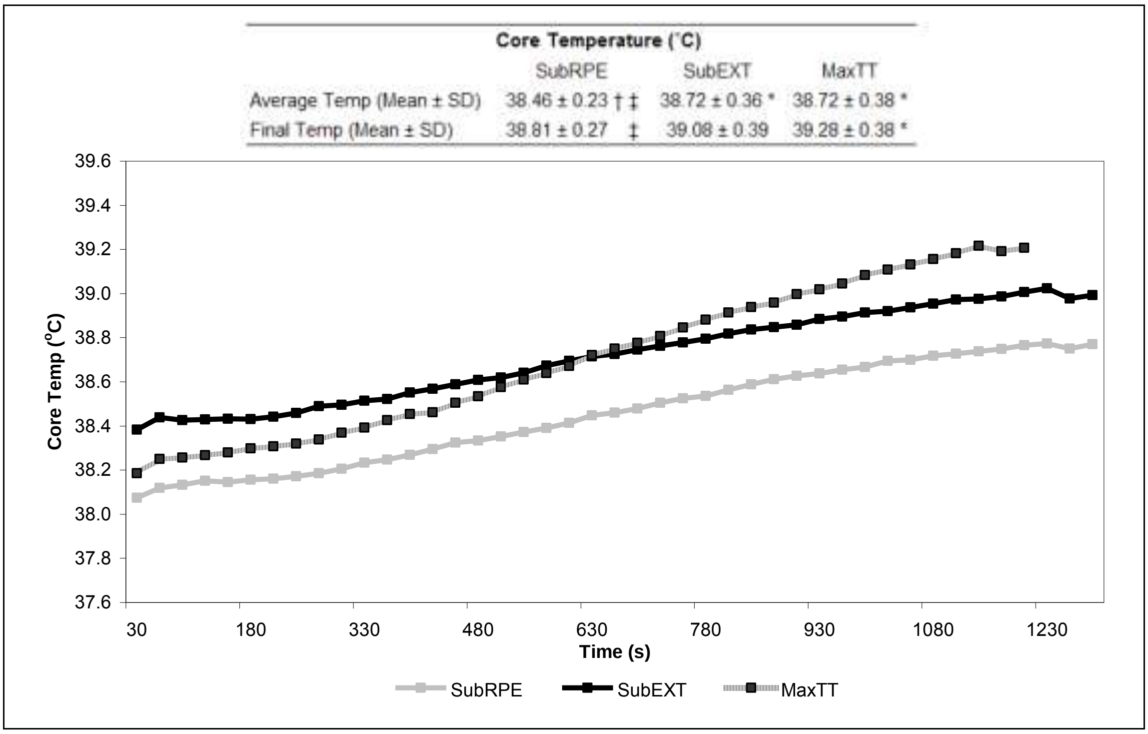
There were no differences in mean or time-trial variability responses of oxygen uptake or heart rate between the sub-maximal conditions (Table 4.3). However, the dynamics of power output (PO_{ttv}) across the time-trials showed significantly greater variability in SubRPE compared with SubEXT ($p<0.01$) (Table 4.2). The variability of power output was further elevated in MaxTT condition compared with both the sub-maximal trials ($p<0.01$) (Table 4.2).



No significant differences observed.

Figure 4.3 Mean and dynamic responses of skin temperature in three experimental conditions expressed as a function of time.

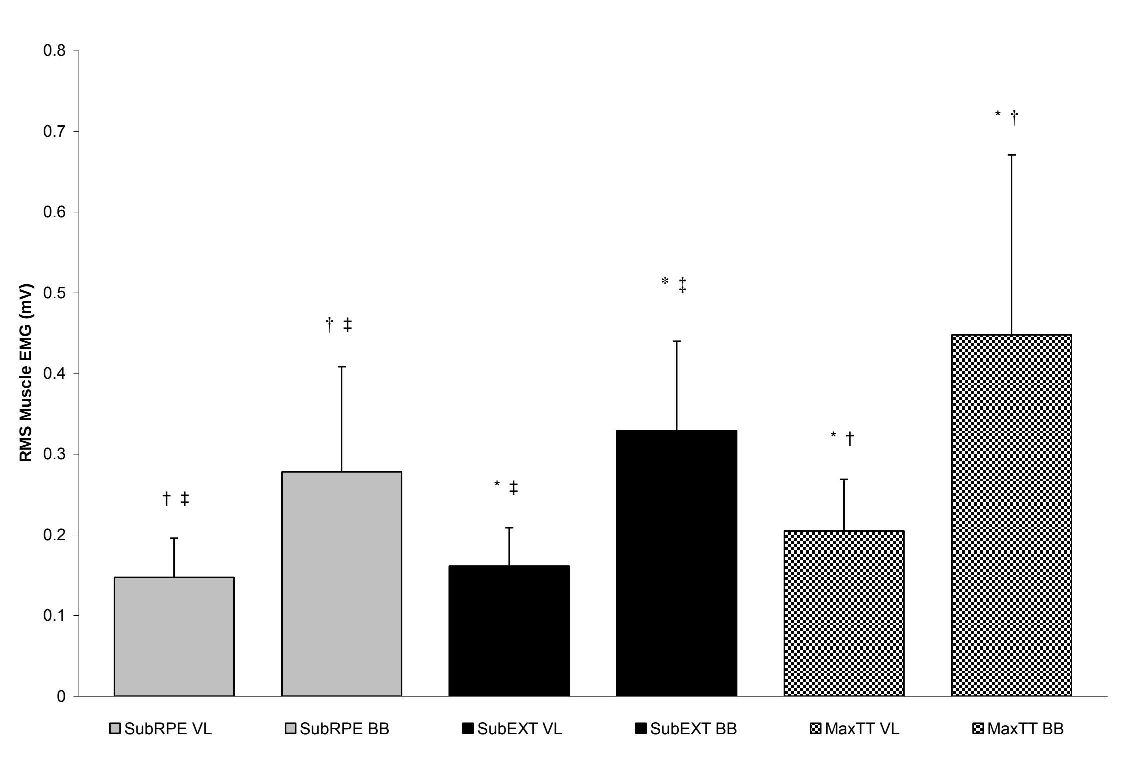
Mean skin temperature was similar across all three (sub-maximal and maximal) conditions (Figure 4.3). Whilst mean core temperature was significantly lower in SubRPE than in both SubEXT ($p<0.05$) and MaxTT ($p<0.01$). Dynamic T_c responses seen in Figure 4.3 demonstrate similar patterns of increase in SubRPE and SubEXT with a greater rate of increase in T_c in the MaxTT condition. Core temperature in the 3 conditions were similar at the start of exercise ($p>0.05$). There was no difference in mean T_c between either SubEXT or MaxTT (Figure 4.4).



Significantly different from; SubRPE $p< 0.01$ * ; SubEXT $p< 0.01$ † ; MaxTT $p< 0.01$ ‡..
No significant differences observed between conditions at the start of the trial.

Figure 4.4 Mean and dynamic responses of core temperature in three experimental conditions expressed as a function of time.

Blood Lactate concentrations taken immediately post-exercise were significantly elevated in SubEXT (6.2 ± 2.5 mmol·L^{-1}) compared with SubRPE (5.2 ± 2.2 mmol·L^{-1}) ($p<0.05$). Both sub-maximal blood lactate responses were significantly lower when compared to the maximal trial (10.9 ± 2.4 mmol·L^{-1}) ($p<0.01$).



Significantly different from; SubRPE p< 0.05 * ; SubEXT p< 0.05 † ; MaxTT p< 0.05 ‡
; SubRPE p< 0.01 * ; SubEXT p< 0.01 † ; MaxTT p< 0.01 ‡

Figure 4.5 Mean responses of sEMG muscle activity at vastus lateralis (VL) and bicep brachii (BB) in three experimental conditions.

Muscle activity recorded at the bicep brachii and vastus lateralis muscles was sampled at the end of each 1000m. Mean sEMG activity measured at both sites was greater at each 1000m interval in SubEXT when compared with SubRPE (p<0.05). The mean sEMG activity of MaxTT was significantly higher than both the sub-maximal conditions at each 1000m measurement (Figure 4.5).

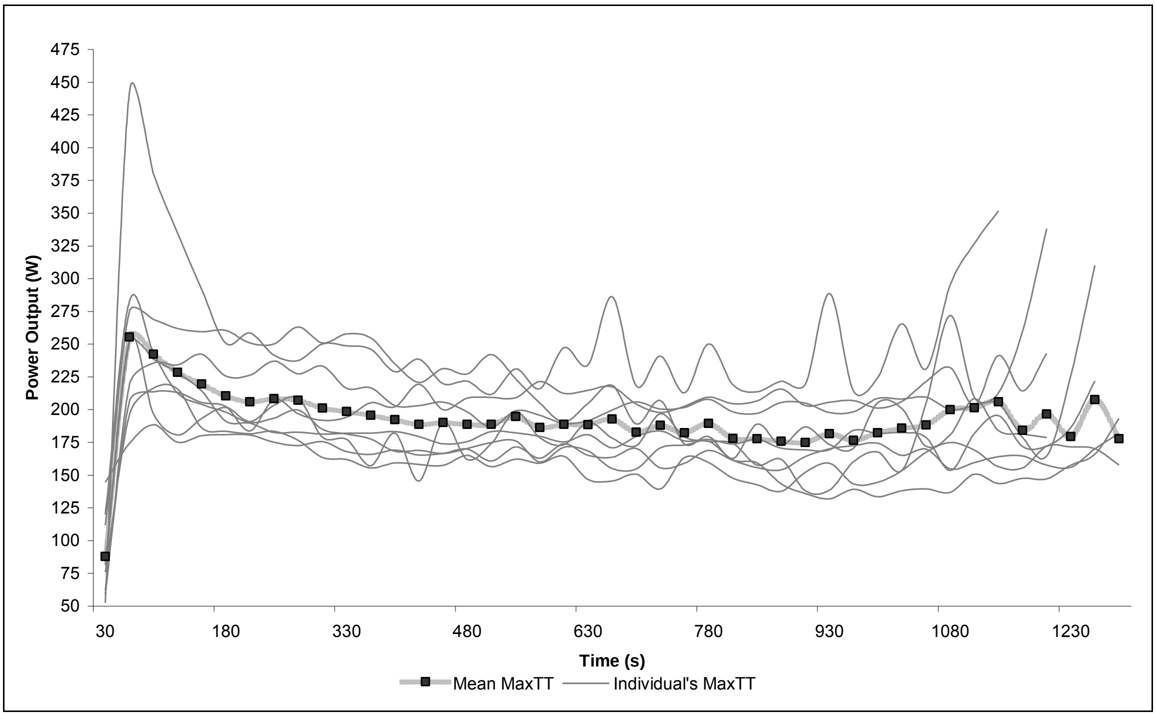


Figure 4.6 Group mean and individual dynamic responses of power output in the MaxTT experimental condition expressed as a function of time.

Scalar evaluation of 30s power output data identified that all participants demonstrated a spurt of power (identified as a visible upward alteration in the trajectory of power output) at a similar stage of their maximal trial (MaxTT) (89 ± 5% trial. Range: 81 – 95% of trial duration). Figure 4.6 shows the mean and individual power output profiles. One individual can be seen to exert a much greater power than the rest of the group at the start of the maximal exercise trial. This performance was considered for exclusion, however following assessment it was found that the performance did not significantly alter the group response ($p<0.05$) and the results were therefore retained in the analysis.

4.6 Discussion

The main finding from this study was that the enforced-pace condition (SubEXT) posed significantly greater physiological and thermoregulatory challenges to homeostasis than the matched-intensity sub-maximal self-paced trial despite there being no difference in performance. Specifically, the SubEXT condition resulted in elevated mean core temperatures ($p<0.01$), greater post-test blood lactate concentrations ($p<0.05$), and elevated sEMG activity at both bicep brachii ($p<0.05$) and vastus lateralis ($p<0.01$). The most likely explanation for this appears to be that self-paced exercise facilitates the opportunity for individuals to continually modify effort via feedback and feedforward mechanisms in response to frequent homeostatic challenges. Thus the greater time-trial variability of power output (PO_{ttv}) observed in the SubRPE condition compared to SubEXT ($p<0.01$) may indicate the presence of a central regulatory mechanism.

The greater variation of PO_{ttv} in the SubRPE condition compared with SubEXT was not accompanied by greater condition-specific variability in either $\dot{V}O_2$ or HR. However, the similarity of HR and $\dot{V}O_2$ between SubRPE and SubEXT is logical as power output is the variable manipulated as a behavioural response (to transient sensations of fatigue) and alterations in both $\dot{V}O_2$ and HR are therefore consequent to that behaviour i.e. they are both responses to that change in power output. This delay in physiological response can also be explained via common system response times. For example, it is well known that the *tau* of oxygen uptake in response to dynamic changes in work is approximately 20-25s among well trained participants (Edwards and Cooke, 2004), while the *tau* of heart rate is appreciably slower (Hughson, 1990). Consequently, in self-paced exercise, dynamic variations in power output are probably too small and frequent for either $\dot{V}O_2$ or heart rate to discreetly follow each alteration. As noted by other authors, (St Clair Gibson et al., 2001b) the importance of such dynamic responses have often been overlooked, probably due to the relatively recent emergence of fast-response technology. Nevertheless, such minor alterations in power output probably implies the existence of a process by which voluntary behaviour (up- or down-regulation of effort) maintains a constant metabolic challenge at a sustainable level throughout an exercise bout (St Clair Gibson and Noakes, 2004). Behavioural change (pacing) therefore acts to defend homeostasis (e.g. by defending core temperature and blood pH) and this process is compromised where self-pacing is not facilitated.

The greater variability of power output observed in the maximal trial ($p<0.01$) compared to the sub-maximal trials was a likely consequence of the greater freedom to alter pace in that condition in comparison to the restricted conditions (fixed RPE or fixed power output) of the sub-maximal trials. It is therefore predictable that the maximal trial would demonstrate greater variability than the two sub-maximal conditions. The maximal trial was included in this study for several comparative purposes but most usefully to identify whether participants were able to distinguish between working at different levels of physical effort in response to a 5000m rowing exercise test. Participants in this experiment were able to accomplish this task.

Previous studies (Catalano, 1973, Catalano, 1974a, Catalano, 1974b) have identified that an end-spurt in performance tends to occur at 90% of task completion and the maximal condition in this study was consistent with those observations. This appears to confirm that the increased final effort in maximal trials is representative of scalar rather than absolute pacing (St Clair Gibson et al., 2006) and provides little support for the concept that maximal intensity exercise progressively induces decreases in force production toward a terminal endpoint of fatigue.

No differences were seen in T_{sk} across sub-maximal and maximal trials. The most likely explanation for this observation is that skin temperature and the consequent sweat production probably reach an optimal level during laboratory exercise, and in the absence of further opportunities for convective cooling attains a steady (optimal) state for these conditions. Our results support this observation across sub-maximal and maximal exercise where body water loss was relatively minor.
It was anticipated that the MaxTT condition would result in significantly faster performances compared to the sub-maximal trials, but the similarity of physiological responses between SubEXT and MaxTT provides further evidence of the greater metabolic challenge of externally-paced sub-maximal work in comparison to self-paced exercise. Indeed where the ability to self-pace is denied, the metabolic challenge progresses toward a similar level to that of maximal exercise.

4.7 Summary

This study demonstrates that self-pacing exercise poses a reduced metabolic challenge when compared to matched-intensity enforced-pace sub-maximal exercise. It is likely that this is attributable to the ability to voluntarily fluctuate power output in accordance with subconscious regulatory mechanisms during the exercise bout. The voluntary behavioural change to fluctuate pace is therefore a conscious decision based on subconscious physiological feedback from an array of peripheral receptors. Externally-paced sub-maximal exercise thereby forces an individual to abandon their own pacing plan and minimise opportunities for self-managing the conscious signs of fatigue. This suggests that pacing is an important physiological mechanism to minimise the adverse conscious sensations of fatigue experienced during exercise which enables homeostasis to be defended during exercise.

To the author’s knowledge, this study is the first to thoroughly examine both the cardiorespiratory and thermoregulatory responses to rowing performance in relation to matched-intensity self- and externally-paced conditions. Further work is now required to establish whether this effect is consistent across more dynamic exercise challenges.

Chapter Five

The test-retest reliability of power output in response to self-paced exercise: within-group and between-group observations.

Chapter Five

The test-retest reliability of power output in response to self-paced exercise: within-group and between-group observations.

5.0 Abstract

The purpose of this study was to investigate the test-retest reliability of a self-paced time-trial in which the power output responses from a sub-maximal 5000m exercise test were compared both within-groups, and between-groups of aerobically-matched participants. Sixteen male participants were randomly assigned into aerobically-matched groups (Group A: age; 30 $\pm$ 7 years, $\dot{V}O_{2peak}$; 52 $\pm$ 3 ml·kg^{-1}·min^{-1} vs. Group B: age; 30 $\pm$ 7 years, $\dot{V}O_{2peak}$; 57 $\pm$ 13 ml·kg^{-1}·min^{-1}). Each group performed a preliminary assessment of $\dot{V}O_{2peak}$, and a 5000m sub-maximal rowing time-trial clamped at RPE 15. Environmental temperature was standardised across all trials (18˚C, 35-45% humidity). An RPE chart was visible throughout each trial and participants were regularly reminded of the required intensity. Average power output for the 5000m matched intensity trials were not significantly different within-groups (Group A: CV; 4.28%, ttv; 13 $\pm$ 3W vs. Group B: CV; 4.46%, ttv; 11 $\pm$ 6W). Furthermore no significant difference in power output was found between-groups (p=0.21, icc=0.912). The primary finding of this study was the excellent reproducibility of power output at RPE 15 both within- and between-groups of aerobically matched participants, suggesting that independent participant groups were able to match effort over the 5000m time-trial based upon a fixed perception of exertion. Previous studies have identified the reproducibility of RPE in prediction and replication experiments (Marriott and Lamb, 1996), and the reliability of RPE in repeated measures time-trials (Schabort et al., 1998). However the replication of results in any repeated measures protocol has the potential to be influenced by a learning effect (Thomas et al., 2005). By using independent samples and a range of statistical measures, the findings of the current study provide evidence of the reliability of a protocol based on a fixed RPE score across independent sampled groups, and suggest that such a study design could be used to observe changes in the pattern of pacing the reliability of a self-paced time-trial using a perceptually regulated scale.

5.1 Introduction

Self-paced exercise bouts are commonly examined using scales of perceived exertion (Edwards et al., 2011, Swart et al., 2009, Tucker et al., 2006c). These scales provide investigators with quantifiable values and participants with a range within which they may gauge the intensity of an effort (Borg, 1970, Faulkner and Eston, 2008). The use of scales of perceived exertion in time-trial protocols is particularly common (Hettinga et al., 2006b, Mauger et al., 2010b, Tucker et al., 2006c). However, whilst the use of RPE and time-trials in protocols have been separately deemed to be reliable, to-date no studies have investigated the reliability of RPE based time-trials, and furthermore, the reliability of such protocols between sample groups has also yet to be identified.

A scale for rating perceived exertion was originally proposed by Gunnar Borg in the 1960's and first published in its entirety in 1970 (Borg, 1970). The Borg scale of perceived exertion posits that the sum of all integrated feedback for physiological and psychological mechanisms can be quantified using a scale from 6-20, with an RPE of 6 corresponding to 'No exertion at all' and an RPE of 20 equating to 'Maximal exertion'. This scalar measure of a conscious perception of effort has been adopted as a reliable measurement tool by the American College of Sports Medicine (2005) and has been adapted by other authors (Grant et al., 2002, Eston et al., 2008, Noble et al., 1983, Borg, 1998) for use with different population groups. A detailed discussion of the reliability of RPE can be found in Chapter 2.

The term reliability is defined as "a measure of the consistency of data" (Vincent, 2005 pp3) and is commonly described using a correlation coefficient such as the Pearson product moment correlation (Weir, 2005), however the use of this statistic is inappropriate for demonstrating reliability when two values from the same variable are effectively being compared (Thomas et al., 2005). In recent years researchers have criticised correlation coefficients such as the Pearson product moment correlation (r) when used as a measure of reliability, suggesting that the statistic is a measure of the relationship between two variables, not the measure of agreement (Bland and Altman, 1995, Hopkins, 2000), and therefore does not account for sample heterogeneity or systematic error (Weir, 2005). This has led to calls for more appropriate statistical techniques to quantify absolute reliability or agreement.

A number of other alternative methods for establishing reliability have been advocated: these include the intra-class correlation coefficient (icc), the coefficient of variation (CV) and the use of limits of agreement (LoA).

The intra-class correlation coefficient is as prone to similar variation as Pearson product moment correlations (Atkinson and Nevill, 1998), and has been acknowledged by some as being too sensitive to a range of measurements in a sample (Bland and Altman, 2010). Its use has been shown by authors such as Ottenbacher and Tomcheck (1994) to be insensitive to marked changes to absolute agreement between 2 methods of measurement, and by Weir (2005) as being calculable using at least 6 different methodologies. However the icc is advocated by Hopkins (2000) as a statistic unbiased by sample size, and the only sensible approach to computing an average correlation between more than 2 trials. Moreover, it is described by Bland (2004a) as a measurement developed for correlation between multiple observations in groups.

In addition to the reliability properties of icc, some researchers have espoused the use of the typical error in reliability studies (Batterham and George, 2003, Hopkins, 2000, Hopkins et al., 2001). The use of typical error to determine reliability can produce an expected value independent of sample size, and this can be used to calculate a coefficient of variation. This statistic calculates reliability through the production of a unit which describes the typical error expressed as a percentage of the participant's mean performance, thus allowing straightforward comparisons of different measurement tools. The coefficient of variation is extensively used in biological and biochemical reliability research, and is considered particularly useful for assessing reliability of athletic events or performance tests (Hopkins, 2010). Although popular, CV may underestimate the true variation between tests (Atkinson and Nevill, 1998) as it assumes that the largest variation occurs in the individuals scoring the highest values on the test (Bland and Altman, 1995). The use of limits of agreement (LoA) has therefore been advocated as a useful alternative to CV for measuring reliability between different variables (Bland and Altman, 2010).

The use of LoA as a method of analysing repeated measurements has emanated from medical literature, and its use in sports science is increasingly accepted. The LoA calculates a range, within which, differences in scores are theoretically located 95% of the time, thus encompassing scores greater or less than two standard deviations from the mean difference. Some authors have championed the LoA as the most appropriate method for assessing within-subject variability (Atkinson and Nevill, 1998) however it too has also been criticised for being biased when applied to studies involving small sample sizes of less than fifty participants (Hopkins, 2000).

In the midst of conflicting opinions when assessing subject variability it has been recommended that researchers should cite a number of statistical measures including LoA for assessing within subject variability (Atkinson and Nevill, 1998). Therefore, LoA has been included in the current study along with CV, icc, and Pearson product moment correlations as appropriate.

Currently, little of the literature has described the reliability of RPE scores during exercise with anything other than correlation coefficients. Marriott and Lamb (1996) demonstrated *r* values of 0.82 and 0.84 in the heart rate and power output responses of participants using rowing ergometry to complete RPE based exercise estimation and production trials. In this experiment participants were initially asked to complete a trial in order to 'estimate' RPE whilst working a range of power outputs. On a subsequent occasion participants were then asked to 'produce' the wattage based on an RPE value. The authors of this study did not report any further statistical measures of reliability, however actual percentage differences revealed that the estimation and production heart rates were similar at RPE's of 15, 17 and 19, whilst power outputs were only similar at RPE 17. This incongruence could be a consequence of the oscillating, rather than incremental order, in which RPE's were requested for production during the trials (RPE 15, 11, 17, 13, 19). Equally, it could be a product of different methods used to record heart rate (final 15s of each stage) and power output (averaged over the whole 3min stage). Previous studies of $\dot{V}O_2$ have shown that the length of sample time can influence the value of the $\dot{V}O_2$ recorded (Johnson et al., 1998), thus a similar response might be expected using different recording intervals in the measurement of HR and power output.

In a later study on the reliability of ratings of perceived exertion in a treadmill based exercise test, Lamb and colleagues were the first to use limits of agreement in the assessment of reliability of RPE (Lamb et al., 1999). This study demonstrated that strong limits of agreement at lower levels of perceived exertion had the potential to mask lower levels of agreement in the latter stages of an incremental exercise test. Using a 4 stage incremental exercise test, Lamb et al., maintained treadmill speed but increased incline with every stage whilst recording RPE and heart rate. This protocol demonstrated LoA's of 0.88-2.02 RPE units in stage 1 (mean RPE 10.05), which increased to -0.13-2.94 RPE units in stage 4 (mean RPE 15.45), suggesting that lower intensities would demonstrate better agreement than at the higher end of their range of intensities. Trends in LoA were mirrored by corresponding changes in intra-class correlation coefficients and Pearson product moment correlations such that r values of 0.81 were found in stage 1, which reduced to 0.60 in stage 4. These trends led the authors to describe icc and Pearson production moment correlations as lending themselves to an interpretation as unfavourable as that of the LoA. The most notable finding from this study was that, in contrast with the 1996 paper, this study found the reliability of RPE to have a converse relationship with exercise intensity albeit over a much smaller range of intensities (RPE 10.05-15.45).

A study by Garcin et al., (2003) involving physical education students showed that RPE and heart rate can demonstrate a Pearson product moment correlation test-retest coefficient of 0.94-1.0 during incremental exercise tests on a running track over exercise intensities from RPE 7.5-18.8. These authors went on to use 95% limits of agreement to show that there was no systematic bias to their measurements (LoA=0.46 $\pm$ 4.40 b·min^{-1}), and bring into question the applicability of Lamb et al.'s earlier treadmill study possibly based on the protocol design and narrower band of exercise intensities used (Lamb et al., 1999).

In a recent study to investigate use of RPE scales in the prediction of $\dot{V}O_{2max}$ in exercise protocols using RPE scores, Lambrick et al., (2009) have demonstrated icc values of 0.97 between $\dot{V}O_2$ and RPE throughout an exhaustive exercise bout. This study has also described intra-class correlation coefficients of 0.94 at RPE 20 and 0.96 at RPE 19 when comparing predicted and measured values in a perceptually regulated sub-maximal exercise test. These data reaffirm support for the reliability of RPE. Similar studies have also used RPE in the prediction of $\dot{V}O_{2max}$. Coquart et al., (2010) showed that power output at RPE 15 can be reliably used to predict $\dot{V}O_{2peak}$ in obese females using an r value of 0.83, whilst Morris et al., (2010) have demonstrated that $\dot{V}O_2$ at RPE 19 and 20 can be reliably predicted using extrapolation from a protocol limited to RPE 15 (LoA -0.6 ± 7.1 and -2.5 ± 9.4 ml·kg^{-1}·min^{-1} respectively). Collectively these studies demonstrate the reliable use of RPE in both self-paced and incremental exercise and to an intensity of RPE 17.

To-date, relatively few articles have addressed the reliability of self-paced time-trials despite their increasing use (Hettinga et al., 2006b, Mauger et al., 2010b, Tucker et al., 2006c), particularly with reference to the reliability of RPE as an independent variable, rather than a dependent response. Work by Schabort et al., (1998) has demonstrated that a 1 hour self-paced time-trial run can be reproducible with a CV of 2.7% and icc of

0.90, but these findings have as yet, not been combined to show the reliability of self-paced exercise based on RPE intensities. In addition, whilst the use of time-trial protocols have been found to be a reliable measure (Laursen et al., 2007), their application is most commonly based on a paired-sample repeated-measures design which can only identify differences within-groups. In such a context, reliability could merely be due to a learning effect thereby masking an ability to yield consistent results.

Experiments of a paired-sample repeated-measures design are known to provide a better opportunity for investigators to control for individual differences in participant characteristics, and thus observe change in a variable rather than artificial changes due to variance brought about by the responses of different participants (Leavitt, 2001) or the initial differences in group characteristics (Graziano and Raulin, 2007). They do however suffer from the potential introduction of learning effects, meaning that participants improve in a second observation merely due to practice, or conversely, decrease performance due to the repetitive nature of trials or boredom (Thomas et al., 2005). An experiment using matched participants in the same condition would demonstrate that the inter-individual reliability of a protocol is not reliant on repeated exposure to a similar protocol and would quantify between-group reliability. Furthermore, it would show that findings from such a protocol could be generalised to a wider population group.

Given the recent growth of interest in self-paced RPE based protocols a timely review of the reliability of a self-paced time-trial protocol is now appropriate. This study was therefore designed to develop further understanding of the reliability of RPE based studies by investigating the reliability of a self-paced RPE-based time-trial protocol using a range of reliability statistics, and a contrasting method of experimental design.

5.2 Purpose of the study

The purpose of this study was to investigate the reliability of a self-paced time-trial at a fixed perceptual rate of exertion (RPE) using 5000m rowing exercise using within-group and between-group comparisons.

5.3 Aims of the study:

To demonstrate the test-retest reliability of a self-paced time-trial protocol at a fixed rate of perceived exertion over 5000m of rowing exercise.

To investigate the differences in performance of a self-paced 5000m rowing time-trial demonstrated by within-group and between-group comparisons.

To quantify the reliability of a self-paced time-trial at a fixed RPE using a range of reliability statistics.

5.4 Methodology

5.4.1 Participants

Sixteen healthy, well-trained male participants were recruited and agreed to take part in this study (Table 5.1). Following the completion of familiarisation and preliminary testing participants were randomly assigned to aerobically-matched sample groups for the purposes of the experiment. All were informed of the procedures in advance and informed consent was provided prior to any data collection. The study was approved by the Central Regional Ethics Committee of New Zealand and by Leeds Metropolitan University Faculty Research Ethics Committee. All participants were recreational gymnasium users and each received technical advice from a qualified rowing coach on using the rowing ergometer during a two-week familiarisation period.

Table 5.1 Participant characteristics of the study participants assigned to groups A and B.

		Participant Characteristics				
	n	Height (m)	Weight (kg)	Age (years)	$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	Power at $\dot{V}O_{2peak}$ (W)
Mean ± SD						
Group A	8	1.77 ± 0.06	77.10 ± 8.11	30 ± 7	52 ± 3	273 ± 24
Group B	8	1.78 ± 0.05	80.14 ± 15.47	30 ± 7	57 ± 13	288 ± 11

5.4.2 Participant screening and familiarisation

Participant screening was followed by a familiarisation in which all participants performed a standardised 10min familiarisation trial which consisted of a four stage incremental protocol, this was subsequently used as a standardised priming exercise in each of the trials and is described in detail in Chapter 3, General Methods.

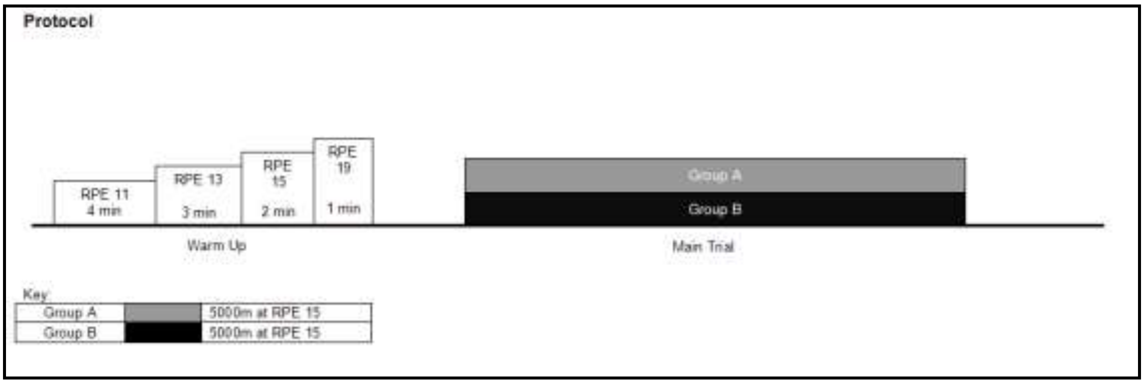
5.4.3 Preliminary testing

On separate and subsequent occasions to familiarisation all participants performed an incremental exercise test to volitional exhaustion on a Concept 2 rowing ergometer (Model D: Concept 2, Tauranga, NZ) for the determination of peak aerobic power ($\dot{V}O_{2peak}$). Oxygen uptake (Cortex MetaMax 3B, Cortex Biophysik, Leipzig, Germany) and power output (RowPro v2.006 software. Digital Rowing, Boston, MA, USA) were continuously monitored stroke-to-stroke. Power output was visible via the Concept 2 display unit at all times. Initial exercise intensity was set at 150 Watts for 3min then increased by 25 Watts each subsequent minute until volitional exhaustion or an inability to maintain the required power output was reached. This protocol has previously been described by Smith (2000) and has been used in assessments by Rowing New Zealand.

Baseline measures of $\dot{V}O_{2peak}$ were used to ensure independent groups were aerobically-matched prior to the investigation of power output test-retest reliability.

5.4.4 Experimental procedures

Following a standardised warm-up, irrespective of grouping, each participant completed a 5000m exercise bout on a rowing ergometer at an intensity of RPE 15 (Hard-Heavy). Each test session was identical. No visual feedback was provided in either bout to ensure participants self-paced, an RPE chart was visible to participants throughout the trial, and participants were positively verbally encouraged, and regularly reminded to maintain the required intensity throughout the trial. (Figure 5.1).



Main trial 5000m at RPE 15.

Figure 5.1 Diagrammatic representation of the warm-up and protocol for the Group A and Group B.

Exercise trials were held at the same time of the day on each of the two occasions to avoid diurnal variations in physiological responses. Participants were instructed to refrain from additional organised physical activity on the day prior to testing and to maintain habitual exercise routines. Ambient laboratory temperature was standardised at 18˚C across all tests, while relative humidity remained consistent (35-45%). All participants consumed a beverage of water 2 hours before the start of the test (5 ml·kg^{-1}·body mass) to ensure comparable levels of euhydration between participants and groups (Montain and Coyle, 1992).

As the study was designed to demonstrate the reliability of the protocol, rather than the physiological response to it, only performance data was recorded.

5.4.5 Power output measurement

Power output measurements followed the pattern described in Chapter 3 General Methods.

In brief: Stroke-to-stroke power output (PO) was assessed using the RowPro v2.006 software (Digital Rowing, Boston, MA, USA) in conjunction with the Concept 2 interface.

5.4.6 Calibration procedures

Calibration procedures followed the pattern described in Chapter 3 General Methods.

In brief: Prior to each warm-up the drag factor on the rowing ergometer was measured and calibrated to a drag factor of 130 10^{-6} $N \cdot m \cdot s^2$ prior to any data recording.

5.4.7 Data analysis

Dynamic variations in power output were recorded stoke-by-stroke and transformed into 30s measures to reduce data noise and create comparable measurement intervals for statistical comparison.
In contrast to the use of scalar reporting of data in Chapter 4, Chapter 5 expresses data as a percentage trial in order to better represent physiological and performance responses of participants without the impact of differences in time to completion.

A simple and effective means of determining time-domain variability is to calculate the standard deviation (SD) of each data point (i.e. each 30s time aligned interval) as a series. This method of analysis is frequently used in the study of heart rate variability (Achten and Jeukendrup, 2003, Aubert et al., 2003). The standard deviation for each data series was therefore used to provide an overall comparative measure of dynamic time-trial variability (ttv) between test groups.

5.4.8 Statistical analysis

The statistical software packages SPSS (version 11.0, SPSS, Chicago, IL, USA) and Graphpad Prism (version 4, GraphPad Software Inc, La Jolla, CA, USA) were used for all statistical analysis. Results were assessed for normal distribution then statistically compared using one-way analyses of variance (ANOVA) with post-hoc Bonferroni correction statistics.

Other comparisons were made using independent Student's *t*-tests. Probability values of less than 0.05 were considered significant. All results are expressed in means ± SD.

A number of measures of reliability were used as advocated by Atkinson and Nevill (1998). Pearson product moment correlations were used to calculate r values. Intra-class coefficients (icc) were calculated using the formula previously described by Bland (2004a). Coefficients of variation (CV) were calculated using the formula previously described by Hopkins (2010) to provide a measure of percentage variation seen in the trials. Limits of agreement (LoA), promoted by Bland and Altman (2010), were also reported once corrected for degrees of freedom as recommended by Hopkins (2000).

Calculating an average coefficient of variation by averaging CV scores can result in a deviation of 0.9 from the correct value (Schabort et al., 1998). Corrected estimates of average CV's were therefore calculated by taking the square root of the average of the square of CV's of individual scores.

5.5 Results

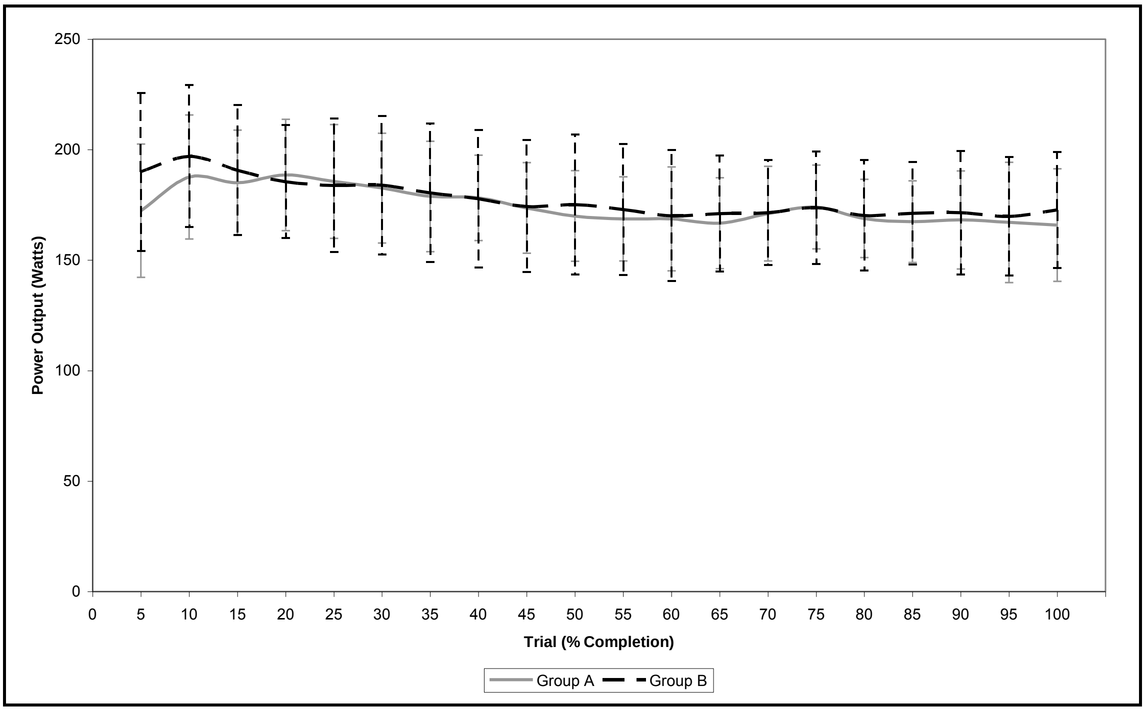
Mean power output at RPE 15 and performance time was found to be similar between the aerobically matched groups (p=0.21; p=0.99). The participant groups were able to accurately replicate a similar performance at RPE 15 with an intra-class correlation coefficient of 0.912. Strong within-group reliability was demonstrated through coefficients of variation of 4.28% and 4.46% in Groups A and B respectively. In addition when power was expressed relatively as a percentage of power at $\dot{V}O_{2peak}$ the group's responses were still similar (p=0.64). Mean power output responses are provided in Table 5.2 and Figure 5.2.

Table 5.2 Mean performance responses and reliability in two experimental groups.

	Group A	Group B
Performance Time (s)	1266 ± 50	1267 ± 61
Mean Power Output (W)	174 ± 7	178 ± 8
Percentage of power at $\dot{V}O_{2peak}$ (%)	64 ± 6	62 ± 10
CV (%)	4.28	4.46
ttv (W)	13 ± 3	11 ± 6
icc	0.912	

No significant differences observed between groups Performance time p=0.99; Power output p=0.21 or Percentage of power at $\dot{V}O_{2peak}$ p=0.64.

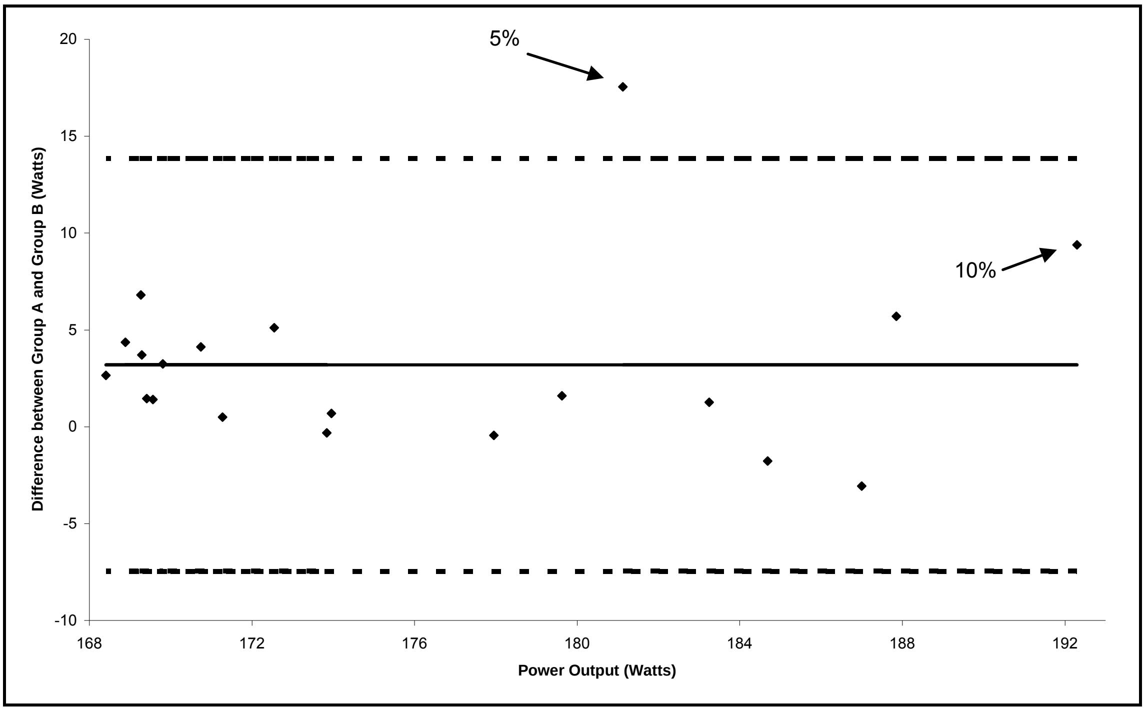
Whilst performance time and power output were similar between the two groups (p=0.99; p=0.21), the mean standard deviation of power output was significantly lower in Group A than in Group B (23 ± 3 Watts vs. 29 ± 3 Watts; p<0.001). However the coefficients of variation of 4.28% vs. 4.46% were notably consistent across the two exercise bouts, as was the time-trial variability of 13 ± 3 Watts in Group A and 11 ± 6 Watts in Group B (p=0.61).



No differences were observed in power output responses between-groups or within-groups in each exercise bout. Mean SD lower in Group A than Group B ($p<0.001$)

Figure 5.2 Mean performance responses in two experimental groups expressed as a function of percentage trial completed.

The limits of agreement are shown in the Bland and Altman plot (Figure 5.3), a mean difference of 3.19 $\pm$ 4.50 Watts when adjusted for degrees of freedom as recommended by Hopkins (2000). Notable outliers in Figure 5.3 are labelled as the power output at 5% and 10% trial completion. These larger differences are created as participants take varying time to get up to pace from a standing start. When the comparisons at 5% and 10% trial completion were removed from the analysis the mean difference dropped to 2.05 $\pm$ 2.63 Watts.



Labels refer to values of agreement at 5% and 10% trial completion.

Figure 5.3 Limits of agreement Group A vs. Group B (Bland and Altman plot) expressed as a function of power output.

5.6 Discussion

These data demonstrate that exercise intensity can be reliably replicated using RPE as an independent variable both within-group and between-groups of aerobically-matched independent participants. RPE has previously been shown to be reliable as a dependent variable, however this work is the first to demonstrate reliability as an independent variable, this finding is supported by the use of a range of reliability statistics as advocated by Atkinson and Nevill (1998). The nature of exercise at a perceived exertion does not lend itself to comparisons between participant groups; thus this study's finding that aerobically-matched independent sample groups can match and maintain work at a similar exercise intensity of perceived exertion is most notable, and opens opportunities for further investigation into exercise at fixed work rates using other independent sample groups.

The primary finding of this study was the excellent reproducibility of power output at RPE 15 both within-groups and between-groups. The low coefficient of variation demonstrated by both Groups A and B (4.28% and 4.46%) provides support for the reliable use of time-trial protocols within participant groups. In addition the high intra-class correlation coefficient (icc=0.912), and similarity in mean power output (p=0.21) between the aerobically-matched groups suggests that independent participant groups were also able to reliably replicate an exercise intensity based on perceptions of exertion. These findings support the work of Garcin et al., in the use of RPE during constant load exercise (Garcin et al., 2003) and extend the field by demonstrating the reliable use of self-paced time-trials at a fixed RPE between aerobically-matched groups.

A self-paced time-trial was used by Tucker et al., (2006a) to demonstrate non-random fluctuations in power output, and similar protocols at fixed rates of perceived exertion have since been used to investigate the influence of variables such as ambient temperature and acetaminophen (Hettinga et al., 2006b, Mauger et al., 2010b) all using time-trial based protocols. The reliability of time-trial based protocols, has however previously been questioned (Hinckson and Hopkins, 2005a). Furthermore the reliability of time-trials based upon a self-paced rate of perceived exertion has hitherto not been identified. Schabort et al., (1998) have previously demonstrated the reliability of a self-paced 1 hour time-trial, which was estimated to be at an intensity of 80-83% $\dot{V}O_{2peak}$, in which participants were asked to run as far as possible in 1 hour (icc 0.90; CV 2.7%). In addition, Laursen et al., (2007) has shown that assessment using time-trial variability is better than the alternative method of log-log modelling a time-to-exhaustion proposed by (Hinckson and Hopkins, 2005a). However the findings of the current study are the first to show the reliability of a time-trial based on fixed rates of perceived exertion, thus providing validity to findings of studies using similar protocols which had previously not been demonstrated to be reliable.

The average coefficient of variation of 4.37% in the current study is slightly higher than that of Schabort (1998), and that may be a product of the between-subject variation (as evidenced by the error bars in Figure 5.2) and the slight but significant difference in the standard deviation between-groups (23 $\pm$ 3W vs. 29 $\pm$ 3W; $p<0.001$). However, this is still much lower than the 17-27% CV's seen in time-to-exhaustion experiments which have previously been employed in reliability studies (Krebs and Powers, 1989, McLellan et al., 1995, Jeukendrup et al., 1996), suggesting that time-trial protocols have a lower variation than those of time-to-exhaustion, despite the ability of participants to vary power output based on changes to perceived exertion. One cause of the slightly greater variation seen in this study, when compared to that of others, may be the inter-participant variation within-groups which is also evident in the variance seen in baseline measures of $\dot{V}O_{2peak}$ particularly in Group B. However the consistency of CV and ttv across the two groups in this independent samples study would tend to discount that suggestion. In addition the intra-class correlation of 0.912 convincingly demonstrates the reproducibility of such a protocol. Despite this, the inter-participant variance within the groups may be considered a limitation of this study.

In contrast to many reliability experiments this study used an independent samples design to assess reliability both within- and between-groups. Conventional paired-sample repeated-measures studies assume that there is a relationship or correlation between the scores in a first trial and a second trial thus only assessing variance within-groups. The result in trial 2 is therefore still partially dependent on trial 1 and thus more likely to produce similar results than the scores of two different groups (Vincent, 2005). Whilst the use of protocols of a repeated-measures design allows a researcher to be more confident that any difference observed is in response to the applied condition, in studies in which differences are not expected, the chance of a type II error occurring is dramatically increased. The use of an independent samples design in this study is therefore unconventional, but appropriate, in order to investigate the reliability of RPE in self-paced trials both within and between sample groups.

The findings of this study demonstrate the reliability of a self-paced time-trial both within- and between-groups of aerobically-matched participants. This is fundamentally important to the use of self-paced protocols as it provides grounds for investigators to confidently reflect on changes in pacing as a response to factors other than participants inability to reliably reproduce a self-paced time-trial at RPE 15.

Limits of agreement are used to demonstrate the range within which differences in scores are theoretically located 95% of the time (Atkinson and Nevill, 1998). In this study notable outliers can be observed in the first 10% of the trial whilst participants ‘dial in’ a pace, thereafter however the differences between the two groups are well within the 95% limits of agreement and clustered consistently around a mean difference as shown in Figure 5.3. In a recent conference presentation Thomas et al., (2010) demonstrated a greater variability at the start of a 20km cycling time trial, which was attributed to the level of uncertainty at the commencement of the trial. Thereafter, they too saw a reduction in power output variability, until the end-spurt in the final kilometre of the trial. When the comparisons at 5% and 10% trial completion were removed from the present analysis the difference between the two groups was reduced to 2.05 ± 2.63W and including the outliers the mean difference was only 3.19 ± 4.5W. In a study by Faulkner et al., (2007) a value of 25W was used to approximate a rise in intensity of 1 RPE unit in an investigation which demonstrated the validity of estimating $\dot{V}O_{2max}$ from a sub-maximal graded exercise test, the work also described a variance in power output at an intensity of RPE 15 of 41W; the equivalent of 1.64 RPE units. The results of Lamb et al. suggest a variance of 2.94 RPE units to be expected at RPE 15 (Lamb et al., 1999). Although using independent samples, the current study was able to demonstrate much closer limits of agreement than that of previous studies which have used paired sample protocols.

5.7 Summary

The findings of this study demonstrate the strong replication of power output intensity both within-groups and between aerobically-matched groups in time-trials at a fixed perceived exertion. This provides evidence to justify the reliability of a protocol based on a fixed RPE score across independent sampled groups and suggests that such a study design could be used to observe changes in the pattern of power output within an exercise bout in order to investigate pacing behaviour. Using a number of statistical measures as recommended when assessing reliability (Atkinson and Nevill, 1998), the findings of the current study therefore provide evidence of the reliability of a self-paced time-trial using a perceptually regulated scale.

Chapter Six

Comparison of self-paced exercise in response to intervals of radiant warming and constant thermoneutral conditions.

Chapter Six

Comparison of self-paced exercise in response to intervals of radiant warming and constant thermoneutral conditions.

6.0 Abstract

The purpose of this study was to investigate the influence of intervals of radiant warming and constant thermoneutral conditions on dynamic physiological responses during self-paced exercise in which the participants were either: non-warmed (NW), warmed (W) or warmed in intervals (IW) for fixed periods throughout the trial. Eleven male participants (age; 30 ± 7 years, $\dot{V}O_{2peak}$; 56 ± 12 ml·kg^{-1}·min^{-1}) performed four exercise trials ($\dot{V}O_{2peak}$, 5000m rowing clamped at RPE 15 in randomly ordered NW, IW or W conditions). Environmental temperature was standardised at 18˚C (35-45% humidity) which was raised to ≈35˚C during warming intervals via radiant heat lamps. Intervals of warming were applied from 1000-2000m (W1) and 3000-4000m (W2). Performance times and average power output for the 5000m matched intensity trials were not significantly different (IW; 1270 ± 68s vs. NW; 1268 ± 61s vs. W; 1264 ± 57s; p=0.10) (IW; 170 ± 12W vs. NW; 172 ± 17W vs. W; 174 ± 21W; p=0.189). However power output per 200m was reduced in W1 from 1200m to 2000m (p=0.03) but not in W2 (p=0.10). T_{sk} increased by 0.51˚C (p=0.05) during W1, and by 0.15˚C in W2 (p=0.28). No significant changes were observed in T_c throughout the trials. Overall performance times were not influenced by the intervention, however a reduction in power output as a consequence of the first period of warming was observed. This is probably attributable to an unexpected homeostatic disturbance which influenced the early stage pre-conceived pacing strategy of the exercise bout. A multi-level pacing plan which incorporates a concept of acceptable homeostatic set points within dynamic exercise has previously been proposed (Edwards and Noakes, 2009) which may explain the altered influence of warming during early stage of the IW condition. The concomitant changes to T_{sk} and PO in this investigation without significant change to T_c suggested that skin temperature may play an important signalling role in the variation in exercise intensity.

6.1 Introduction

Homeostasis is known to be influenced by changes in core body temperature (Benzinger, 1969), and an increase in core temperature has been previously linked with premature fatigue during maximal and sub-maximal exercise (Casa, 1999). The development of fatigue has been associated with intra-trial fluctuations which allow the performer vary effort as part of a behavioural responses in order to defend homeostasis (Edwards and Noakes, 2009, St Clair Gibson et al., 2006, Tucker and Noakes, 2009). The changes in pace during an exercise bout may therefore be considered as important behavioural responses to challenges of homeostasis, such as those brought about by changes in internal temperature, but this can only be observed in exercise where pace is free to vary. The impact of changes in a thermal environment on self-paced exercise may consequently provide a potent model through which thermoregulatory behaviour may be observed (Schlader et al., 2010a, Schlader et al., 2010b) and the mechanisms of pacing further defined.

During exercise, up to 75% of the energy liberated by the body takes the form of heat energy, due to the relatively low mechanical efficiencies of skeletal muscles (Prampero, 1981, Astrand et al., 2003). The consequential rise in internal temperature developed during exercise invokes a sweating response, which serves to defend core temperature (Ekblom et al., 1971). In addition to the challenge to core temperature brought about by exercise itself, exercise performed in the hot conditions is also known to result in premature sensations of fatigue when compared with exercise in an equivalent thermoneutral environment (Tucker et al., 2004, Gonzalez-Alonso et al., 1999). It is likely that the thermoregulatory systems of the body may be linked to a mechanism of control which can detect changes in temperature and alter perception accordingly, in order to defend against unacceptable challenges to core temperature, and the development of premature fatigue or a catastrophic failure of systems.

Ratings of perceived exertion (RPE) in response to exercise have been previously shown to be well correlated with core body temperature during cycling exercise in a hyperthermic (40˚C) and thermoneutral (18˚C) environment ($r=0.98$, $p<0.001$) (Nybo and Nielsen, 2001b). Because exercise is known to increase core body temperature, it is possible that during prolonged exercise at a fixed RPE, power output may progressively decline in order to maintain core temperature and thus homeostasis. In support of this, reductions in power output at the onset of self-paced exercise in the heat have been noted in both cycling and running events (Kay et al., 2001, Marino et al., 2004). The reductions in power output were observed prior to an exercise-induced elevation of body temperature (Nybo and Nielsen, 2001a), and suggest that an anticipatory central regulatory process may be influential from the onset of exercise.

A study by Marino et al., (2004) investigated running speeds of African and Caucasian runners in hot and cool conditions, and identified that Caucasian runners reduced running speed in warm conditions, a response which was not seen in African runners. Furthermore, although African runners commenced an 8km performance run at similar speeds in both cool and warm conditions, the Caucasian runners significantly reduced the run speed at the start of the warm trial, prior to any significant rises in rectal temperature. The reduction in running pace by the Caucasian runners in the warm condition was attributed to their greater body size and the consequential higher rates of heat storage which were developed by the Caucasian runners in comparison with the African runners. This lead Marino et al., to suggest that changes in pacing in hot conditions were unlikely to be limited by failure of sweating mechanisms, and were more probably regulated by a mechanism of complex metabolic control which invokes a pacing plan appropriate to the environmental conditions.

Evidence for the concept of temperature influencing a pacing strategy has been provided by Byrne et al., (2006) who indirectly demonstrated that changes in pace can be linked to changes in core temperature during a self-paced, mass participation running event in the heat. Participants were monitored during a marathon conducted in temperatures of 26.3-30.6˚C dry bulb temperature with 75-90% humidity, in which 22% of participant's demonstrated concomitant reductions in core temperature (T_c) and heart rate (HR). During the same event a further 33% of participants conversely demonstrated concomitant increases in T_c and HR. No dynamic measures of pace were recorded, however if the participants altered performance based upon thermoregulatory feedback and a perception of effort rather than performance time (as is common in sporting practices), it becomes clear why inter-individual responses in HR and T_c, may be identified and why the authors failed to observe a significant relationship between performance time and any T_c variable. To justify the inter-individual variance in T_c during exercise the authors cite the work of Davies et al., (1976) who asserted that the major determinant of a rise in T_c is the relative oxygen uptake. However it should be noted that oxygen uptake itself is only increased in response to, and not in advance of, an increase in work rate. In this context, it could be argued that a model of complex control would better explain the inter-individual responses.

Support for the influence of complex metabolic control in self-paced exercise has been provided by Edwards and Noakes (2009), who have previously described the application of multi-level pacing plans with specific reference to elite soccer. The meso- and macro-pacing plans proposed by Edwards and Noakes are suggested to allow players to defend set points of homeostatic imbalance, whilst an additional micro-pacing strategy is also employed in order to respond to dynamic moment-by-moment changes in a game. Collectively, these plans allow players to complete a full match and still avoid the failure of any single physiological mechanism through a dynamic up and down-regulation of effort. Evidence for this proposal has been presented in light of the absence of core temperatures sufficiently critical to cause the immediate cessation of exercise, and in response to the failure of numerous previous studies to identify a single metabolic factor linked to the development of fatigue in self-paced exercise (Lambert et al., 2005, Edwards and Noakes, 2009).

The application of a pacing strategy implies the understanding of the effort yet to come in an exercise bout, and evidence of this can be derived from a laboratory based study by Tucker et al., (2004), which demonstrated that participants in a bout of self-paced cycling collectively down-regulated their power output at 30% of trial duration in warm conditions, compared with down-regulation at 80% trial duration in a cool condition. This behavioural reduction in effort occurred despite a similarity in rectal temperatures (T_{re}) until 95% of the trial completion. The reduction in power output prior to a significant difference in T_{re} was proposed to be part of an anticipatory response to ensure that relative thermal homeostasis was retained in altered environmental conditions. This could be considered part of an overall pacing strategy to avoid the development of critical core temperatures. Further evidence from these authors (Tucker et al., 2006c) has proposed that the integration of feedback on the rate of heat storage and the participant's rate of perceived exertion is combined to regulate work rate in order to ensure that the rate of heat storage does not reach levels unacceptable to any mechanism of central complex control.
Recent work by Schlader et al., (2010a) has demonstrated differences in work done when progressively heating or cooling participants during exercise. In a 60min cycling protocol, Schlader et al., found that greater work was completed in the trial which went from cold to hot when compared with the trial which went from hot to cold. Due to rises in temperature brought about through exercise and the known benefits of maintaining cool core temperatures prior to exercise, this finding is surprising, but this protocol may be considered to represent an environment in which a contrast to normal responses was detected by the thermoregulatory system and a down-regulation of effort was therefore accordingly invoked.

The changes in temperature in the Schlader study (2010a) were progressive, and may therefore be predicted or incorporated into a pacing plan. To-date, no studies have investigated the influence of interval-based changes in the thermal environment during exercise in order to identify a relationship between dynamic changes in body temperatures and alterations in power output. If, as proposed, athletes prescribe a macro-pacing strategy prior to exercise which identifies set point tolerable limits to physiological parameters, then the introduction of interval warming would present a challenge to such a strategy and should result in a distinguishable change in either physiological or performance parameters.

Recently authors have identified that changes to a pacing template in order to impose an optimal pacing profile can actually result in negative performance effects (Hettinga et al., 2011). Whilst no difference was observed in the physiological parameters measured in these trials, the imposition of changes in the distribution of effort produced a poorer performance despite the pacing being theoretically optimal. Changes to core temperature have been previously proposed as a factor capable of influencing work rate during exercise (Byrne et al., 2006, Marino et al., 2004, Tucker et al., 2006c), thus investigation into the effect of a changing thermal environment during exercise which would alter core temperature, and may have a concomitant influence on power output, is pertinent to the investigation of pacing and fatigue.

This study will investigate the imposition of radiant heat, and the imposition of changes in thermal environment during exercise. It is proposed that these impositions will result in a dynamic reduction in power output in self-paced exercise when compared with that of self-paced exercise in a consistent thermoneutral environment. It is further suggested that any dynamic changes in power output will not bring about changes in the performance outcomes which may be controlled by a preset macro-pacing strategy.

6.2 Purpose of the study

The purpose of this study was to compare dynamic physiological responses to a self-paced 5000m rowing exercise bout at a fixed rate of perceived exertion (RPE) in which the participants were either warmed (W) not warmed (NW), or warmed in intervals (IW) for fixed periods throughout the trial.

6.3 Aims of the study

To compare physiological responses in a self-paced exercise bout at a fixed RPE over 5000m of rowing exercise in response to intervals of radiant warming and constant thermoneutral conditions.

To investigate the influence of changes in the thermal environment on dynamic physiological and performance characteristics in self-paced exercise at a fixed RPE over 5000m of rowing exercise.

To investigate the existence of multi-level pacing strategies in self-paced rowing exercise at a fixed RPE in constant and changing thermal environments.

6.4 Methodology

6.4.1 Participants

Eleven healthy, well-trained male participants were recruited and agreed to take part in this study (Table 6.1). All were informed of the procedures in advance and informed consent was provided prior to any data collection. The study was approved by the Central Regional Ethics Committee of New Zealand and by the Faculty Research Committee at Leeds Metropolitan University. All participants were recreational gymnasium users and each received technical advice from a qualified rowing coach on using the rowing ergometer during a two-week familiarisation period.

Table 6.1 Anthropometric and cardiovascular characteristics of study participants.

	Participant Characteristics				
	Height (m)	Weight (kg)	Age (years)	$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	HR at $\dot{V}O_{2peak}$ ($b \cdot min^{-1}$)
Mean ± SD	1.79 ± 0.05	80.05 ± 13.7	30 ± 7	56 ± 12	183 ± 11

6.4.2 Participant Screening and Familiarisation

Participant screening and familiarisation followed the pattern described in Chapter 3 General Methods with the following additions:

Participants were introduced to equipment specific to this study which included the lighting rig (adapted from Twin Flood Tripod, Arlec ,Victoria, AU) with either warming bulbs (Siccatherm R125 250 Watt Red Bulbs) (OSRAM, Auckland, New Zealand), or placebo bulbs (Philips Partytone PAR38 80 Watt Red Bulbs) (Philips Lighting, Wellington, New Zealand), and Protective eyewear (UVEX Duoflex 9180-945, UVEX Auckland, NZ). Images of the experimental equipment can be found in Figures 6.2 and 6.3.

10min familiarisation sessions were conducted with the lights turned on in order for the participants to become accustomed to the experience of the lights in the testing environment. Protective eyewear was worn by the participants at all times during all trials.

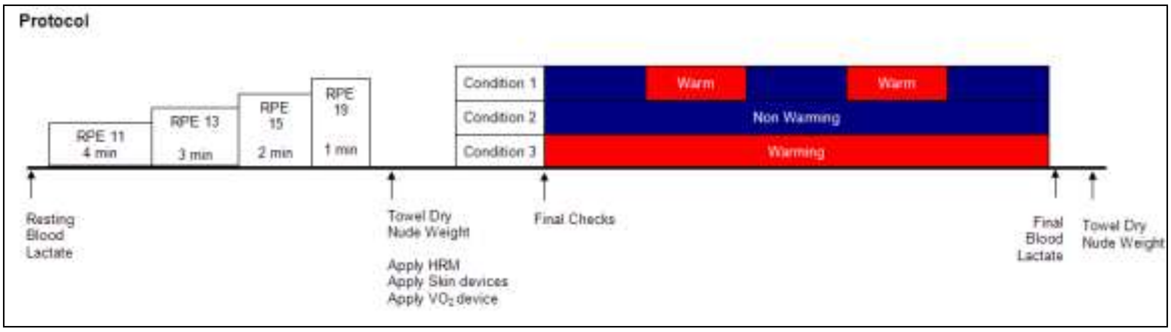
6.4.3 Preliminary testing

All participants performed a standardised 10min familiarisation trial which consisted of a four stage incremental protocol, this was subsequently used as a standardised priming exercise in each of the trials and is described in detail in Chapter 3, General Methods.

On separate and subsequent occasions all participants performed an incremental exercise test to volitional exhaustion on a Concept 2 rowing ergometer (Model D: Concept 2, Tauranga, NZ) for the determination of peak aerobic power ($\dot{V}O_{2peak}$). Oxygen uptake (Cortex MetaMax 3B, Cortex Biophysik, Leipzig, Germany) and power output (RowPro v2.006 software. Digital Rowing, Boston, MA, USA) were continuously monitored stroke-to-stroke. Power output was visible via the Concept 2 display unit at all times. Initial exercise intensity was set at 150 Watts for 3min then increased by 25 Watts each subsequent minute until volitional exhaustion or an inability to maintain the required power output was reached. This protocol has previously been described by Smith (2000) and has been used in assessments by Rowing New Zealand.

6.4.4 Experimental procedures

Each participant completed three, 5000m rowing trials in three different experimental conditions, in an individually randomised order. In condition one (IW), participants completed 5000m at a constant rating of perceived exertion (RPE: 15-Hard) whilst being warmed from 1000-2000m (W1) and from 3000-4000m (W2). In condition two (NW) participants performed 5000m at a constant rating of perceived exertion (RPE: 15-Hard) whilst not being warmed at any point in the trial. Finally in condition three (W) participants performed 5000m at a constant rating of perceived exertion (RPE: 15-Hard) whilst being warmed throughout the trial. Warming raised the temperature of the region surrounding the athlete to ≈ 35˚C (Kestrel 2000 Wind Meter, Nielsen-Kellerman, Boothwyn, PA, USA). A graphical representation of the protocol can be found in Figure 6.1 whilst images of the experimental equipment can be found in Figures 6.2 and 6.3.



Condition 1; Interval Warming, 5000m RPE 15 warmed in alternate 1k intervals with a heating bulb. Condition 2: Non-Warming, 5000m RPE 15 lit with a non-warming placebo bulb throughout the trial. Condition 3: Warming, 5000m RPE 15 lit with warming with a heating bulb throughout the trial.

Figure 6.1 Diagrammatic representation of the warm-up and protocol in three experimental conditions.

Placebo lamps of similar Lux (light intensity) were used in the non-warming trial in order to maintain similar light intensity conditions as changes to the intensity (brightness) of lights have been previously shown to influence changes in core temperature (Zhang and Tokura, 1999, Atkinson et al., 2008). In addition, participants were not made aware of the true purpose of the investigation or the systematic changes in pacing that the heat lamps were hypothesised to bring about.

No visual feedback was provided in any condition to ensure participants self-paced, an RPE chart was visible to participants throughout the trial, and participants were positively verbally encouraged, and regularly reminded to maintain the required intensity throughout the trial.

Figure 6.2 Physical representation of the experimental environment. Lighting rig in position fitted with warming bulbs set at a neutral height and direction (additional recording equipment is not pictured).

Figure 6.3 Physical representation of the experimental environment. Lamps fitted with warming bulbs set at a neutral height and direction.

Exercise trials were held at the same time of the day on each of the three occasions to avoid diurnal variations in body temperature, and were each separated by approximately one week. Participants were instructed to refrain from additional organised physical activity during the testing period and to maintain habitual exercise routines. Ambient laboratory temperature was standardised at 18˚C across all tests while relative humidity remained consistent (35-45%). All participants consumed a beverage of water 2 hours before the start of the test (5 $ml \cdot kg^{-1}$ body mass) to ensure comparable levels of euhydration between participants and trials (Montain and Coyle, 1992).

6.4.5 Power output, oxygen uptake, and heart rate measurement

Power output, oxygen uptake, and heart rate measurements followed the pattern described in Chapter 3 General Methods.

In brief: Stroke-to-stroke power output was assessed using the RowPro v2.006 software (Digital Rowing, Boston, MA, USA) in conjunction with the Concept 2 interface. Oxygen uptake was continuously recorded breath-by-breath (Cortex MetaMax 3B, Cortex Biophysik, Leipzig, Germany). Whole blood capillary samples were drawn from the finger tip prior to exercise and at the immediate cessation of time-trial performances for the analysis of blood lactate concentration (Lactate Pro, Akray Inc, Kyoto, Japan). Heart rates (HR) were continuously recorded (S610i, Polar, Kempele, Finland).

6.4.6 Measurement of thermoregulatory factors

Thermoregulatory measurements followed the pattern described in Chapter 3 General Methods.

In brief: Core temperature (T_c) was measured via telemetry from the intestine using a silicon-coated thermometer pill (CorTemp2000, HQ, Palmetto, Florida, USA) which was swallowed by all participants 5-8 hours before exercise. Skin temperatures (T_{sk}) were measured at four sites using stainless steel surface skin thermistors (Grant Logistics, Cambridge, UK). Temperatures were recorded continuously throughout the trial using a data logger (SQ400 Squirrel Data logger, Grant Logistics, Cambridge UK). Mean body skin temperature was calculated using the formula previously described by Ramanathan (1964).

6.4.7 Calibration procedures

Calibration procedures followed the pattern described in Chapter 3 General Methods with the following addition:

6.4.8 Warming Procedures

The lighting rig was repositioned prior to each trial in order to produce consistent heating across the length of each participant's stroke. When repositioned, temperature was measured (Kestrel 2000 Wind Meter, Nielsen-Kellerman, Boothwyn, PA, USA) at three locations (catch, mid-drive, start of recovery) throughout the stroke to eliminate cool spots in any trial.

6.4.9 Data analysis

Dynamic variations attributable to pacing were assessed by the measurement of oxygen uptake, heart rate and power output which were recorded individually and transformed into 30s measures to reduce data noise and create comparable measurement intervals. Due to variations in the time to complete 5000m the bout was considered as 100% and measures were then time aligned and batched into 5% bout means for each outcome measurement. To represent changes in power output during the interval warmed condition power output was also dynamically analysed as a function of distance completed and expressed per 200m completed in order to quantify dynamic changes to performance responses.

6.4.10 Statistical analysis

The statistical software packages SPSS (version 11.0, SPSS, Chicago, IL, USA) and GraphPad Prism (version 4, GraphPad Software Inc, La Jolla, CA, USA) were used for statistical analysis. Results were assessed for normal distribution then statistically compared using one-way repeated measures analyses of variance (ANOVA) with post-hoc Bonferroni correction statistics. Other comparisons were made using paired Student's *t*-tests. Pearson product moment correlations were used to calculate r values. Probability values of less than 0.05 were considered significant. All results are expressed in means ± SD.

6.5 Results

There were no differences in the average power output between the interval condition (IW, 170 ± 12W), and the non-warmed environment (NW, 172 ± 16W) (p=0.617) or between interval warmed and the warmed environment (W, 174 ± 21W) (p=0.189). There was also no difference between power output in the constant environmental conditions (NW and W, p=0.134). However significant differences were found between the average $\dot{V}O_2$ in IW and NW (p=0.005) and between NW and W (p=0.016) conditions, and also between heart rate (HR) in IW versus W condition (p=0.037). Table 6.2 shows the average physiological and performance responses in each of the 3 conditions.

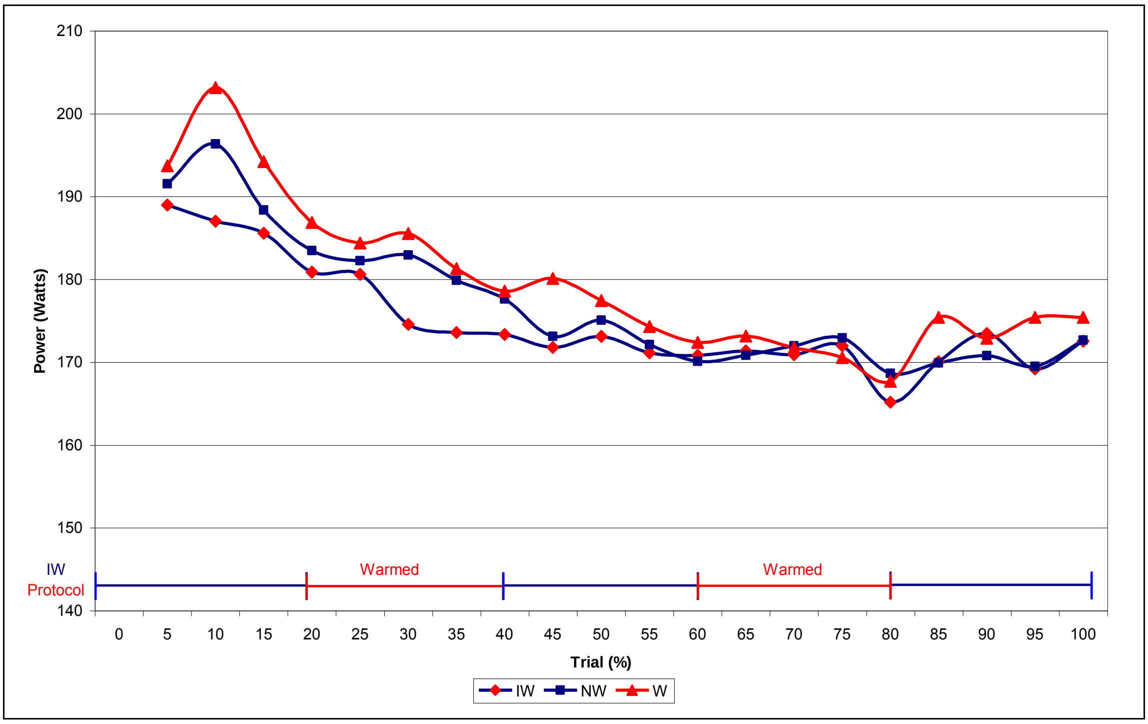
Table 6.2 Mean performance and physiological responses of participants in three experimental conditions.

	Performance Time (s)	Power Output (Watts)	$\dot{V}O_2$ ($ml \cdot kg \cdot min^{-1}$)	Heart Rate ($b \cdot min^{-1}$)	Core Temperature (˚C)	Skin Temperature (˚C)
IW	1270 ± 68	170 ± 12	37 ± 3 ‡	155 ± 10 *	38.6 ± 0.3 ‡	31.0 ± 0.4 ‡
NW	1268 ± 61	172 ± 17	38 ± 4	155 ± 10 (nd W p=0.06)	38.7 ± 0.3	31.3 ± 0.2 (nd W p=0.09)
W	1264 ± 57	174 ± 21	37 ± 4 ‡	156 ± 11	38.4 ± 0.3 ‡	31.2 ± 0.2 (nd IW p=0.07)

* Sig diff W p<0.05 ; ‡ Sig diff NW p<0.01 ; nd No significant difference.

To identify dynamic changes in variables each physiological and performance response was interpolated into 5% batches of trial duration. The 5000m bout was completed in between 1264 ± 57 to 1270 ± 68s, thus 5% of the trial duration equates to approximately 60s of exercise or ≈250m of trial distance completed.

Figure 6.4 shows the power output in the three experimental conditions. Periods of warming and non-warming in the intermittent protocol are indicated by an alternating blue and red bar along the *x*-axis. In each condition participants exerted their peak power output within the first 10% of the trial. Similar patterns of effort were observed in the warmed and non-warmed trials such that W and NW trials were not significantly different at any 5% of trial duration (p>0.05). In addition IW was also not significantly different from NW or W conditions at any 5% time point.



No significant differences observed.

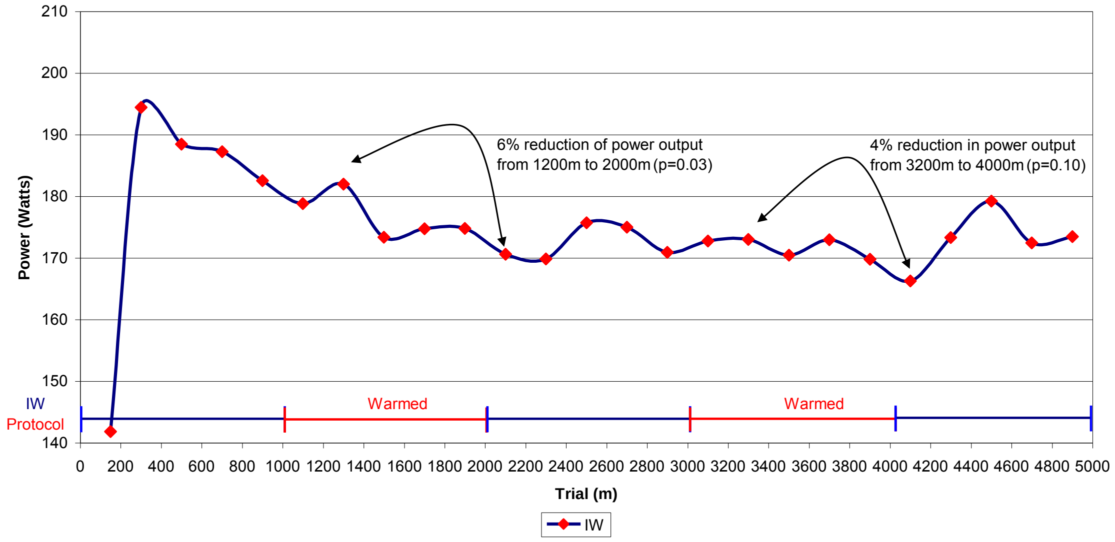
Figure 6.4 Mean power output in three experimental conditions expressed as a function of percentage trial completed.

Power output was dynamically analysed as a function of distance completed and batched into 200m bins in order to quantify dynamic changes to the performance response. Distance domain analysis was conducted at 100m, 200m and 250m intervals in order to identify the most appropriate interval to represent the data. Figure 6.4 appears to show a reduction in power output at a similar distance in each experimental condition. Table 6.3 quantifies these changes in power output at comparable distances in each experimental condition.

Table 6.3 Power output change at comparable distance markers in three experimental conditions.

	Power Output (W)					
	1200m	2000m	**Change**	3200m	4000m	**Change**
IW	182 ± 33	171 ± 34	**-11W 6% (p=0.03)**	173 ± 29	166 ± 26	**-7W 4% (p=0.10)**
NW	184 ± 35	176 ± 27	**-7W 4% (p=0.27)**	175 ± 28	171 ± 25	**-4W 2% (p=0.12)**
W	183 ± 25	175 ± 25	**-8W 4% (p=0.17)**	175 ± 24	175 ± 27	**0W 0% (p=0.94)**

Dynamic analysis of power output in the IW condition, as expressed as a function of distance completed, showed that the first warming interval caused a significant decrease in power output from 1200m to 2000m of trial (p=0.03). This equated to a reduction of 6% of the power output at 1200m. In the second warming interval a decrease in power output of only 4% was observed from 3200-4000m. This reduction in power was not found to be significantly different (p=0.10). These reductions are shown in Table 6.3 and in Figure 6.5 as part of the dynamic plot of IW data.

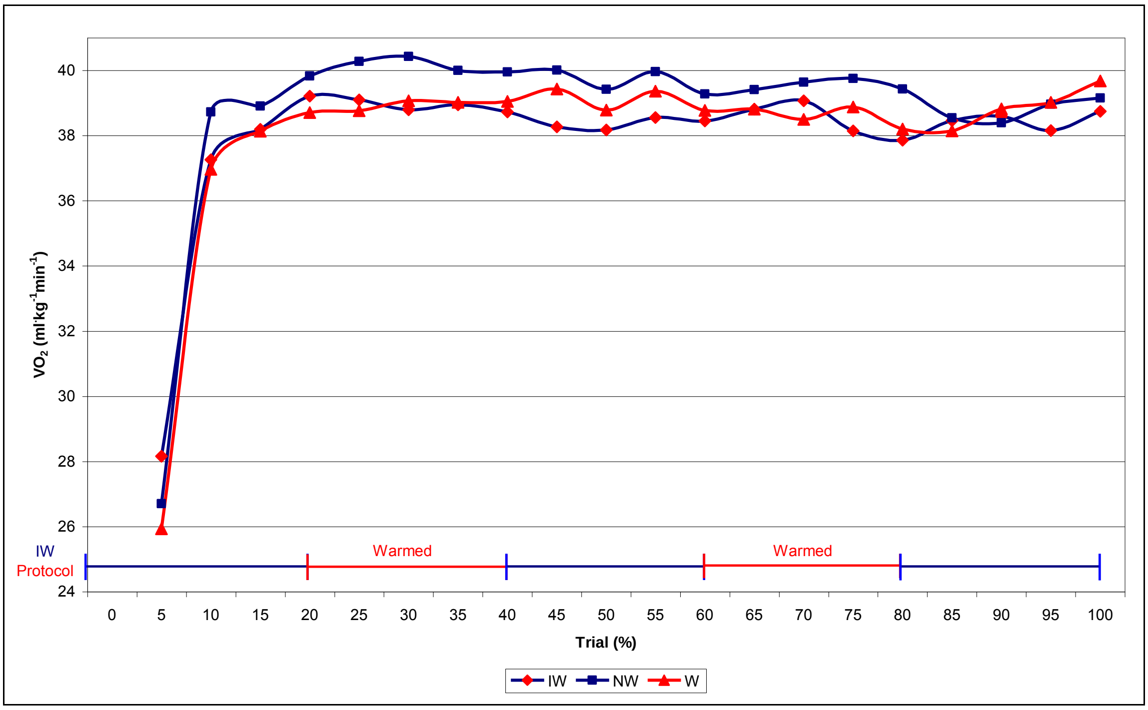


	Power Output (W)					
		1200m	2000m	3200m	4000m	
IW		182 ± 33	171 ± 34 †	173 ± 29	166 ± 26	

† Lower than 1200m p=0.03

†; Significantly different 1200m p<0.05

Figure 6.5 Mean power output in interval warmed condition expressed as a function of distance completed.



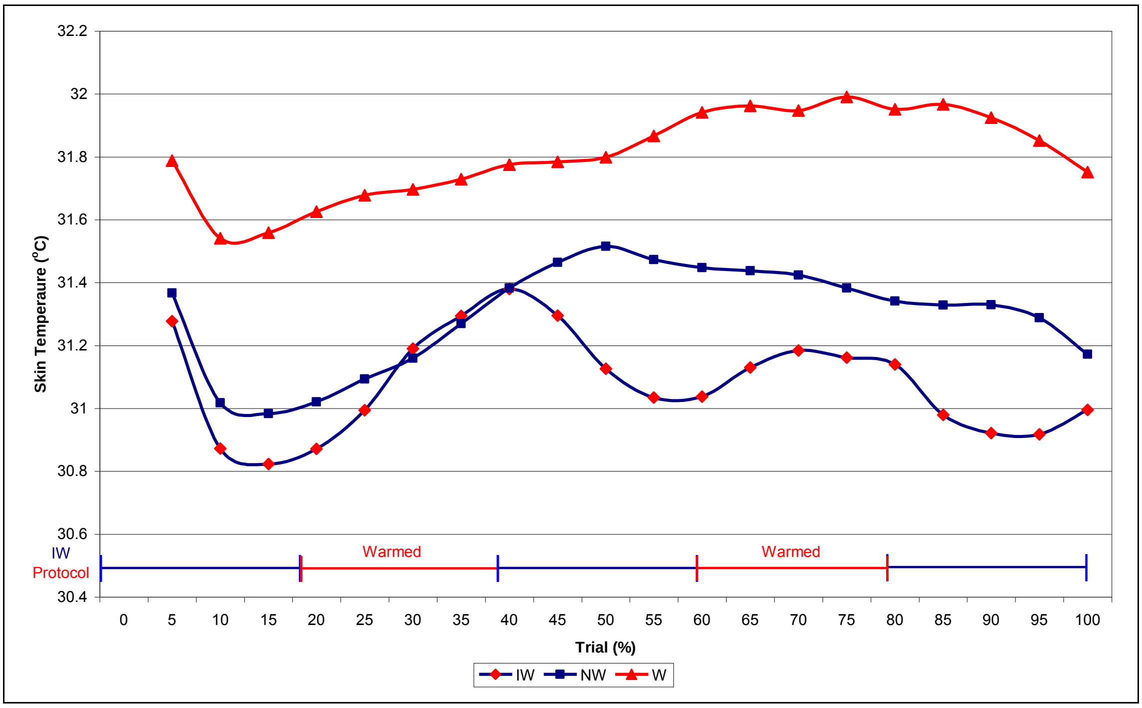
No significant differences observed from 10% of bout until trial completion.

Figure 6.6 Mean oxygen uptake in three experimental conditions expressed as a function of percentage trial completed.

Dynamic analysis revealed that oxygen uptake was significantly lower at 5% trial completion than at any other time point in all three conditions ($p<0.001$). Thereafter no differences were observed between relative oxygen uptakes in the three conditions ($p>0.05$) as seen in Figure 6.6. Following an initial rise in heart rate no differences in heart rate were also observed from 10% of the bout until trial completion. Final heart rates were 162 $\pm$ 20 b.min^{-1} in the IW, 161 $\pm$ 16 b.min^{-1} in the NW and 165 $\pm$ 19 b.min^{-1} in W conditions respectively ($p>0.05$)

Core temperature measures revealed no significant differences between start and end core temperatures. Rises of 1.11 $\pm$ 0.62˚C, 1.20 $\pm$ 0.5˚C, and 1.18 $\pm$ 0.08˚C were demonstrated in the IW, NW and W conditions respectively ($p>0.05$). Final core temperatures were 38.55 $\pm$ 0.27˚C in the IW condition, 38.64 $\pm$ 0.31˚C in the NW condition, and 38.38 $\pm$ 0.30˚C in W condition ($p>0.05$).

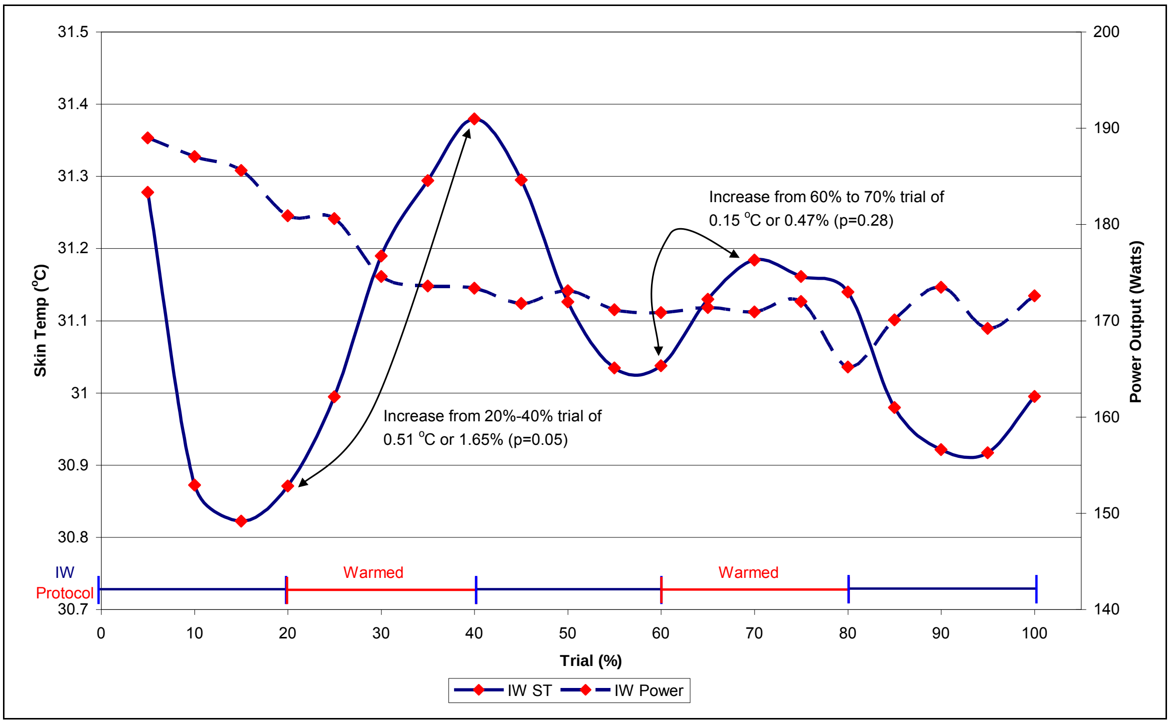
Mean skin temperatures in the warmed condition were not significantly different at any time point throughout the exercise bout, however skin temperatures were an average 0.51 $\pm$ 0.1˚C higher in the warmed condition compared with the non-warmed condition. Skin temperature data from one participant in the warmed condition may have been compromised by poor thermistor connections, for consistency of comparisons skin temperature from this participant was removed from all conditions. Changes in mean skin temperature in the non-warmed trial demonstrated a period of temperature increases from 15-50% trial (0.53˚C; p=0.04) after which no significant changes were observed. Changes in the interval warming condition reflected a distinct condition specific response. Figure 6.7 demonstrates the mean skin temperature response in each of the three conditions.



No significant differences observed between trials at any time point.
Significant increase in IW from 20-40% trial completion (p=0.05). Significant increase in NW 15-50% trial completion (p=0.04). (n=7).

Figure 6.7 Mean skin temperature in three experimental conditions expressed as a function of percentage trial completed.

Dynamic analysis revealed a significant increase in T_{sk} of 0.51˚C in the interval warmed condition between 20-40% trial completion (p=0.05) in response to the first warming interval. The second warming interval from 60-80% trial completion caused a rise of 0.15˚C but this value failed to reach significance (p=0.28). These changes in T_{sk} are plotted in conjunction with changes in power output in Figure 6.8.



Significant increases from 20-40% trial completion (p=0.05).

Figure 6.8 Skin temperature and power output in the interval warmed condition expressed as a function of percentage trial completed.

Pearson product moment correlations revealed significant relationships between core temperature (T_c) and performance time (r=0.828), T_c and power output (r=0.826), and T_c and heart rate (r=0.815) in the IW condition. There was also a significant correlation between skin temperature and $\dot{V}O_2$ (r=0.806) in the same condition. There were no correlations between these variables in the warmed and non-warmed conditions.

Finally qualitative feedback from participants noted that the use of warming lights was not perceived as off-putting in any condition, and despite the ability to change the local temperature from ≈18˚C to ≈35˚C in a short space of time, 25% of the participants commented that they did not immediately notice when the warming commenced in the interval trial.

6.6 Discussion

The main observation from this study was that the periodic introduction of direct radiant heat (35˚C) to the thermoneutral environment (18˚C) resulted in significant reductions in power output (p=0.03) during the first warming period (W1). This intervention significantly altered the pacing profile of the interval warmed condition, however, it did not significantly impede overall average power output or performance time.

Despite the disturbance of the thermal environment during the interval warmed (IW) exercise bout, participants were still able to match efforts with, non-warmed (NW) and warmed (W) trials at RPE 15. This study is the first to demonstrate the influence of a changing thermal environment on dynamic power output profiles during a self-paced bout of exercise.

The dynamic fluctuation of power output across a self-paced bout of exercise without alteration to an overall outcome measure, has previously been described by Edwards and Noakes (2009). In the review of dehydration as a sign of pacing, Edwards and Noakes proposed a strategy of macro-pacing, made of up intermediate meso-pacing, and dynamic micro-pacing strategies, which allow athletes to complete an exercise bout with similar overall outcome effects despite dynamic micro-pacing changes in physiological measures. This concept has however never been applied to an investigation of changes in the thermal environment.

The interval warming condition in this study presented an opportunity to investigate the influence of changes in a thermal environment during an exercise bout and the consequential effect on pacing strategies and provides partial support for the concept of multi-level pacing plans described by Edwards and Noakes (2009). The significant reduction in effort of 6% (p=0.03) which can be observed from 1200m-2000m trial distance in the absence of overall differences in performance demonstrates that participants were able to dynamically alter their pacing strategy without impacting on overall performance. However, with the Edwards and Noakes concept of multi-level pacing strategies, would suggest this reduction in effort should have consequently been balanced by an increase in power output later in the bout in order to match the expected effort required for the overall performance.

The inconsistency between these findings and the theoretical expectations may be attributed to the use of the RPE clamp in the trial which limited participants by asking them to maintain an effort equivalent to RPE 15 consistently throughout the bout.

Whilst the combination of the clamp and thermal disturbance would result in a reduction in their effort in the first period of warming, with a large proportion of the trial still unknown, the clamp would not allow for an increase in effort in the latter stages of the bout when participants are more confident of the effort yet to come, and thus more likely to consider increasing intensity accordingly.

The Edwards and Noakes (2009) model of multi-level pacing plans was developed on the premise that footballers would work as hard as they could in an overall game, whilst in this study participants where asked to maintain a consistent sub-maximal level of perceived exertion. It may thus be argued that use of an RPE clamp limited the participants ability to respond the imposed thermal changes, and fluctuate effort based upon innate pacing plans creating discrepancies between the observed and expected pattern of multi-level pacing plans.

This study's observation of aspects of a multi-level pacing strategy in self-paced rowing is in addition to the description of such strategies in football and world record athletics (Edwards and Noakes, 2009, Noakes et al., 2009) and suggests that the ability to alter pace may no longer be considered a singular shift within a bout of exercise. The impact of challenges during exercise may therefore be influenced by the point at which they are applied during a trial. Noakes et al., (2009) have previously identified that in order to complete a world record mile the greater application of effort is most often exerted in laps 1 and 4 rather than laps 2 and 3. In the current study, the disturbance to power output was brought about by changes in the thermal environment, this disturbance, seen in the first warming interval was not seen the second warming interval. The timing of this application within a pacing strategy may, in part, also explain the findings of Schlader et al., (2010a) who observed a greater impact of changes in temperature upon exercise intensity upon the commencement of exercise than during the remainder of a 60min cycling exercise trial.

Evidence of the altered impact of thermal challenges, dependent upon their point of application in a bout, may be demonstrated by the disturbance to power output caused by interval warming in the first warming interval, which was however not significantly different during the second interval ($p=0.10$) from 3200m to 4000m. In line with the proposition of macro- and meso-pacing plans being based upon individualised homeostatic set-points (Edwards and Noakes, 2009), it may be suggested that the second period of warming was insufficiently intense in order to trigger a disturbance in excess of the proposed set point and thus there was less of a reduction in power output than was observed in the first warming interval. Indeed the effect of the second bout of warming on skin temperature was 29% less than that of the first bout of warming. Set-points around which thermoregulation may be based were initially used to describe how deep body temperature was regulated in mammals (Hammel et al., 1963), the concept may now be better described as an interthreshold zone, but this area is still considered somewhat of a mystery (Cooper, 2002, Mekjavic and Eiken, 2006). The interaction between power output and skin temperature seen in this study fits well with the proposal of a tolerable threshold of thermoregulation (Mekjavic and Eiken, 2006). Furthermore it has parity with a macro-pacing strategy and the theory of a complex metabolic controller capable of adjusting the effort in response to events which occur during a bout of exercise (Edwards and Noakes, 2009, Tucker, 2009).

The consistency of oxygen uptake and heart rate in each condition in the present study shows that performers were able to maintain the exercise intensity. The average $\dot{V}O_2$ response equated to 66% of $\dot{V}O_{2peak}$ and supports the suggestion that performers on rowing ergometers are able to maintain an exercise intensity at RPE 15 (Marriott and Lamb, 1996) despite the difference in the environmental thermal conditions. The consistency of these physiological measures in different thermal environments is in contrast to recognised opinion on exercise in the heat (Casa, 1999) which would suggest that $\dot{V}O_2$ and heart rate should increase similarly with the same increase in work intensity. This assumes however, that intensity is fixed and isn't able to fluctuate in response to biological mechanisms. In self-paced exercise trials previous authors have identified a reduction in power output (intensity) in order to maintain homeostasis (effort) which may be influenced by a number of biological mechanisms, furthermore that such a reduction may occur prior to changes in biological markers such as core temperature (Tucker et al., 2004). The consistency seen in oxygen uptake and heart rate in the present study may be considered as evidence of participant's ability to match intensity to effort, rather than effort to intensity; however it could also be considered that the similarity of these data may reflect the use of exercise intensity insufficient to produce significant challenges to cardiovascular system.

Previous studies involving self-paced exercise have identified a reduction in effort prior to changes in core temperature (Tucker et al., 2006c, Tucker et al., 2004). The data from this study does not show a significant difference in dynamic core temperatures across the three conditions, which may also be a consequence of the relatively minor perturbation in temperature employed in this study. However, it should be noted that in each of the studies which have demonstrated an anticipatory reduction in power output, participants were asked to complete a set amount of work in the quickest time possible.

Such protocols could be considered maximal self-paced trials, rather than the sub-maximal self-paced exercise trial employed in the present study, in this context it becomes more apparent why differences in physiological variables in this study might have a lesser magnitude. This presents an interesting dichotomy in which an anticipatory reduction is seen in maximal self-paced exercise but not in sub-maximal self-paced exercise, which may be of interest to future research.

Average core temperature (T_c) and mean skin temperatures in the present study were highest in the non-warmed trial, this reflects participants' abilities to maximise thermal efficiency in the environment best able to remove heat, a finding which is in agreement with work by Saunders et al., (2005). The heating of skin in the warmed condition, which artificially elevated T_{sk}, was perhaps also responsible for the suppression of T_c in the warming trial, as T_c and T_{sk} have been previously suggested to have an inverse relationship in order to maintain thermoneutrality (previously described by Huizenga et al., 2004). In the presence of the changing thermal environment in the interval warmed condition the changing influence of these physiological parameters cannot be overlooked. The work of Frank et al., (1999) has previously shown that skin temperature is as likely as core temperature to influence thermoregulatory behaviour in humans at rest. Furthermore, Flouris and Cheung (2009) have shown that during 10min of exercise participants selectively adopt a strategy in order to maintain thermoneutrality. It is certainly plausible that the reduction in power output in the first warming period of the current study was in response to an unanticipated increase in skin temperature thus bringing about a behavioural change. The practical application of this information is unclear, however it could be suggested that, based on this evidence, a strategy of early intervention may have a better chance of disrupting an opponent's strategy than one introduced later in an exercise bout.

Irrespective of condition, an end-spurt in power output at 80-85% can be observed in each of the three conditions. The end-spurt, initially identified by Catalano (1973), and discussed in detail in Chapter 4, seems to be an integral part of self-paced exercise bouts, and in the current study, occurred at a similar time and to a similar amplitude in spite of different thermal conditions. The mechanisms behind such a consistent behaviour clearly require a more detailed exploration, but it is suggested that an end-spurt of effort may be a core component of any self-regulated multi-level pacing strategy.

6.7 Summary

This study has demonstrated that over a 5000m time-trial participants were able to match an RPE 15 (hard) perceived effort despite different thermal conditions. In an interval warming environment, participants in this study significantly reduced power output in response to an initial thermal challenge (p=0.03), the down-regulation of effort in a second period of warming was reduced to a magnitude which did not present a significant reduction in performance (p=0.10). Significant correlations between physiological and performance responses were observed in the interval condition which were not apparent in the constant thermal conditions. This ability to significantly alter a pacing plan during exercise without change to the overall outcome measures is evidence of the use of multi-level pacing plans during a bout of self-paced exercise; however the influence of changes may be contingent upon the period of the exercise bout in which they are applied.

Chapter Seven

Comparison of self-paced and enforced-pace exercise protocols on the assessment of maximal oxygen uptake.

Chapter Seven

Comparison of self-paced and enforced-pace exercise protocols on the assessment of maximal oxygen uptake.

7.0 Abstract

The purpose of this study was to compare the performance and physiological responses of participants in a conventional protocol to assess of maximal oxygen uptake with a self-paced perceptually regulated protocol to assess peak oxygen uptake. Ten male participants (age; 29 $\pm$ 6 years) performed four maximal exercise trials in two different experimental conditions; 1) a conventional incremental exercise test to maximal exertion (Conv) and 2) a self-paced perceptually regulated incremental exercise test also to maximal exertion (SP). Each trial was randomly ordered. In the conventional condition enforced increments of 25 watts per minute were applied until volitional exhaustion at an unknown endpoint. In the self-paced condition participants increased intensity every 2min based upon RPE scores of 11, 13, 15,17 and 20, the experiment therefore ended after 10min with a final 2min stage at RPE 20; maximal exertion. Peak oxygen uptake was similar across the 4 trials (p=0.523 to p=1.0, range; 3ml·kg^{-1}·min^{-1}). Peak power output was also similar in each trial (p=1.0, range; 8 Watts). The only peak response to display a significant difference was the peak heart rate in Conv1 vs. SP2 (186 $\pm$ 9 b·min^{-1} vs. 178 $\pm$ 10 b·min^{-1}; p=0.01). Dynamic analysis revealed the time spent at an oxygen uptake similar to $\dot{V}O_{2peak}$ was significantly longer in the conventional condition when compared with the self-paced condition (p<0.05) whilst measures of reliability revealed a lower coefficient of variation at 90-100% trial completion in the self paced condition when compared with the conventional condition. Subtle reductions in power output at RPE 17 and 20 also suggested the presence of energy-sparing behaviour in tests of maximal exertion unobservable in the conventional protocol. This study showed that a perceptually based maximal exercise test can match the physiological and performance responses of a conventional $\dot{V}O_{2max}$ test and could thus be used in multiple modalities. Furthermore, the reduced variation in $\dot{V}O_{2peak}$ in the self-paced condition and the observation of energy-sparing reductions in pace during the self-paced bouts suggest the influence of complex metabolic control which cannot be observed using conventional protocols.

7.1 Introduction

The assessment of $\dot{V}O_{2max}$ is perhaps the most common measure in exercise physiology (Howley et al., 1995). Its origin dates back to the early work of A.V. Hill (Hill et al., 1924a, Hill et al., 1924b, Hill et al., 1924c) who challenged himself and his colleagues to run repeated laps of a 90m grass track observing that:

> "the oxygen intake attains a maximum value, which in athletic individuals of about 73 kilograms bodyweight is strikingly constant (in the case of running) at about 4 litres per minute". p 157 (Hill et al., 1924a)

Since this pioneering work, high levels of oxygen uptake in a maximal exercise test have been shown to increase following aerobic training, and are considered a key marker of endurance capacity (McArdle et al., 2001). It could be argued however, that the role of maximal oxygen uptake in exercise has now reached a position in which its importance has perhaps been overstated. For example, whilst a high $\dot{V}O_{2max}$ is imperative in endurance exercise, as long as a 'trained' status is achieved, the relative/absolute value does not change dramatically year on year (Brooks et al., 1996a, Clark et al., 2008). In addition, it is now commonly accepted that measures of blood lactate accumulation more closely reflect the training status of athletes than $\dot{V}O_{2max}$ (Astrand et al., 2003, Edwards et al., 2003).

A test to assess maximal oxygen uptake is an integral part of most exercise-based investigations as it provides a baseline description of participants' characteristics (Winter, 2006). However, the common use of secondary criteria to establish maximal oxygen uptake, such as those described by the British Association of Sport and Exercise Science (BASES) criteria (Bird and Davison, 1997), can lead to underestimation of $\dot{V}O_{2max}$ by as much as 27% (Poole et al., 2008). In addition, the use of differing exercise modalities has also shown that the measurement of maximum oxygen uptake can vary by as much as 29% depending on the modality used in the protocol (Jensen and Katch, 1991, Bassett et al., 1984). An inability to record similar values of $\dot{V}O_2$ at maximum effort across multiple modalities and / or most commonly, a failure to demonstrate a $\dot{V}O_2$ plateau has led to the use of potentially confusable terms such as $\dot{V}O_{2peak}$ and $\dot{V}O_{2max}$.

The use of the descriptive labels ‘peak’ and ‘maximal’ have both been previously applied to oxygen uptake responses in incremental exercise tests (Day et al., 2003, Whipp, 2010). Traditionally, a peak oxygen uptake response defines the highest oxygen uptake observed in an exercise test in which a $\dot{V}O_2$ plateau has not been observed (Day et al., 2003, Whipp, 2010). In contrast, the descriptor of $\dot{V}O_{2max}$ is reserved for a test in which $\dot{V}O_2$ demonstrates an increase of less than 2 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ or 3% with a concomitant increase in exercise intensity, and in which some form of secondary criteria is met (Brooks et al., 1996a, Bird and Davison, 1997). Together, these primary and secondary criteria are used to give confidence to the term $\dot{V}O_{2max}$. It has however been argued, that any exercise termed maximal cannot in theory be surpassed, and therefore must be followed by complete exhaustion (Noakes, 2008a). Since this is rarely the case in exercise tests, which are by their very nature only ever to ‘volitional exhaustion’, the term $\dot{V}O_{2peak}$ is used by some authors to represent what others would term a maximal oxygen uptake (St Clair Gibson et al., 2001b, Baden et al., 2005). The occasionally ambiguous use of the terms peak and max, combined with the philosophical suggestion that a truly maximal effort would elicit death, brings into question the term maximal oxygen uptake and consequentially the use of conventional methods used to elicit a $\dot{V}O_{2max}$ response in which researchers can have unequivocal confidence.

In an effort to clarify the relevance of a $\dot{V}O_2$ plateau during a maximal exercise test (discussed further in Chapter 2), recently a number of authors (Midgley and Carroll, 2009, Rossiter et al., 2006, Snell et al., 2007, Poole et al., 2008) have developed the concept of a supra-maximal exercise test to confirm that a maximal measure has been achieved. Supra-maximal testing involves the use a verification phase following an incremental exercise test in order to verify that a maximal response has been achieved, a concept originally described by Thoden (1991). In short, participants would complete a conventional incremental exercise test, then, following 5-15min recovery, an additional run to exhaustion at an intensity one stage higher than that at which a maximal score had just been identified. Should the $\dot{V}O_{2peak}$ in the verification phase be less than 2% different than the $\dot{V}O_{2max}$ demonstrated in the incremental phase, it is suggested that researchers can be confident that a maximal $\dot{V}O_2$ response has been achieved (Midgley et al., 2007b). Whilst the concept of $\dot{V}O_2$ verification is not without its merits the concept is still based upon the use of the conventional $\dot{V}O_{2max}$ exercise test which has itself demonstrated inconsistencies.

The conventional $\dot{V}O_{2max}$ test is used to assess individuals deemed capable of exercising to a maximal intensity, and most commonly comprises of a continuous incremental effort which requires participants to respond to an ever-increasing work rate. Effort increases are applied often by stage or by ramp, dependent upon the requirements of the investigation; however common factors are those of an enforced exercise intensity, in an exercise bout to which participants do not know the endpoint, until fatigue. These factors are all incongruent with a model of fatigue based on complex metabolic interaction (Noakes et al., 2005) in which no single physiological marker has been shown to bring about fatigue (Edwards and Noakes, 2009). Indeed many of the previous measures of $\dot{V}O_{2max}$ are based on a peripheral model of fatigue in which the perception of effort and the pacing of an exercise bout plays no part. This inability to fluctuate the pace of an exercise bout or know the endpoint of the bout is in opposition to a complex model of fatigue (Noakes, 2008b). In light of advances in the understanding of fatigue, the strength and relevance of conventional measures of $\dot{V}O_{2max}$ in exercise testing may once again be questioned (Hawley and Noakes, 1992).

Relatively limited attention has been given to the psychophysiological components associated with the determination of $\dot{V}O_{2max}$ (Midgley et al., 2007b) and whilst methods of sub-maximal prediction of $\dot{V}O_{2max}$ based on perceptually regulated scales have previously been described (Lambrick et al., 2009), to-date, no-one has attempted to validate a perceptually based maximal oxygen uptake test. The recent study by Lambrick et al., used data from an incremental sub-maximal exercise test to predict $\dot{V}O_{2max}$ at RPE 19 and 20, these predictions where then correlated with a $\dot{V}O_{2max}$ response elicited by a conventional max test on a separate occasion. Using a treadmill, participants were asked to complete an incremental step test in which the steps were linked to conventional increases and then adjusted to match a predetermined RPE. The authors found that this protocol was capable of predicting an accurate $\dot{V}O_{2max}$ as measured using the conventional test, but also found that the extrapolated prediction for $\dot{V}O_2$ at RPE 19 was a better predictor of a peak value than that of the $\dot{V}O_2$ at RPE 20. Their work provides support for the concept that an absolute maximal $\dot{V}O_2$ response cannot be elicited in a volitional exercise trial. But this is tempered by the design of protocol which still has large reliance on the enforced imposition of pace.

The concept of pacing is paramount to successful production of any maximal effort. When considered alongside the suggestion that pacing may be related to anticipation of an effort yet to come (Ulmer, 1996, St Clair Gibson et al., 2006), and that knowledge of an exercise performance end point may influence pacing (Tucker, 2009), it seems plausible that a conventional exercise test may not represent the best way to elicit a maximal exercise response. Chapter 6 of this thesis demonstrated that sub-maximal self-paced exercise presents a reduced metabolic challenge when compared with matched intensity enforced pace exercise (Lander et al., 2009). Furthermore, the design of the conventional maximal exercise test prevents the participant from utilising any anticipation of the exercise end point, on either a scalar or chronologically based judgment.

If exercise were grouped as either enforced paced or self-paced, the majority of exercise, be it recreational training or race performance, would most likely be considered self-paced, and with a relatively familiar or known endpoint. Self-paced exercise has been shown to demonstrate non-random fluctuations in power output which have been proposed to represent physiological responses governed by a complex metabolic control system (Tucker et al., 2006a). The fluctuations seen in self-paced exercise are thought to up- and down-regulate work done in order to defend against homeostatic imbalance. It is thought that certain perturbations in metabolic measures are tolerated in the context of an overall performance, which is mapped against an anticipated experience and expressed through conscious perceptions of fatigue (Edwards and Noakes, 2009). A perceptually based maximal exercise test with a known exercise endpoint would provide participants with the opportunity to vary pace throughout an exercise trial, and to use the teleoanticipatory mechanisms, described by recent authors, as fundamental to the complex control of physiology during exercise to fatigue (St Clair Gibson et al., 2006). But, as yet, such an exercise protocol has not been described.

This study was therefore designed to investigate and attempt to validate a perceptually regulated maximal test which was proposed to result in similar levels of peak oxygen uptake when compared with responses from a conventional $\dot{V}O_{2max}$ test.

7.2 Purpose of the study

The purpose of this study was to compare performance and physiological responses of participants to a conventional test of maximal oxygen uptake (Conv) with a self-paced, perceptually regulated test of peak oxygen uptake (SP).

7.3 Aims of the study

To validate a self-paced, perceptually regulated test of peak oxygen uptake.

To compare physiological responses in a perceptually based maximal exercise test to those of a conventional maximal exercise test.

To compare performance responses in a perceptually based maximal exercise test to those of a conventional maximal exercise test.

7.4 Methodology

7.4.1 Participants

Ten healthy, well-trained male participants agreed to take part in this study (Table 7.1). All were informed of the procedures in advance and informed consent was provided prior to any data collection. The study was approved by the Central Regional Ethics Committee of New Zealand and from the Faculty Research Ethics Committee at Leeds Metropolitan University. All participants were recreational gymnasium users and each received technical advice from a qualified rowing coach on using the rowing ergometer during a two-week familiarisation period.

Table 7.1 Anthropometric characteristics of the study participants.

	Anthropometric Characteristics		
	Height (m)	Weight (kg)	Age (years)
Mean ± SD	1.80 ± 0.05	81.86 ± 13.06	29 ± 6

7.4.2 Participant screening and familiarisation

Participant screening and familiarisation followed the pattern described in Chapter 3 General Methods.

7.4.3 Preliminary testing

All participants performed a standardised 10min familiarisation trial which consisted of a four stage incremental protocol which was subsequently used as a standardised priming exercise in each of the conditions and is described in detail in Chapter 3 General Methods.

7.4.4 Experimental procedures

Each participant completed four maximal bouts of rowing in two different experimental conditions in an individually randomised order. In condition one (Conv) participants completed an incremental exercise test to maximal exertion. In condition two (SP) participants completed a novel self-paced perceptually regulated incremental exercise test also to maximal exertion. For the purposes of reliability and validity, both trials were repeated in a randomised order.

Condition one consisted of an incremental step test to volitional exhaustion on a Concept 2 rowing ergometer (Model D: Concept 2, Tauranga, NZ) for the determination of peak aerobic power ($\dot{V}O_{2peak}$). Oxygen uptake (Cortex MetaMax 3B, Cortex Biophysik, Leipzig, Germany) and power output (RowPro v2.006 software. Digital Rowing, Boston, MA, USA) were continuously monitored stroke-to-stroke. Power output was visible via the Concept 2 display unit at all times. Initial exercise intensity was set at 150 Watts for 3min then increased each minute in 25 Watts increments until volitional exhaustion, or an inability to maintain the required power output was reached. This protocol has previously been described by Smith (2000) and is used in assessments by Rowing New Zealand.

Condition two also consisted of an incremental exercise test to volitional exhaustion, however the intensity at each stage was set by a rate of perceived exertion (RPE) rather than by an externally imposed target power output. At the beginning of the trial, participants were told to start at an RPE of 11 (Light) and increase their intensity by 2 RPE points every 2min, such that the final 2min were at RPE 20 (Maximal exertion). Stage intensities were therefore RPE 11, 13, 15, 17 and 20. A final increment of 3 RPE points was used as pilot study data had identified that the difference between RPE 19 and 20 was not sufficient to observe meaningful differences in exertion levels.

Pilot study data also identified that 1min stages were not sufficient for participants to feel comfortable at having replicated a given intensity, before having to increase effort again to progress to the following stage, 2min stages were therefore used.
No visual feedback in the form of power output was provided in this condition to ensure participants self-paced, however participants were made aware of the total exercise duration and were regularly made aware of the stages remaining to exercise endpoint. In addition, an RPE chart was visible to participants throughout the trial for participants' reference.

Exercise trials were held at the same time of the day on each of the four occasions to avoid potential diurnal variations, and were each separated by approximately one week. Participants were instructed to refrain from additional organised physical activity during the testing period and to maintain habitual exercise routines. Ambient laboratory temperature was standardised at 18˚C across all tests while relative humidity remained consistent (35-45%). All participants consumed a beverage of water 2 hours before the start of the test (5 ml·kg^{-1}·min^{-1}) to ensure comparable levels of euhydration between participants and condition (Montain and Coyle, 1992). All participants were positively encouraged, and regularly reminded to maintain the required intensity throughout the trial. (Figure 7.1).

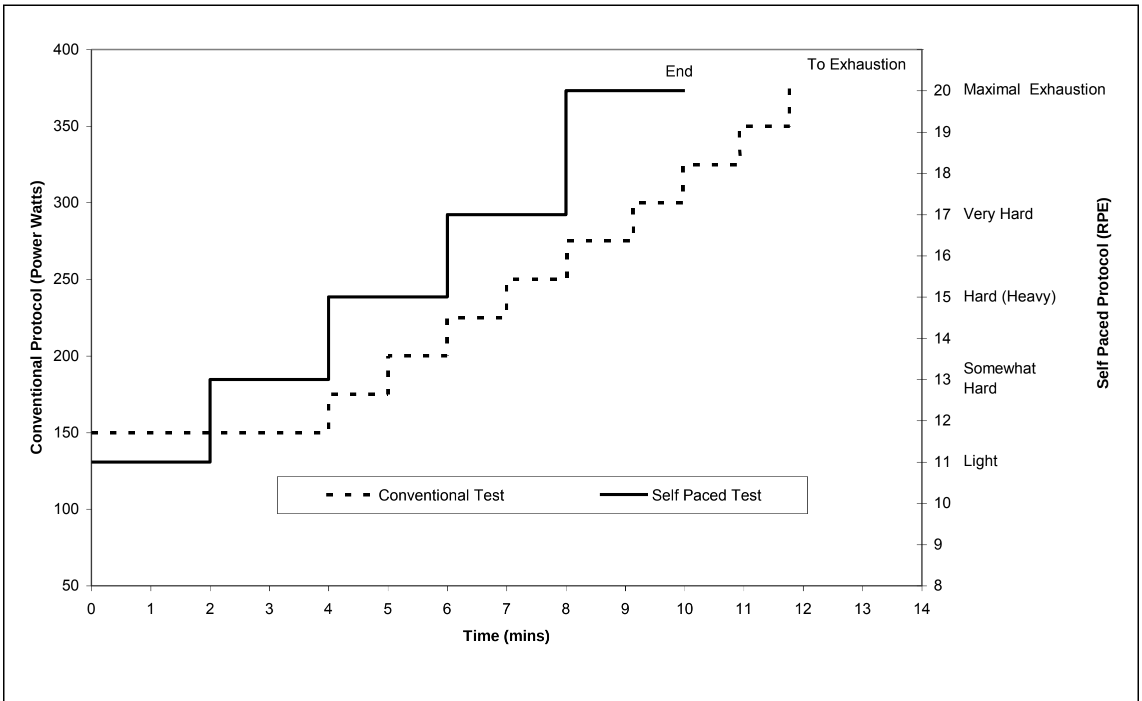


Figure 7.1 A diagrammatic representation of the self-paced and conventional exercise protocols.

7.4.5 Oxygen uptake, heart rate and power output measurement

Oxygen uptake, heart rate and power output measurements followed the pattern described in Chapter 3 General Methods.

In brief: Oxygen uptake was continuously recorded breath-by-breath (Cortex MetaMax 3B, Cortex Biophysik, Leipzig, Germany). Whole blood capillary samples were drawn from the finger tip prior to exercise and at the immediate cessation of time-trial performances for the analysis of blood lactate (BLa) concentration (Lactate Pro, Akray Inc, Kyoto, Japan). Heart rates (HR) were continuously recorded (S610i, Polar, Kempele, Finland). Stroke-to-stroke power output was assessed using the RowPro v2.006 software (Digital Rowing, Boston, MA, USA) in conjunction with the Concept 2 interface.

7.4.6 Calibration procedures

Calibration procedures followed the pattern described in Chapter 3 General Methods.

In brief: Prior to each exercise trial the Cortex Metamax portable online gas analysis system was calibrated using a certified mixture of gases (15% O_2 5%, CO_2 stored with a N_2 balance). The digital volume transducer was calibrated using a certified 3L syringe with an equivalent of 5 inspirations and expirations. Drag factor for the ergometer was set to 130 10^{-6} N·m·s^2 prior to any data recording.

7.4.7 Data analysis

Peak values of oxygen uptake, heart rate and power output were individually identified according to BASES guidelines (Bird and Davison, 1997). In order to assess dynamic variations the data was transformed into 30s measures to reduce data noise and create comparable measurement intervals. Due to variations in the time to complete each trial the bout was considered as 100% and measures were then time aligned and batched into 5% bout means for each outcome measurement.

7.4.8 Statistical analysis

The statistical software packages SPSS (version 11.0, SPSS, Chicago, IL, USA) and Graphpad Prism (version 4, GraphPad Software Inc, La Jolla, CA, USA) were used for all statistical analysis. Results were assessed for normal distribution then statistically compared using one-way repeated measures analyses of variance (ANOVA) with post-hoc Bonferroni correction statistics. Other comparisons were made using paired Student's *t*-tests. Probability values of less than 0.05 were considered significant. All results are expressed in means ± SD.

A number of measures of reliability were used as advocated by Atkinson and Nevill (1998). Pearson product moment correlations were used to calculate r values. Intra-class coefficients (icc) were calculated using the formula previously described by Bland (2004b) to provide another measure of the consistency of measures. Coefficients of variation (CV) were also calculated using the formula previously described by Hopkins (2010) to provide a measure of percentage variation seen in the final stage of each trial. Limits of Agreement (LoA), promoted by Bland and Altman (2010) are also reported once corrected for degrees of freedom as recommended by Hopkins (2000).

7.5 Results

Peak $\dot{V}O_2$ was similar across the 4 trials with a range of 3 ml·kg^{-1}·min^{-1} across the 4 bouts (range: 52 $\pm$ 11 to 55 $\pm$ 12 ml·kg^{-1}·min^{-1}) as shown in Table 7.2 and Figure 7.2. Peak power output and peak heart rate were also statistically similar across the 4 bouts (ranging from p=0.098 to p=1.0). The only peak measure to reach a statistically significant difference of $p<0.05$ was the comparison between the heart rate seen in Conv1 and SP2; the average values in these trials were 186 $\pm$ 9 in Conv1 and 178 $\pm$ 10 b·min^{-1} in SP2 (p=0.01).

Values of peak $\dot{V}O_2$, peak power and peak heart rate taken over stationary 5s averages can be found in Table 7.2 along with post exercise blood lactate values and a record of ventilatory threshold and respiratory exchange ratio at $\dot{V}O_{2peak}$.

Table 7.2 Performance and physiological responses in four experimental trials.

	PPO (Watts)	$\dot{V}O_{2peak}$ (ml·kg^{-1}·min^{-1})	HR peak (b·min^{-1})	BLa post (mmol·L^{-1})	T_{vent} (% $\dot{V}O_{2peak}$)	RER (@ $\dot{V}O_{2peak}$)
SP1	320 $\pm$ 34	52 $\pm$ 11	181 $\pm$ 10	12.7 $\pm$ 3.3	75 $\pm$ 9	1.35 $\pm$ 0.09
SP2	328 $\pm$ 36	54 $\pm$ 10	178 $\pm$ 10	11.2 $\pm$ 3.7	72 $\pm$ 5	1.30 $\pm$ 0.11
Conv1	325 $\pm$ 25	55 $\pm$ 12	186 $\pm$ 9	13.0 $\pm$ 3.2	78 $\pm$ 9	1.33 $\pm$ 0.07
Conv2	324 $\pm$ 19	54 $\pm$ 11	181 $\pm$ 9	12.4 $\pm$ 3.1	78 $\pm$ 7	1.32 $\pm$ 0.08

Post exercise blood lactate responses were shown to be similar across the 4 trials (p=0.109-1.0) and whilst trials were randomly assigned, and no learning effect was demonstrated, it is interesting to note a tendency for BLa and peak heart rate to be lower in the second trial than in the first in both the self-paced and conventionally paced maximal conditions. p values for all statistical comparisons seen in Table 7.2 can be found in Table 7.2a.

Table 7.2a p values for mean performance and physiological responses in four experimental trials.

PPO			
	SP1	SP2	Conv1
SP2	1.0		
Conv1	1.0	1.0	
Conv2	1.0	1.0	1.0

$\dot{V}O_{2peak}$			
	SP1	SP2	Conv1
SP2	1.0		
Conv1	0.523	1.0	
Conv2	1.0	1.0	1.0

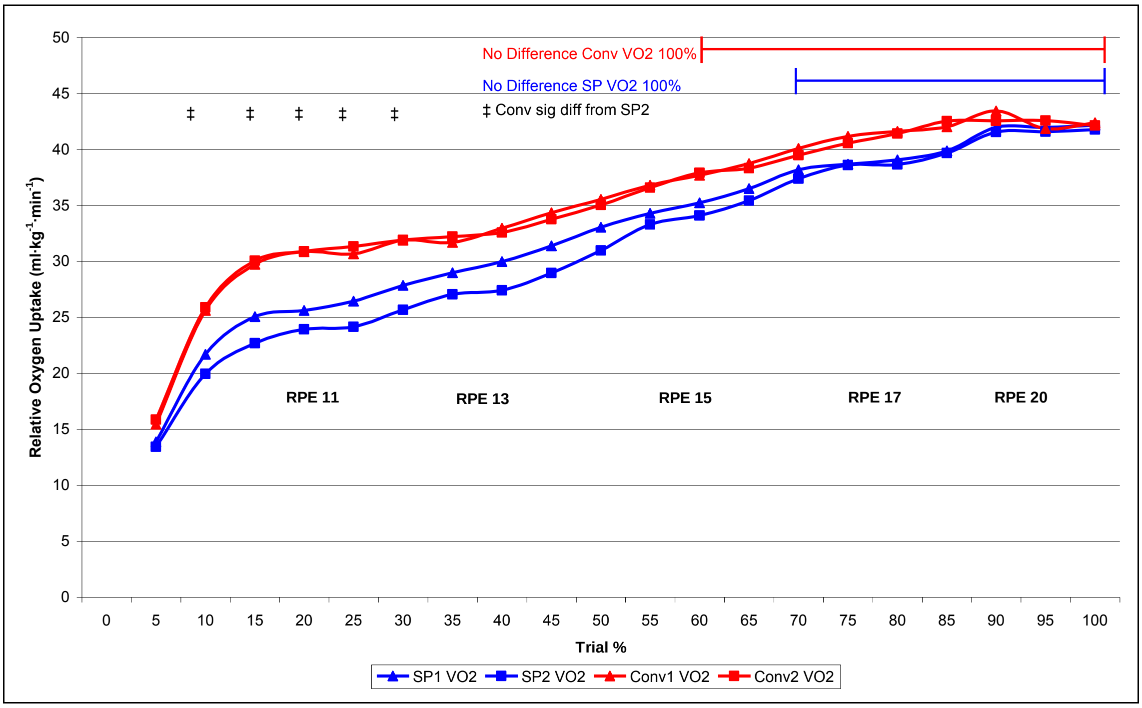
HR peak			
	SP1	SP2	Conv1
SP2	0.988		
Conv1	0.098	0.001*	
Conv2	1.0	0.798	0.221

BLa post			
	SP1	SP2	Conv1
SP2	1.0		
Conv1	1.0	0.109	
Conv2	1.0	1.0	1.0

T_{vent}			
	SP1	SP2	Conv1
SP2	1.0		
Conv1	0.876	1.0	
Conv2	0.247	0.080	0.434

RER			
	SP1	SP2	Conv1
SP2	1.0		
Conv1	1.0	1.0	
Conv2	1.0	1.0	1.0

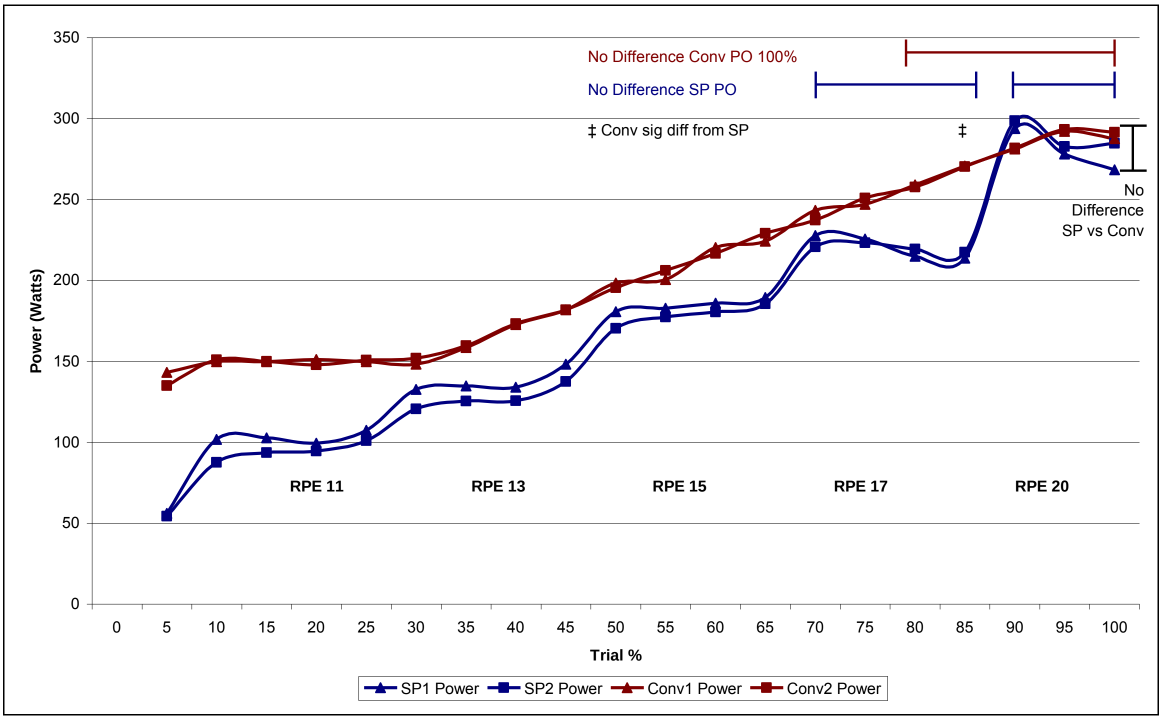
* = $p<0.05$.



‡ Conventional trials significantly different from SP2.

Figure 7.2 Relative oxygen uptake responses in four trials expressed as a function of percentage trial completed.

Post-hoc testing showed that the peak $\dot{V}O_2$ in the self-paced trials was not significantly different from $\dot{V}O_2$ values from 70% trial completion onwards (p>0.05). However, peak $\dot{V}O_2$ in the conventional trials was statistically similar from 60% trial completion onwards. The similarity of these data can be accounted for in the variability of individual performance responses as recorded in the standard deviation of scores as shown in Table 7.2. For example the standard deviation of $\dot{V}O_{2peak}$ in the SP1 trial of 11ml·kg^{-1}·min^{-1} represents a variation of 21% above or below the mean value of 52ml·kg^{-1}·min^{-1}.



‡ Conventional trials significantly different from SP trials.

Figure 7.3 Power output responses in four trials expressed as a function of percentage trial completed.

Power output also expressed a similar pattern to that of $\dot{V}O_2$, with participants spending 10% less of the condition at a power output similar to peak power output in the self-paced bouts compared to that in the conventional bouts (Figure 7.4). Power output in the self-paced trials was not significantly different at RPE 20 (SP1 vs. SP2 from 90-100% trial completion), however it was significantly higher than power output at RPE 17 (70-85% trial completion) (Figure 7.3).

Pearson product moment correlations, shown in Table 7.3, reveal significant correlations between the peak power output in the SP1 trial and all other trials (r=0.79-0.82 p<0.01). $\dot{V}O_{2peak}$ was also well correlated across the 4 trials. SP1 was correlated with SP2 with an r value of 0.93 and with r values of 0.91 in Conv1 and Conv2 trials.

Table 7.3 Measures of reliability in four experimental trials (Pearson product moment correlations).

PPO			
	SP1	SP2	Conv1
SP1			
SP2	0.89 ‡		
Conv1	0.69 *	0.79 ‡	
Conv2	0.81 ‡	0.75 *	0.67 *

$\dot{V}O_{2peak}$			
	SP1	SP2	Conv1
SP1			
SP2	0.93 ‡		
Conv1	0.91 ‡	0.93 ‡	
Conv2	0.91 ‡	0.91 ‡	0.90 ‡

* =p<0.05. ‡ =p<0.01.

Intra-class correlation coefficients demonstrate the reliability of these findings with correlations of no less than 0.97 across all peak responses in all bouts. The best test-retest reliability was seen in $\dot{V}O_2$ peak with an icc of 0.999. All icc's along with upper and lower limits of agreement are shown in Table 7.4.

Table 7.4 Measures of reliability in two experimental conditions (Intra-class correlation coefficients and Limits of Agreement).

	PPO (Watts)		$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)		HR peak ($b \cdot min^{-1}$)		BLa post ($mmol \cdot L^{-1}$)		T_{vent} (% $\dot{V}O_{2peak}$)		RER (@ $\dot{V}O_{2peak}$)	
icc	0.972		0.999		0.999		0.996		0.999		0.998	
	U	L	U	L	U	L	U	L	U	L	U	L
LoA	55	-54	12	-9	16	-8	9	-7	18	-21	0.2	-0.2

icc; Intra-class correlation coefficient. LoA; Upper and Lower Limits of Agreement.

Measures of heart rate, $\dot{V}O_2$, and power output were not significantly different across all 4 bouts in the final 10% (90-100%) of trial completion. Therefore coefficients of variation from 90-100% trial completion were calculated to further demonstrate the reliability in the primary purpose of this protocol. The lowest coefficient of variation in the final 10% of trial was observed in the $\dot{V}O_2$ in the self-paced condition (CV=0.54%) whilst the highest was observed in the self-paced power output (CV=3.51%) (Table 7.5).

Table 7.5 Measures of reliability in two experimental conditions
(Coefficients of Variation from 90-100% trial completion).

	Power Output	Relative $\dot{V}O_2$	HR
Self-Paced condition	3.51 %	0.54 %	0.65 %
Conventional condition	1.69 %	0.99 %	0.78 %

A number of statistical measures have been cited in order to provide the reader with demonstrable confidence in the reliability of these research findings (Atkinson and Nevill, 1998).

7.6 Discussion

This study shows that a perceptually based exercise maximal test can match the physiological and performance responses of a conventional $\dot{V}O_{2max}$ test. $\dot{V}O_{2peak}$ was shown to be statistically similar across all 4 trials with a range of only 3 ml·kg^{-1}·min^{-1} (or 5%) in average $\dot{V}O_{2peak}$. The traditional measurement of maximal oxygen uptake is an integral part of most exercise-based experiments (Winter, 2006), however this is the first study to describe a perceptually rated maximal exercise test in which participants can self-pace, which can be easily adapted to multiple exercise modalities, and which fits better with a model of complex metabolic control (Noakes, 2008b).

Previous research by Poole et al., (2008) has shown that $\dot{V}O_{2max}$ can be underestimated by as much as 27% through the use of secondary criteria in a conventional $\dot{V}O_{2max}$ test. In their study Poole et al., measured $\dot{V}O_{2max}$ in a ramp protocol and then calculated when $\dot{V}O_{2max}$ might have been achieved had traditional secondary markers been applied. Using these secondary criteria the authors showed that an RER of 1.10 could be demonstrated at an intensity which would elicit only 73% of a true $\dot{V}O_{2max}$ response. The application of other criteria associated with a $\dot{V}O_{2max}$ would have resulted in the rejection of 3 of 8 participants (HRmax $\pm$10 b·min^{-1}) whilst the use of blood lactate criteria ($\geq$8 mmol·L^{-1}) would have excluded 5 of 8 of the participants from the final analysis. The Poole et al., study did not include the criterion of RPE 19-20, however given the variation in other secondary criteria it may be postulated that not all of the 8 participants would have achieved this either. These findings suggest distinct flaws in the use of secondary criteria which have the potential to bring about both intra- and inter-participant variability. The design of the self-paced protocol used in the current study reduces the potential for intra-participant variability in maximal responses by encouraging them to work toward their perceived maximum in every bout, a criteria sometimes uncommon in the reporting of peak $\dot{V}O_2$ trials (Faulkner and Eston, 2008).

All trials in this study demonstrated excellent reliability in the performance measures which were the primary purpose of the experiment. A coefficient of variation of 0.54% was found in the $\dot{V}O_2$ responses from 90-100% trial in the self-paced condition compared with 0.99% in the conventional condition, whilst peak heart rate demonstrated a CV of 0.65% in the self-paced condition and 0.78% in the conventional condition. Coefficient of variation was not significantly different between the two conditions, and reliability in the findings was further supported by icc's of 0.972 in PPO to 0.999 in $\dot{V}O_{2peak}$ and HR peak. The strong reliability in these measures suggests that the self-paced protocol may reduce the intra-participant variability seen in conventional studies, allowing researchers to invest greater confidence that they have recorded a participant's maximal effort.

Value in this self-paced protocol may additionally be found in the potential of its application in multiple modalities. Jensen and Katch (1991) have previously shown that $\dot{V}O_{2max}$ in rowing exercise can vary by as much as 29% when compared with oxygen uptake response on a treadmill. Although the familiarity of an exercise medium may have a role in these differences, so too will the protocol employed (Howley et al., 1995). The variance of 5% in the $\dot{V}O_{2peak}$ values exhibited in the present study has parity with the findings of other investigations of $\dot{V}O_{2max}$, however the design of this self-paced perceptually based exercise test presents an additional opportunity for the same protocol to be applied in multiple exercise modalities, a characteristic much less accessible in conventional designs, which are commonly based upon power outputs and which may differ across modalities.

Comparisons of peak power output in this study revealed no significant differences between the 4 trials. In previous studies, peak power output in conventional maximal exercise tests has been demonstrated as comprising of 92-94% of the variance seen in peak oxygen uptake (Hawley and Noakes, 1992, Storer et al., 1990). This suggests that the majority of the $\dot{V}O_{2peak}$ is determined by peak power output, and in a conventional design where both factors increase linearly, this may be the case. However the staged increase in power output used in the self-paced trials of the current study showed power output to be significantly lower than peak power output from 70-85% trial completion and similar to peak power output from 90-100% trial completion. Despite this, peak oxygen uptake was statistically similar from 70-100% trial completion. Whilst this finding does not refute the work of Hawley and Noakes, it does imply that the relationship between peak power output and peak oxygen uptake may not be as linear as previously suggested when compared under self-paced conditions. This finding is of particular significance to the paper by Hawley and Noakes, as the authors went on to advocate the use of the relationship between $\dot{V}O_{2peak}$ and PPO to predict performance in a self-paced maximal time-trial. Indeed following the recent increase in the use of self-paced protocols (Hettinga et al., 2006b, Mauger et al., 2010b, Tucker et al., 2006c) the findings of this study justify the use of peak values taken from conventional $\dot{V}O_{2max}$ tests, but urge caution in the use of values from conventional protocols to identify sub-maximal self-paced intensities.

The non-linear increase in power output and oxygen uptake at RPE 15 and beyond in the self-paced protocol is in contrast with the responses in the conventional $\dot{V}O_{2max}$ protocol, and with the design of the Borg scale itself. This observation may be a consequence of the contrasting measurement intervals used in the conventional (increments every 1min) and self-paced conditions (increments every 2min) but it could also be considered that factors such as motivation or experience of maximal exercise intensities may cause participants to hold back at sub-maximal intensities in order to pace their performance to achieve a maximal effort at the end of protocol. The impact of motivation and experience on psychobiological factors in exercise has previously been demonstrated (Wright, 1996) the impact of motivation and measurement intervals on this novel protocol may however warrant further investigation.

The ability of participants to identify an exercise end point has been previously suggested to be the most important factor that influences the pacing of a bout of exercise (St Clair Gibson et al., 2006) in which increases in physiological measures are tolerated in comparison to a pre-planned pacing strategy (St Clair Gibson et al., 2006, Tucker, 2009). However the conventional test of $\dot{V}O_{2max}$ requires participants to respond to an ever increasing workload without a chronological or scalar guide to exercise endpoint. This practice is incongruent with the majority of exercise participation, and further, with a model of fatigue in which the knowledge of an exercise end point is integral to the ability to pace an exercise bout and to maximise performance. Previous authors have questioned the use of exercise tests without a 'known endpoint' in the investigation of endurance performance (Krebs and Powers, 1989, Jeukendrup et al., 1996) indeed the use of time-trial protocols over those without a known endpoint (i.e. trials to exhaustion) have, for some time, been considered more reliable (Jeukendrup and Currell, 2005), it is surprising therefore, that this study is the first to validate an exercise test to measure peak oxygen uptake based on a known endpoint.

The reliability of the $\dot{V}O_2$ measures from 90-100% trial completion (as described by the coefficient of variation) was 0.54% in the self-paced condition and 0.99% in the conventional condition, indicating that the final stages of the self-paced condition were less variable than those of the conventional $\dot{V}O_{2peak}$ protocol. This is further evidenced by a lower coefficient of variation in the peak heart rate in the SP condition (0.65% SP vs. 0.77% Conv). The reduced variation seen in physiological markers ($\dot{V}O_2$ HR) from 90-100% trial completion in the self-paced condition of the present study may be considered to represent an accepted tolerance of the physiological stress. Conversely the variation of measures at 90-100% trial completion in the conventional condition are lowest in power output, or performance measures, signalling that in a conventional test, power output may be the primary consideration. Whilst both conditions required a peak effort, participants appear to have placed greater emphasis on maintaining power output, to the detriment of variance in oxygen uptake in the conventional condition. However in the self-paced condition, the reduced variation of physiological measures appears to be the factor of greater weighting. In a protocol which is designed to measure a maximal physiological response, this clearly has important implications for future assessments designed to elicit maximal physiological responses.

The decrement in power output observed over the 2min RPE 20 stage in the self-paced condition in this study, although not statistically significant, does suggest that, at least at the higher levels of perceived exertion, 2min stages may be too long to maintain a maximal effort. Eston et al., (2006) have previously utilised 2min stages in a perceptually based study, in which participants were asked to complete a graded exercise test and then return on a subsequent occasion and reproduce the same wattage based on the RPE rating from the earlier trial. However their study did not require participants to work to an RPE of 20. Historically 2min stages have previously been important in exercise testing in order to achieve steady state $\dot{V}O_2$, to demonstrate a plateau in $\dot{V}O_2$, and in order to facilitate the sheer mechanics of gas collection using the Douglas bag method. With the advent of breath-by-breath $\dot{V}O_2$ measures, it has been demonstrated that $\dot{V}O_{2max}$ scores can be reliably estimated using averages of less than 30s (Midgley et al., 2007a). Indeed, the use of longer time averages has the potential to result in significantly lower $\dot{V}O_2$ max values (Astorino, 2009, Johnson et al., 1998). Furthermore the development of other methods of demonstrating a $\dot{V}O_{2peak}$, such as supra-maximal testing as advocated by Midgley and Carroll (2009), mean there is increasingly less of a requirement to ask participants to maintain their peak effort for the sort of time frame that now equates to longer than a world record 800m athletic performance (International Association of Athletics Federations, 2010). Thus, whilst the use of stages of two minutes or longer may be appropriate for measures other than that of peak oxygen uptake, this study suggests that in a self-paced maximal exercise bout, subjects are unlikely to maintain the same power output throughout the duration of that stage.

Other perception based exercise tests in order to predict $\dot{V}O_{2peak}$, have previously been described (Eston et al., 2006, Faulkner et al., 2007), but this study goes further by actually measuring $\dot{V}O_{2peak}$, and moreover by allowing participants to set their own pace in the exercise stages rather than increasing effort by a fixed parameter then asking participants to engage in a bidding process in order to fine tune intensity to a designated RPE, a protocol which seems unlikely to elicit a true RPE score. The use of rate of perceived exertion in exercise tests has recently enjoyed a growth in popularity (Duffield et al., 2010, Tucker and Noakes, 2009, Schabort et al., 1998, Kay et al., 1999). If, as this study shows, a perception based exercise test can be used to replicate the responses seen in a maximal exercise test, its ease of use and versatility across multiple exercise modalities may put pay to the variation previously seen in $\dot{V}O_{2max}$ in multiple modalities (Bassett et al., 1984, Jensen and Katch, 1991). Furthermore, such a test is less likely to be impacted upon by a participant's familiarity with what stage of an enforced pace trial is really a maximal effort, or when to signal that they have one more minute of maximal effort left; both of which are factors that have been previously acknowledged as bringing variability to true maximal score (Thoden, 1991).

In addition to the convenience of a perceptually regulated test for peak oxygen consumption, it may be that this protocol brings about a reduced metabolic disturbance when compared to the conventional protocol. The proposition that self-paced exercise represents a reduced metabolic demand when compared to a matched intensity directed pace effort is discussed in Chapter 4 of this thesis, this proposal is further strengthened by the observation in this study of a reduced time spent at a $\dot{V}O_2$ similar to $\dot{V}O_{2peak}$ in the self-paced condition when compared with the conventional condition. In the self-paced condition $\dot{V}O_2$ at 65% trial completion was significantly lower than the $\dot{V}O_{2peak}$ responses. However in the conventional condition $\dot{V}O_2$ was statistically similar to that of $\dot{V}O_{2peak}$ from 60% trial completion. This suggested that in the self-paced test although similar $\dot{V}O_{2peak}$, peak HR and peak power outputs were observed, the participants had to spend less time working at a $\dot{V}O_2$ similar to that of peak. This finding should be of interest to any researcher or coach as it suggests that the use of a self-paced maximal exercise test creates a reduced metabolic disturbance and thus is likely to impact less on training or other commitments than that of a conventional maximal exercise measure.

An interesting, and unexpected gradual reduction in power output was seen in self-paced condition at RPE 17, which appears without a concomitant reduction in $\dot{V}O_2$. This may be considered a result of the pacing plan which allows performers to complete an exercise bout without a catastrophic failure of systems (Edwards and Noakes, 2009). Numerous previous authors (Billaut et al., 2010, Catalano, 1974a, Tucker et al., 2006b) have now identified end-spurts in advance of trial completion, and it has been suggested to be related to a method of teleoanticipation of the effort yet to come as part of complex metabolic control or a multi-level pacing plan. In this study the reduction in power output prior to a maximal effort certainly fits such a method of explanation. The gradual reduction of power output at this intensity is not significant, nor is it matched by reductions in heart rate or $\dot{V}O_2$, furthermore previous studies do not support a suggestion that athletes are not able to match intensity at RPE 17 (Marriott and Lamb, 1996). It may therefore be considered that this reduction is evidence of some sort of energy-sparing behaviour in preparation for an anticipated maximal effort. An energy-sparing practice such as this cannot be observed in a conventional maximal trial, which has little ecological validity to real racing, as such the observation of this energy-sparing behaviour in a 10min trial is in itself also worthy of further investigation and greater evidence of a mechanism which is capable of feedforward anticipation of an effort yet to come.

Finally, the proposal of any novel protocol would not be complete without a demonstration of its reproducibility. Work by Schabort et al., (1998) has demonstrated that a 1hr self-paced time-trial run can be reproduced with a CV of 2.7% and icc of

0.90. The current study has parity with these findings demonstrating a CV 0.54% and of icc of 0.999 in measures of $\dot{V}O_{2peak}$. Whilst debate over the validity of $\dot{V}O_{2peak}$ testing will continue (Hawley et al., 1994, Midgley et al., 2007b, Whipp, 2010), this study demonstrates that a reliable peak can be identified using a perceptually-based self-paced test, and that this may represent a less variable measure than the conventional tests of $\dot{V}O_{2peak}$. Furthermore, this study introduces a reliable valid protocol that fits with a model of fatigue in which the effort yet to come is identified, and a protocol in which the disturbance to homeostasis is tolerated on the terms of the participant and not on the terms of the investigator.

7.7 Summary

In summary, this study shows that a self-paced $\dot{V}O_{2peak}$ does not significantly differ from a traditional $\dot{V}O_{2max}$ test ($p>0.05$). Similarity was observed between the peak responses in repeated conventional and self-paced trials supported by high intra-class correlation coefficients and low coefficients of variation. This work presents a protocol which can be applied across multiple modalities, additionally it provides evidence of trends toward an inability to maintain a maximal self-paced effort for two minutes, and of a subtle reduction in power output prior to a maximal perceived exertion. Further research using self-paced maximal protocols is required to elucidate the effects of a self-paced protocol in multiple modalities, however findings from this study suggest there is a reliable perceptually regulated alternative to the use of the conventional enforced-pace test of maximal oxygen uptake.

Chapter Eight

General Discussion

Chapter 8

General Discussion

The purpose of this thesis was to investigate the role of pacing in the development of fatigue through four studies which examined the impact of environmental and protocol manipulations, and evaluated the role of an ability to fluctuate pace during exercise at sub-maximal and maximal intensities. This Chapter brings together the collective findings of the previous Chapters to identify limitations of the thesis, draw conclusions based upon the preceding Chapters, and to provide directions for future research.

8.1 General discussion

This thesis was designed to bring together the concepts of pacing and fatigue by comparing the physiological and performance responses of self-paced and enforced-pace exercise on the development of fatigue. The term fatigue has previously been poorly defined, and the concept of pacing has remained a relatively undeveloped area of exercise physiology until recently, perhaps because of the incongruence of fluctuations in pace and conventional models of fatigue. Self-paced exercise bouts are known to demonstrate considerable intra-trial fluctuations of power output (Tucker et al., 2006a), and it is unlikely that these are simply due to random misjudgements of pace. It is probable that these fluctuations of power output are important behavioural responses during exercise at times when homeostasis is challenged, and form part of a mechanism of complex metabolic control which serves to regulate intensity during exercise (St Clair Gibson et al., 2006). The fluctuations observed during self-paced exercise have been suggested to form part of a multi-level pacing plan which is primarily devised to avoid a catastrophic failure of systems, but which allows altered levels of disturbance to homeostasis based upon set points and an anticipation of the effort yet to come (Edwards and Noakes, 2009).

By considering the influence of complex metabolic control on pacing and fatigue, this thesis has demonstrated key differences between self-paced and enforced-pace exercise trials in both sub-maximal and maximal exercise conditions; furthermore it has identified condition-specific altered pacing responses, which appear to form part of a multi-level pacing plan.

8.2 Limitations of the thesis

The construction of the aims, experimental design, and procedures used in this thesis were based on scientific methodology and peer-reviewed articles discussed in previous Chapters. Specific limitations of this work were identified in each of the preceding Chapters; however the following shortcomings are more generally applicable.

Since commencing this thesis in 2006 the investigation of pacing and fatigue has enjoyed an increase in publications from authors based in research groups from around the world (Hettinga et al., 2011, Mauger et al., 2010a, Edwards et al., 2011, Tucker and Noakes, 2009, Abbiss and Laursen, 2008). Such developments in the field have enlightened the area of pacing and fatigue and now provide evidence of limitations to this thesis which were previously unobserved at the start of this investigation.

One notable limitation is brought about by the development of supra-maximal testing to identify and validate a true $\dot{V}O_{2max}$ (Midgley et al., 2009, Midgley and Carroll, 2009, Snell et al., 2007). This development influences the findings from Chapters 4 and 7 of this thesis which both incorporate measures of maximal effort within their protocol and discussion. Developments in the use of this $\dot{V}O_{2max}$ validation technique have been incorporated into the review of literature, but were not sufficiently advanced to have been included in study designs. As discussed in the review of literature (Chapter 2), supra-maximal testing is still based upon a peripheral model of fatigue in which the participant needs no knowledge of the exercise endpoint, and during which the only way a participant can influence exercise intensity is to stop exercising. These concepts are incongruent with investigations of pacing in which an endpoint, and a perception of the effort yet to come, are considered influential upon the exercise intensity and transient feelings of fatigue. The incorporation of supra-maximal testing may have provided additional confidence in the elicitation of a true $\dot{V}O_{2max}$, and its exclusion may therefore be considered a limitation, however aspects of its design are still opposed to some of the concepts fundamental to pacing, which are discussed in the development of study protocols.

The availability of willing volunteers impacted upon the number of participants in each of the studies described in the thesis. Despite wide publication of the opportunity to participate in each study, volunteer numbers were consistently limited, this was predominantly a reflection of the population of the region, and the size of the student body, rather than the nature of the studies. Recruitment may have impacted upon the strength of findings in this research, and thus the size of participant cohorts may be considered a limitation of this thesis.

The use of a contemporary perspective on fatigue such as the complex model of fatigue is not without its opponents (Shephard, 2010, Hopkins, 2009), and the use of such a model may be considered a limitation of the thesis. However the study of pacing is best explained by a physiological model of fatigue which incorporates some knowledge of the requirement of physical effort yet to come, and which has the potential to up- and down-regulate effort during exercise. To-date, no other model of fatigue incorporates such attributes, making the complex model of fatigue a worthy basis from which to compare the influence of self-paced and enforced-pace exercise, however this is also acknowledged as a potential limitation to preceding work.

The investigation of self-paced exercise at sub-maximal and maximal intensities has relied heavily on the work of Borg and the concept of ratings of perceived exertion. Whilst shown to be a valid and reliable measurement tool in rowing (Marriott and Lamb, 1996), ratings of perceived exertion are by their nature only ratings within the conscious and may be influenced factors beyond the exercise environment (Micklewright and St Clair Gibson, 2010, Wright, 1996). RPE scales and the use of RPE clamps may therefore be considered as a factor which limits participants' ability to truly alter pace in accordance with biological feedback and sensations of fatigue; as discussed in Chapter 6. Furthermore, the use of RPE scales in Chapter 7 demonstrates, contrary to expectations, that the relationship between incremental increases in power output and RPE is not linear, whilst Chapter 5 demonstrates that RPE 15, which one would expect to elicit an effort of approximately 75% power at $\dot{V}O_{2peak}$, reliably demonstrates an effort of 62-64% of power at $\dot{V}O_{2peak}$.

To-date the use of ratings of perceived exertion represent a recognised measurement tool in the investigation of pacing in exercise physiology, however the use of a factor which inhibits the true ability to fluctuate effort and factor which is demonstrated by the thesis to be non-linear at RPE values greater than 14 may be considered as a limitation, or an interesting outcome to this thesis.

8.3 Conclusions

The following conclusions have been drawn from the aims of this thesis as discussed in Chapter 1.

Thesis aims:

To examine the relative impacts of self-paced and enforced-pace exercise on markers of fatigue.

To investigate the influence of environmental variables such as radiant warming on self-paced exercise.

To identify reliable methods of scientific observation which have relevance to current sporting practices.

This thesis has added to the understanding of self-paced exercise when compared to enforced-pace exercise by demonstrating a reduced physiological demand in self-paced exercise when compared with matched intensity enforced-pace sub-maximal exercise performances (Chapter 4).

It has shown that participants are capable of reliably matching the same effort in self-paced sub-maximal trials at a consistent perceived exertion both within-groups and between-groups of aerobically matched participants. These findings quantify the reliability and validity of time-trial protocols based upon perceived exertion. In addition, these study findings provide grounds for investigators to confidently reflect on changes in pacing as a response to factors other than participants inability to reliably reproduce a self-paced time-trial performance (Chapter 5).

The thesis has shown the influence of multi-level pacing plans in self-paced exercise in both Chapters 6 and 7. In Chapter 6, pacing plans were shown to alter based upon an environmental manipulation; the impact of radiant heat. Notably, the influence of such challenges on pacing appeared to impact differently dependent upon the point of application during the trial.

Chapter 7 has shown the reliability and validity of a self-paced perceptually regulated maximal exercise test, which identifies $\dot{V}O_2$ responses with similar peak values to those of a conventional enforced-pace maximal test, but which incorporates concepts such as a known endpoint and an ability to fluctuate pace, aspects of exercise performance previously shown as lacking in conventional protocols.

The use of ratings of perceived exertion in Chapters 4, 5, 6 and 7 of this thesis has provided the opportunity to compare aspects of the RPE scale with physiological responses to matched-intensity exercise and incremental exercise. It has demonstrated evidence to suggest that increases in power output and rating of perceived exertion may not be linear at intensities above RPE 15 and highlighted the need for further investigation of ratings of perceived exertion in self-paced exercise.

Common to self-paced exercise with a known endpoint is the observation of an end-spurt or the ability to increase effort in advance of the completion of an exercise bout. End-spurts were observed in Chapters 4, 6, and 7 of the current thesis, and have previously been considered by some, as evidence of ineffective pacing strategies (Hinckson and Hopkins, 2005a); however their consistent presence in self-paced exercise may be better described as evidence of an anticipatory mechanism, and fundamental to the understanding of pacing and fatigue, particularly as an artefact unobservable in conventional enforced-pace protocols.

8.4 Directions for future research

The validity and reliability of self-pacing in the present studies has been confined to the use of rowing ergometry. As discussed in Chapter 2, rowing exercise presents a mode of exercise in which each stroke can be influenced by inputs from a complex metabolic controller, providing a finer response to changes than may be observed in cycle or running based interventions. Whilst rowing and cycling studies have previously shown to provide similar maximal responses in enforced-pace exercise (Wiener et al., 1995), future research should identify the impact of self-pacing in exercise modalities other than rowing and compare the impact of modality on the reliability and validity of self-paced exercise.

The observation of multi-level pacing plans in a number of the studies in this thesis presents a departure from previous pacing models, which have only considered a singular plan to pacing exercise (Foster et al., 1994), or a plan supplemented by dynamic changes based upon teleoanticipation and the coordination of complex feedback (Tucker, 2009). Recent research has identified a reduction in performance through the imposition of altered 'theoretically optimal' pacing plans (Hettinga et al., 2011), thus future research is advised to investigate the impact of disruption to multi-level pacing plans and the concomitant effects on physiological and performance responses.

The consistent observation of an end-spurt of effort in self-paced exercise is striking, and may be fundamental to the understanding of pacing and fatigue. As an artefact unobservable in conventional enforced-pace protocols, its role and implication on performance, is relatively unexplored, yet it could be vital to increasing understanding of the anticipatory mechanisms involved in the avoidance of fatigue. Future research into this phenomenon is therefore recommended.

This thesis has shown that self-paced exercise presents a reduced physiological demand when compared to enforced-pace exercise in matched intensity sub-maximal conditions, and demonstrated evidence of multi-level pacing plans which cannot be observed in enforced-pace protocols. Furthermore, this challenge to conventional practices in exercise physiology has shown the model of complex metabolic control to be central to the investigation of pacing and fatigue. Future research is now required to build on the findings of this thesis and further understanding of the mechanisms which contribute to the effectiveness and efficiency of self-pacing during exercise.

Chapter Nine

References

References

Abbiss, C. R. and Laursen, P. B. (2005) Models to explain fatigue during prolonged endurance cycling. **Sports Medicine,** 35 (10), 865-98.

Abbiss, C. R. and Laursen, P. B. (2007) Is part of the mystery surrounding fatigue complicated by context? **Journal of Science and Medicine in Sport,** 10 (5), 277-279.

Abbiss, C. R. and Laursen, P. B. (2008) Describing and understanding pacing strategies during athletic competition. **Sports Medicine,** 38 (3), 239-252.

Achten, J. and Jeukendrup, A. E. (2003) Heart rate monitoring: Applications and limitations. **Sports Medicine,** 33 (7), 517-538.

ACSM (2005) **American College of Sports Medicine's Guidelines for Exercise Testing and Prescription.** 7th ed. Philadelphia, Lippincott, Williams & Wilkins.

Acworth, I., Nicholass, J., Morgan, B. and Newsholme, E. A. (1986) Effect of sustained exercise on concentrations of plasma aromatic and branched-chain amino acids and brain amines. **Biochemical and Biophysical Research Communications,** 137 (1), 149-153.

Aisbett, B., Lerossignol, P., McConell, G. K., Abbiss, C. R. and Snow, R. (2009) Influence of all-out and fast start on 5-min cycling time trial performance. **Medicine & Science in Sports & Exercise,** 41 (10), 1965-1971.

Astorino, T. A. (2009) Alterations in VO2max and the VO2 plateau with manipulation of sampling interval. **Clinical Physiology and Functional Imaging,** 29 (1), 60-67.

Astorino, T. A., Willey, J., Kinnahan, J., Larsson, S. M., Welch, H. and Dalleck, L. C. (2005) Elucidating determinants of the plateau in oxygen consumption at VO2max. **British Journal of Sports Medicine,** 39 (9), 655-660.

Astrand, P. O., Rodahl, K., Dahl, H. A. and Stromme, S. B. (2003) **Textbook of work physiology: physiological bases of exercise.** 4th ed. Champaign, Human Kinetics.

Atkinson, G., Barr, D., Chester, N., Drust, B., Gregson, W., Reilly, T. and Waterhouse, J. (2008) Bright light and thermoregulatory responses to exercise. **International Journal of Sports Medicine,** 29 (3), 188-93.

Atkinson, G. and Nevill, A. (2005) Mathematical constants that vary? **Medicine & Science in Sports & Exercise,** 37 (10), 1822.

Atkinson, G. and Nevill, A. M. (1998) Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. **Sports Medicine,** 26 (4), 217-238.

Aubert, A. E., Seps, B. and Beckers, F. (2003) Heart rate variability in athletes. **Sports Medicine,** 33 (12), 889-919.

Baden, D. A., McLean, T. L., Tucker, R., Noakes, T. D. and St Clair Gibson, A. (2005) Effect of anticipation during unknown or unexpected exercise duration on rating of perceived exertion, affect, and physiological function. **British Journal of Sports Medicine,** 39 (10), 742-746.

Bangsbo, J., Norregaard, L. and Thorso, F. (1991) Activity profile of competition soccer. **Can J Sport Sci,** 16 (2), 110-6.

Basmajian, J. V. and De Luca, C. J. (1985) **Muscles Alive: Their functions revealed by electromyography.** 5th ed. Baltimore, Williams & Wilkins.

Bassett, D. J. (2002) Scientific contributions of A. V. Hill: exercise physiology pioneer. **Journal of Applied Physiology,** 93 (5), 1567-1582.

Bassett, D. R. (2009) Comments on Point:Counterpoint: Maximal oxygen uptake is/is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 343-344.

Bassett, D. R., Smith, P. A. and Getchwell, L. H. (1984) Energy Cost associated of simulated rowing using a wind resistance device. **The Physician and Sportsmedicine,** 12 (8), 113-116.

Batterham, A. M. and George, K. P. (2003) Reliability in evidence-based clinical practice: a primer for allied health professionals. **Physical Therapy in Sport,** 4 (3), 122-128.

Beneke, R., Leithauser, R. M. and Hutler, M. (2001) Dependence of the maximal lactate steady state on the motor pattern of exercise. **British Journal of Sports Medicine,** 35 (3), 192-196.

Bentley, D. J., Newell, J. and Bishop, D. (2007) Incremental exercise test design and analysis: Implications for performance diagnostics in endurance athletes. **Sports Medicine,** 37 (7), 575-586.

Benzinger, T. H. (1969) Heat regulation: homeostasis of central temperature in man. **Physiological Reviews,** 49 (4), 671-759.

Bernard, C. (1878) Leçons sur les phénomènes de la vie communs aux animaux et végétaux. **Oeuvres,** 16, p 113.

Bernstein, I. A., Webber, O. and Woledge, R. (2002) An ergonomic comparison of rowing machine designs: possible implications for safety. **British Journal of Sports Medicine,** 36 (2), 108-12.

Bigland-Ritchie, B., Furbush, F. and Woods, J. J. (1986) Fatigue of intermittent submaximal voluntary contractions: central and peripheral factors. **Journal of Applied Physiology,** 61 (2), 421-429.

Billaut, F., Davis, J. M., Smith, K. J., Marino, F. E. and Noakes, T. D. (2010) Cerebral oxygenation decreases but does not impair performance during self-paced, strenuous exercise. **Acta Physiologica,** 198 (4), 477-486.

Bird, S. and Davison, R. (eds.) (1997) **British Association of Sports and Exercise Sciences guidelines for the physiological testing of athletes.** Leeds, BASES.

Bland, J. M. (2004a) **An introduction to medical statistics.** 3rd ed. Oxford, Oxford University Press.

Bland, J. M. and Altman, D. G. (1995) Comparing two methods of clinical measurement: A personal history. **International Journal of Epidemiology,** 24 (Supplement 1), S7-14.

Bland, J. M. and Altman, D. G. (2010) Statistical methods for assessing agreement between two methods of clinical measurement. **International Journal of Nursing Studies,** 47 (8), 931-936.

Bland, M. (2004b) **An introduction to medical statistics.** 3rd ed. Oxford, Oxford University Press.

Bogdanis, G. C., Nevill, M. E. and Lakomy, H. K. A. (1994) Effects of previous dynamic arm exercise on power output during repeated maximal sprint cycling. **Journal of Sports Sciences,** 12 (4), 363-370.

Borg, G. A. (1970) Perceived exertion as an indicator of somatic stress. **Scandinavian Journal of Rehabilitation Medicine,** 2 (2-3), 92-98.

Borg, G. A. (1998) **Borg's Perceived Exertion and Pain Scales.** Leeds, Human Kinetics.

Borg, G. A. and Ohlsson, M. (1975) **A study of two variants of a simple run-test for determining physical working capacity.** Stockholm, University of Stocklom.

Brooks, G., Fahey, T. and White, T. (1996a) Cardiovascular dynamics during exercise. In: **Exercise Physiology: human bioenergetics and its applications.** London, Mayfield, pp.281-299.

Brooks, G., Fahey, T. and White, T. (1996b) Fatigue during muscular exercise. In: **Exercise Physiology: human bioenergetics and its applications.** London, Mayfield, pp.701-21.

Brooks, G., Hittelman, K., Faulkner, J. and Beyer, R. (1971) Temperature, skeletal muscle mitochondrial functions, and oxygen debt. **American Journal of Physiology,** 220 (4), 1053-1059.

Budgett, R. G. and Fuller, G. N. (1989) Illness and injury in international oarsmen. **Clinical Sports Medicine,** 1, 57-61.

Bulcao, C. F., Frank, S. M., Raja, S. N., Tran, K. M. and Goldstein, D. S. (2000) Relative contribution of core and skin temperatures to thermal comfort in humans. **Journal of Thermal Biology,** 25 (1-2), 147-150.

Burden, A. and Bartlett, R. (1999) Normalisation of EMG amplitude: an evaluation and comparison of old and new methods. **Medical Engineering and Physics,** 21 (4), 247-257.

Burden, A. M., Trew, M. and Baltzopoulos, V. (2003) Normalisation of gait EMGs: a re-examination. **Journal of Electromyography and Kinesiology,** 13 (6), 519-32.

Byrne, C. (2007) Accuracy of radiopill telemetry during distance running in the heat: Response. **Medicine & Science in Sports & Exercise,** 39 (2), 394.

Byrne, C., Lee, J. K., Chew, S. A., Lim, C. L. and Tan, E. Y. (2006) Continuous thermoregulatory responses to mass-participation distance running in heat. **Medicine & Science in Sports & Exercise,** 38 (5), 803-10.

Byrne, C. and Lim, C. L. (2007) The ingestible telemetric body core temperature sensor: a review of validity and exercise applications. **British Journal of Sports Medicine,** 41 (3), 126-133.

Calbet, J. A. L. and Lundby, C. (2009) Comments on Point:Counterpoint: Maximal oxygen uptake is/is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 346.

Casa, D. J. (1999) Exercise in the heat. I. Fundamentals of thermal physiology, performance implications, and dehydration. **Journal of Athletic Training,** 34 (3), 246-252.

Catalano, J. F. (1973) Effect of perceived proximity to end of task upon end-spurt. **Perceptual & Motor Skills,** 36 (2), 363-377.

Catalano, J. F. (1974a) End-spurt following simple repetitive muscular movement. **Perceptual & Motor Skills,** 39, 763-766.

Catalano, J. F. (1974b) End-spurt in addition of numbers. **Perceptual & Motor Skills,** 39, 121-122.

Celik, O., Kosar, N., Korkusuz, F. and Bozkurt, M. (2005) Reliability and validity of the modified Conconi test on Concept II rowing ergometers. **Journal of Strength & Conditioning Research,** 19 (4), 871-877.

Challis, G. G. and Kolb, J. C. (2010) Agreement between an ingestible telemetric sensor system and a mercury thermometer before and after linear regression correction. **Clinical Journal of Sport Medicine,** 20 (1), 53-57.

Cheung, S. S. and Flouris, A. D. (2009) Comments on Point:Counterpoint: Maximal oxygen uptake is/is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 345.

Cheung, S. S. and Sleivert, G. G. (2004) Multiple triggers for hyperthermic fatigue and exhaustion. **Exercise and Sport Sciences Reviews,** 32 (3), 100-106.

Clark, N. A., Edwards, A. M., Morton, R. H. and Butterly, R. J. (2008) Season-to-season variations of physiological fitness within a squad of professional male soccer players. **Journal of Sports Science and Medicine,** 7, 157-165.

Cooper, K. E. (2002) Molecular biology of thermoregulation: Some historical perspectives on thermoregulation. **Journal of Applied Physiology,** 92 (4), 1717-1724.

Coquart, J., Eston, R., Grosbois, J.-M., Lemaire, C., Dubart, A.-E., Luttenbacher, D.-P. and Garcin, M. (2010) Prediction of peak oxygen uptake from age and power output at RPE 15 in obese women. **European Journal of Applied Physiology,** 110 (3), 645-649.

Cosgrove, M. J., Wilson, J., Watt, D. and Grant, S. F. (1999) The relationship between selected physiological variables of rowers and rowing performance as determined by a 2000 m ergometer test. **Journal of Sports Sciences,** 17 (11), 845-52.

Craven, R. P., Kinch, R. F. T., Parker, D. F. and Walter, S. J. (1993) Stroke analysis using a modified Concept II rowing ergometer. **The Journal of Physiology,** 459, 113.

Crenshaw, A. G., Karlsoon, S., Gerdle, B. and Friden, J. (1997) Differential responses in intramuscular pressure and EMG fatigue indicators during low- vs. high-level isometric contractions to fatigue. **Acta Physiologica Scandinavica,** 160 (4), 353-361.

Davies, C. T., Brotherhood, J. R. and Zeidifard, E. (1976) Temperature regulation during severe exercise with some observations on effects of skin wetting. **Journal of Applied Physiology,** 41 (5), 772-6.

Day, J. R., Rossiter, H. B., Coats, E. M., Skasick, A. and Whipp, B. J. (2003) The maximally attainable VO2 during exercise in humans: the Peak vs. Maximum issue. **Journal of Applied Physiology,** 95 (5), 1901-7.

De Luca, C. J. (1997) The use of surface electromyography in biomechanics. **Journal of Applied Biomechanics,** 13 (2), 135-165.

De Luca, C. J. (2002) **Surface electromyography: detection and recording.** Boston, Delsys Incorporated.

Domitrovich, J. W., Leiberg, E., Plante, N., Marshal, I., Cuddy, J. and Ruby, B. C. (2006) Core temperature comparison based on time of pill ingestion prior to exercise. **Medicine & Science in Sports & Exercise,** 38 (5), S465.

Dreissigacker, P. D., Dreissigacker, R. A. and Williams, J. V. (1981) Stationary rowing unit. [Internet], Available from: <http://www.google.co.uk/patents/about?id=uNExAAAAEBAJ> [Accessed 30/03/2010].

Dudhia, A. (2008) The physics of ergometers: Measuring the damping. [Internet], Available from: <http://www.atm.ox.ac.uk/rowing/physics/ergometer.html#section7> [Accessed 08/05/08].

Duffield, R., Green, R., Castle, P. and Maxwell, N. (2010) Precooling can prevent the reduction of self-paced exercise intensity in the heat. **Medicine & Science in Sports & Exercise,** 42 (3), 577-584.

Dunbar, C. C., Robertson, R. J., Baun, R., Blandin, M. F., Metz, K., Burdett, R. and Goss, F. L. (1992) The validity of regulating exercise intensity by ratings of perceived exertion. **Medicine & Science in Sports & Exercise,** 24 (1), 94-9.

Edwards, A. M., Bentley, M. B., Mann, M. E. and Seaholme, T. S. (2011) Self-pacing in interval training: A teleoanticipatory approach. **Psychophysiology,** 48 (1), 136-141.

Edwards, A. M. and Clark, N. A. (2006) Thermoregulatory observations in soccer match play: professional and recreational level applications using an intestinal pill system to measure core temperature. **British Journal of Sports Medicine,** 40 (2), 133-8.

Edwards, A. M., Clark, N. A. and Macfadyen, A. M. (2003) Lactate and ventilatory thresholds reflect the training status of professional soccer players where maximum aerobic power is unchanged. **Journal of Sports Science and Medicine,** 2, 23-29.

Edwards, A. M. and Cooke, C. B. (2004) Oxygen uptake kinetics and maximal aerobic power are unaffected by inspiratory muscle training in healthy subjects where time to exhaustion is extended. **European Journal of Applied Physiology,** 93 (1-2), 139-144.

Edwards, A. M. and Noakes, T. D. (2009) Dehydration: Cause of fatigue or sign of pacing in elite soccer? **Sports Medicine,** 39 (1), 1-13.

Ekblom, B. (2009a) Counterpoint: Maximal oxygen uptake is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 339-341.

Ekblom, B., Greenleaf, C. J., Greenleaf, J. E. and Hermansen, L. (1971) Temperature regulation during continuous and intermittent exercise in man. **Acta Physiologica Scandinavica,** 81 (1), 1-10.

Ekblom, B. T. (2009b) Last Word on Point:Counterpoint: Maximal oxygen uptake is/is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 348.

Ely, B. R., Ely, M. R., Cheuvront, S. N., Kenefick, R. W., DeGroot, D. W. and Montain, S. J. (2009) Evidence against a 40C core temperature threshold for fatigue in humans. **Journal of Applied Physiology,** 107 (5), 1519-1525.

Enoka, R. M. (1995) Morphological Features and Activation Patterns of Motor Units. **Journal of Clinical Neurophysiology,** 12 (6), 538-559.

Enoka, R. M. and Stuart, D. G. (1992) Neurobiology of muscle fatigue. **Journal of Applied Physiology,** 72 (5), 1631-1648.

Eston, R., Faulkner, J., Mason, E. and Parfitt, G. (2006) The validity of predicting maximal oxygen uptake from perceptually regulated graded exercise tests of different durations. **European Journal of Applied Physiology,** 97 (5), 535-541.

Eston, R., Lambrick, D., Sheppard, K. and Parfitt, G. (2008) Prediction of maximal oxygen uptake in sedentary males from a perceptually regulated, sub-maximal graded exercise test. **Journal of Sports Sciences,** 26 (2), 131 - 139.

Eston, R. G., Lambrick, D. M. and Rowlands, A. V. (2009) The perceptual response to exercise of progressively increasing intensity in children aged 7-8 years: validation of a pictorial curvilinear ratings of perceived exertion scale. **Psychophysiology,** 46 (4), 843-51.

Faulkner, J. and Eston, R. (2007) Overall and peripheral ratings of perceived exertion during a graded exercise test to volitional exhaustion in individuals of high and low fitness. **European Journal of Applied Physiology,** 101 (5), 613-620.

Faulkner, J. and Eston, R. G. (2008) Perceived exertion research in the 21st century: Developments, reflections and questions for the future. **Journal of Exercise Science & Fitness,** 6 (1), 1-14.

Faulkner, J., Parfitt, G. and Eston, R. (2007) Prediction of maximal oxygen uptake from the ratings of perceived exertion and heart rate during a perceptually-regulated sub-maximal exercise test in active and sedentary participants. **European Journal of Applied Physiology,** 101 (3), 397-407.

Fletcher, E. (2010) Factsheet 1-5. **Document Gallery** [Internet], Available from: <http://concept2.co.uk/assets/docs/factsheet1-5.pdf> [Accessed 24/02/2010].

Flouris, A. D. and Cheung, S. S. (2009) Human conscious response to thermal input is adjusted to changes in mean body temperature. **British Journal of Sports Medicine,** 43 (3), 199-203.

Foster, C. and Lucia, A. (2009) Comments on Point:Counterpoint: Maximal oxygen uptake is/is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 343.

Foster, C., Schrager, M., Snyder, A. and Thompson, N. N. (1994) Pacing strategy and athletic performance. **Sports Medicine,** 17 (2), 77-85.

Foster, C., Snyder, A. C., Thompson, N. N., Green, M. A., Foley, M. and Schrager, M. (1993) Effect of pacing strategy on cycle time trial performance. **Medicine & Science in Sports & Exercise,** 25 (3), 383-8.

Frank, S. M., Raja, S. N., Bulcao, C. F. and Goldstein, D. S. (1999) Relative contribution of core and cutaneous temperatures to thermal comfort and autonomic responses in humans. **Journal of Applied Physiology,** 86 (5), 1588-1593.

Galloway, S. D. and Maughan, R. J. (1995) Effects of ambient temperature on the capacity to perform prolonged exercise in man. **The Journal of Physiology,** 489, 35P-36P.

Gant, N., Atkinson, G. and Williams, C. (2006) The validity and reliability of intestinal temperature during intermittent running. **Medicine & Science in Sports & Exercise,** 38 (11), 1926-31.

Garcin, M., Wolff, M. and Bejma, T. (2003) Reliability of rating scales of perceived exertion and heart rate during progressive and maximal constant load exercises till exhaustion in physical education students. **International Journal of Sports Medicine,** 24 (4), 285-90.

Gass, G. C., Rogers, S. and Mitchell, R. (1981) Blood lactate concentration following maximum exercise in trained subjects. **British Journal of Sports Medicine,** 15 (3), 172-176.

Gleeson, M. (1998) Temperature regulation during exercise. **International Journal of Sports Medicine,** 19, S96-S99.

Gonzalez-Alonso, J. and Mortensen, S. P. (2009) Comments on Point:Counterpoint: Maximal oxygen uptake is/is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 344-345.

Gonzalez-Alonso, J., Teller, C., Andersen, S. L., Jensen, F. B., Hyldig, T. and Nielsen, B. (1999) Influence of body temperature on the development of fatigue during prolonged exercise in the heat. **Journal of Applied Physiology,** 86 (3), 1032-9.

Goodman, D. A., Kenefick, R. W., Cadarette, B. S. and Cheuvront, S. N. (2009) Influence of sensor ingestion timing on consistency of temperature measures. **Medicine & Science in Sports & Exercise,** 41 (3), 597-602.

Grant, S., Corbett, K., Todd, K., Davies, C., Aitchison, T., Mutrie, N., Byrne, J., Henderson, E., Dargie, H. J. and Stensel, D. (2002) A comparison of physiological responses and rating of perceived exertion in two modes of aerobic exercise in men and women over 50 years of age. **British Journal of Sports Medicine,** 36 (4), 276-281.

Graziano, A. and Raulin, M. (2007) **Research methods: a process of inquiry.** Boston, Pearson Allyn and Bacon.

Green, H. J. (1997) Mechanisms of muscle fatigue in intense exercise. **Journal of Sports Sciences,** 15 (3), 247-256.

Gregson, W. A., Altareki, N. A., Noureddin, A., Cable, N. T., Atkinson, G., Drust, B. and K, G. (2006) Telemetry pill and oesophageal assessment of core temperature during moderate duration, high intensity exercise. **Medicine & Science in Sports & Exercise,** 38 (5), S466.

Hagerman, F. C. (1984) Applied physiology of rowing. **Sports Medicine,** 1 (4), 303-26.

Hammel, H. T., Jackson, D. C., Stolwijk, J. A. J., Hardy, J. D. and Stromme, S. B. (1963) Temperature regulation by hypothalamic proportional control with an adjustable set point. **Journal of Applied Physiology,** 18 (6), 1146-1154.

Hardy, J. D. and Dubois, E. F. (1938) The technique of measuring radiation and convection. **Journal of Nutrition,** 15, 461.

Hargreaves, M. (2008) Fatigue mechanisms determining exercise performance: integrative physiology is systems biology. **Journal of Applied Physiology,** 104 (5), 1541-1542.

Hawley, J. A., Myburgh, K. H. and Noakes, T. D. (1994) Maximal oxygen consumption: A contemporary perspective. **Sportscience** [Internet], Available from: <http://www.sportsci.org/encyc/drafts/VO2max.doc> [Accessed 01/12/2008].

Hawley, J. A. and Noakes, T. D. (1992) Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. **European Journal of Applied Physiology and Occupational Physiology,** 65 (1), 79-83.

Hettinga, F. J., De Koning, J. J., Broersen, F. T., Van Geffen, P. and Foster, C. (2006a) Pacing strategy and the occurrence of fatigue in 4000-m cycling time trials. **Medicine & Science in Sports & Exercise,** 38 (8), 1484-91.

Hettinga, F. J., de Koning, J. J., de Vrijer, A., Wust, R. C. I., Daanen, H. A. M. and Foster, C. (2006b) The effect of a high ambient temperature on gross efficiency in cycling at sub-maximal intensities. **Medicine & Science in Sports & Exercise,** 38 (5), S353.

Hettinga, F. J., De Koning, J. J., Schmidt, L. J. I., Wind, N. A. C., MacIntosh, B. R. and Foster, C. (2011) Optimal pacing strategy: from theoretical modelling to reality in 1500-m speed skating. **British Journal of Sports Medicine,** 45 (1), 30-35.

Hickey, M. S., Costill, D. L., McConell, G. K., Widrick, J. J. and Tanaka, H. (1992) Day to day variation in time trial cycling performance. **International Journal of Sports Medicine,** 13 (06), 467-470.

Hill, A., Long, C. and Lupton, H. (1924a) Muscular exercise, lactic acid and the supply and utilisation of oxygen. VII-VIII. **Proceedings of the Royal Society of London,** 97 (682), 155-176.

Hill, A. V. (1932) The revolution in muscle physiology. **Physiological Reviews,** 12 (1), 56-67.

Hill, A. V., Long, C. N. H. and Lupton, H. (1924b) Muscular exercise, lactic acid and the supply and utilisation of oxygen. IV-VI. **Proceedings of the Royal Society of London,** 97 (681), 84-138.

Hill, A. V., Long, C. N. H. and Lupton, H. (1924c) Muscular exercise, lactic acid and the supply and utilisation of oxygen. I-III. **Proceedings of the Royal Society of London,** 96 (679), 438-475.

Hill, C. A., Thompson, M. W., Ruell, P. A., Thom, J. M. and White, M. J. (2001) Sarcoplasmic reticulum function and muscle contractile character following fatiguing exercise in humans. **The Journal of Physiology,** 531 (3), 871-878.

Hinckson, E. A. and Hopkins, W. G. (2005a) Reliability of time to exhaustion analyzed with critical-power and log-log modelling. **Medicine & Science in Sports & Exercise,** 37 (4), 696-701.

Hinckson, E. A. and Hopkins, W. G. (2005b) Should time trial performance be predicted from three serial time-to-exhaustion tests: Response. **Medicine & Science in Sports & Exercise,** 37 (10), 1821.

Hopkins, W. G. (2000) Measures of reliability in sports medicine and science. **Sports Medicine,** 30 (1), 1-15.

Hopkins, W. G. (2009) The improbable central governor of maximal endurance performance. **Sportscience** [Internet], 13, pp.9-12. Available from: <www.sportsci.org/2009/wghgov.htm> [Accessed 03/06/2009].

Hopkins, W. G. (2010) Calculations of reliability. **A new view of statistics** [Internet], Available from: <http://www.sportsci.org/resource/stats/> [Accessed 07/08/10].

Hopkins, W. G., Schabort, E. J. and Hawley, J. A. (2001) Reliability of power in physical performance tests. **Sports Medicine,** 31 (3), 211-234.

Houdas, Y. and Ring, E. F. J. (1982) **Human Body Temperature.** New York, Plenum.

Howley, E. T. (2007) VO2max and the plateau-needed or not? **Medicine & Science in Sports & Exercise,** 39 (1), 101-2.

Howley, E. T., Bassett, D. J. and Welch, H. G. (1995) Criteria for maximal oxygen uptake: review and commentary. **Medicine & Science in Sports & Exercise,** 27 (9), 1292-301.

Hughson, R. L. (1990) Exploring cardiorespiratory control mechanisms through gas exchange dynamics. **Medicine & Science in Sports & Exercise,** 22 (1), 72-79.

Huizenga, C., Zhang, H., Arens, E. and Wang, D. (2004) Skin and core temperature response to partial- and whole-body heating and cooling. **Journal of Thermal Biology,** 29 (7-8), 549-558.

Hulleman, M., De Koning, J. J., Hettinga, F. J. and Foster, C. (2007) The effect of extrinsic motivation on cycle time trial performance. **Medicine & Science in Sports & Exercise,** 39 (4), 709-715.

Hultman, E. and Sjoholm, H. (1986) Biochemical causes of fatigue. In: Jones, N. L., McCarney, N. and J, M. A. (eds.) **Human Muscle Power.** Champaign, Human Kinetics, pp.215-238.

Huxley, A. F. and Hanson, J. (1954) Changes in the cross-striations of muscle during contraction and stretch and their structural interpretation. **Nature,** 22 (4122), 973-976.

Huxley, A. F. and Niedergerke, R. (1954) Structural changes in muscle during contraction: interference microscopy of living muscle fibres. **Nature,** 173 (4412), 971-973.

Ingham, S., Carter, H., Whyte, G. and Doust, J. (2007) Comparison of the oxygen uptake kinetics of club and olympic champion rowers. **Medicine & Science in Sports & Exercise,** 39 (5), 865-71.

Ingham, S. A., Whyte, G. P., Jones, K. and Nevill, A. M. (2002) Determinants of 2,000 m rowing ergometer performance in elite rowers. **European Journal of Applied Physiology,** 88 (3), 243-6.

International Association of Athletics Federations (2010) Records by Event. [Internet], Available from:

<http://www.iaaf.org/statistics/records/inout=o/discType=5/disc=800/detail.html>
[Accessed 28/09/10].

Jensen, R. and Katch, F. (1991) A new approach to rowing ergometry: establishing exercise intensity relative to maximum force output. **European Journal of Applied Physiology and Occupational Physiology,** 62 (1), 44-48.

Jeukendrup, A., Saris, W. H. M., Brouns, F. and Kester, A. D. M. (1996) A new validated endurance performance test. **Medicine & Science in Sports & Exercise,** 28 (2), 266-270.

Jeukendrup, A. E. and Currell, K. (2005) Should time trial performance be predicted from three serial time-to-exhaustion tests-Response. **Medicine & Science in Sports & Exercise,** 37 (10), 1820.

Johnson, J. S., Carlson, J. J., VanderLaan, R. L. and Langholz, D. E. (1998) Effects of sampling interval on peak oxygen consumption in patients evaluated for heart transplantation. **Chest,** 113 (3), 816-819.

Jurell, K. C. (1998) Surface EMG and fatigue. **Physical medicine and rehabilitation clinics of North America.,** 9 (4), 933-47.

Kang, J., Hoffman, J., Walker, H., Chaloupka, E. C. and Utter, A. C. (2003) Regulating intensity using perceived exertion during extended exercise periods. **European Journal of Applied Physiology,** 89 (5), 475-82.

Kay, D., Marino, F. E., Cannon, J., St Clair Gibson, A., Lambert, M. I. and Noakes, T. D. (2001) Evidence for neuromuscular fatigue during high-intensity cycling in warm, humid conditions. **European Journal of Applied Physiology,** 84 (1), 115-121.

Kay, D., Taaffe, D. R. and Marino, F. E. (1999) Whole-body pre-cooling and heat storage during self-paced cycling performance in warm humid conditions. **Journal of Sports Sciences,** 17 (12), 937-44.

Kemi, O. J. (2009) Comments on Point:Counterpoint: Maximal oxygen uptake is/is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 345.

Kennedy, M. D. and Bell, G. J. (2003) Development of race profiles for the performance of a simulated 2000-m rowing race. **Canadian Journal of Applied Physiology,** 28 (4), 536-46.

Kenney, W. L. (1998) Heat flux and storage in hot environments. **International Journal of Sports Medicine,** 19, S92-S95.

Kirkendall, D. T. (1990) Mechanisms of peripheral fatigue. **Medicine & Science in Sports & Exercise,** 22 (4), 444-449.

Kolka, M. A., Quigley, M. D., Blanchard, L. A., Toyota, D. A. and Stephenson, L. A. (1993) Validation of a temperature telemetry system during moderate and strenuous exercise. **Journal of Thermal Biology,** 18 (4), 203-210.

Korge, P. (1995) Factors limiting adenosine triphosphatase function during high intensity exercise. Thermodynamic and regulatory considerations. **Sports Medicine,** 20 (4), 215-25.

Kramer, J. F., Leger, A., Paterson, D. H. and Morrow, A. (1994) Rowing performance and selected descriptive, field, and laboratory variables. **Canadian Journal of Applied Physiology,** 19 (2), 174-84.

Krebs, P. S. and Powers, S. K. (1989) Reliability of laboratory endurance tests. **Medicine & Science in Sports & Exercise,** 21 (S10).

Lamb, D. H. (1989) A kinematic comparison of ergometer and on-water rowing. **American Journal of Sports Medicine,** 17 (3), 367-73.

Lamb, K. L., Eston, R. G. and Corns, D. (1999) Reliability of ratings of perceived exertion during progressive treadmill exercise. **British Journal of Sports Medicine,** 33 (5), 336-339.

Lambert, E. V., St Clair Gibson, A. and Noakes, T. D. (2005) Complex systems model of fatigue: integrative homoeostatic control of peripheral physiological systems during exercise in humans. **British Journal of Sports Medicine,** 39 (1), 52-62.

Lambrick, D. M., Faulkner, J. A., Rowlands, A. V. and Eston, R. G. (2009) Prediction of maximal oxygen uptake from submaximal ratings of perceived exertion and heart rate during a continuous exercise test: the efficacy of RPE 13. **European Journal of Applied Physiology,** 107 (1), 1-9.

Lander, P. J., Butterly, R. J. and Edwards, A. M. (2009) Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. **British Journal of Sports Medicine,** 43 (10), 789-795.

Laursen, P. B., Francis, G. T., Abbiss, C. R., Newton, M. J. and Nosaka, K. (2007) Reliability of time-to-exhaustion versus time-trial running tests in runners. **Medicine & Science in Sports & Exercise,** 39 (8), 1374-1379.

Leavitt, F. (2001) **Evaluating scientific research. Separating fact from fiction.** New Jersey, Prentice-Hall.

Lee, S. M. C., Williams, W. J. and Schneider, S. M. (2000) Core temperature measurement during submaximal exercise: esophageal, rectal, and intestinal temperatures. **NASA Center for AeroSpace Information Technical Report NASA/TP**, 210113.

Levine, B. D. (2008) VO2max: what do we know, and what do we still need to know? **The Journal of Physiology,** 586 (1), 25-34.

Macfarlane, D. J., Edmond, I. M. and Walmsley, A. (1997) Instrumentation of an ergometer to monitor the reliability of rowing performance. **Journal of Sports Sciences,** 15 (2), 167-73.

Mackowiak, P. A., Wasserman, S. S. and Levine, M. M. (1992) A critical appraisal of 98.6 degrees F, the upper limit of the normal body temperature, and other legacies of Carl Reinhold August Wunderlich. **Journal of the American Medical Association,** 268 (12), 1578-80.

Maestu, J., Jurimae, J. and Jurimae, T. (2005) Monitoring of performance and training in rowing. **Sports Medicine,** 35 (7), 597-617.

Mahony, N., Donne, B. and O'Brien, M. (1999) A comparison of physiological responses to rowing on friction-loaded and air-braked ergometers. **Journal of Sports Sciences,** 17 (2), 143-9.

Mairiaux, P., Sagot, J. C. and Candas, V. (1983) Oral temperature as an index of core temperature during heat transients. **European Journal of Applied Physiology and Occupational Physiology,** 50 (3), 331-41.

Marcora, S. M. (2009) Comments on Point:Counterpoint: Maximal oxygen uptake is/is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 344.

Marieb, E. N. (2005) **Anatomy and Physiology,** 2nd ed. Pearson, San Francisco.

Marino, F. E. (2010) Is it time to retire the 'Central Governor'? A philosophical and evolutionary perspective. **Sports Medicine,** 40 (3), 265-8.

Marino, F. E., Lambert, M. I. and Noakes, T. D. (2004) Superior performance of African runners in warm humid but not in cool environmental conditions. **Journal of Applied Physiology,** 96 (1), 124-130.

Maron, M. B., Wagner, J. A. and Horvath, S. M. (1977) Thermoregulatory responses during competitive marathon running. **Journal of Applied Physiology,** 42 (6), 909-914.

Marriott, H. E. and Lamb, K. L. (1996) The use of ratings of perceived exertion for regulating exercise levels in rowing ergometry. **European Journal of Applied Physiology and Occupational Physiology,** 72 (3), 267-71.

Marsh, D. and Sleivert, G. (1999) Effect of precooling on high intensity cycling performance. **British Journal of Sports Medicine,** 33 (6), 393-7.

Mauger, A., Jones, A. and Williams, C. (2010a) Influence of exercise variation on the retention of a pacing strategy. **European Journal of Applied Physiology,** 108 (5), 1015-1023.

Mauger, A. R., Jones, A. M. and Williams, C. A. (2009) Influence of feedback and prior experience on pacing during a 4-km cycle time trial. **Medicine & Science in Sports & Exercise,** 41 (2), 451-8.

Mauger, A. R., Jones, A. M. and Williams, C. A. (2010b) Influence of acetaminophen on performance during time trial cycling. **Journal of Applied Physiology,** 108 (1), 98-104.

Maughan, R., Leiper, J. B. and Shirreffs, S. M. (1996) Restoration of fluid balance after exercise induced dehydration: effect of food and fluid intake. **European Journal of Applied Physiology and Occupational Physiology,** 73, 317.

Mc Naughton, L. R., Thompson, D., Philips, G., Backx, K. and Crickmore, L. (2002) A Comparison of the Lactate Pro, Accusport, Analox GM7 and Kodak Ektachem Lactate Analysers in Normal, Hot and Humid Conditions. **International Journal of Sports Medicine,** 23 (02), 130-135.

McArdle, W. D., Katch, F. I. and Katch, V. L. (2001) **Exercise Physiology: Energy, Nutrition and Human Performance.** 5th ed. Baltimore, Maryland, Lippincott Williams Wilkins.

McLellan, T. M. (2007) Accuracy of radiopill telemetry during distance running in the heat. **Medicine & Science in Sports & Exercise,** 39 (2), 393.

McLellan, T. M., Cheung, S. S. and Jacobs, I. (1995) Variability of time to exhaustion during submaximal exercise. **Canadian Journal of Applied Physiology,** 20 (1), 39-51.

Meeusen, R. and De Meirleir, K. (1995) Exercise and brain neurotransmission. **Sports Medicine,** 20 (3), 160-188.

Meeusen, R., Watson, P., Hasegawa, H., Roelands, B. and Piacentini, M. F. (2006) Central fatigue: the serotonin hypothesis and beyond. **Sports Medicine,** 36 (10), 881-909.

Mekjavic, I. B. and Eiken, O. (2006) Contribution of thermal and nonthermal factors to the regulation of body temperature in humans. **Journal of Applied Physiology,** 100 (6), 2065-2072.

Meyer, T., Georg, T., Becker, C. and Kindermann, W. (2001) Reliability of gas exchange measurements from two different spiroergometry systems. **International Journal of Sports Medicine,** 22 (8), 593-7.

Micklewright, D., Papadopoulou, E., Swart, J. and Noakes, T. (2010) Previous experience influences pacing during 20 km time trial cycling. **British Journal of Sports Medicine,** 44 (13), 952-960.

Micklewright, D. and St Clair Gibson, A. (2010) Is it time to change? A proposed multidimensional scale of percieved fatigue. **'Challenging the dogma' 2010 BASES Annual Conference**, Glasgow, UK. S174.

Midgley, A. W. and Carroll, S. (2009) Emergence of the verification phase procedure for confirming 'true' VO2max. **Scandinavian Journal of Medicine & Science in Sports,** 19 (3), 313-322.

Midgley, A. W., Carroll, S., Marchant, D., McNaughton, L. R. and Siegler, J. (2009) Evaluation of true maximal oxygen uptake based on a novel set of standardized criteria. **Applied Physiology, Nutrition & Metabolism,** 34 (2), 115-123.

Midgley, A. W., McNaughton, L. R. and Carroll, S. (2007a) Effect of the VO2 time-averaging interval on the reproducibility of VO2max in healthy athletic subjects. **Clinical Physiology and Functional Imaging,** 27 (2), 122-125.

Midgley, A. W., McNaughton, L. R., Polman, R. and Marchant, D. (2007b) Criteria for determination of maximal oxygen uptake: A brief critique and recommendations for future research. **Sports Medicine,** 37 (12), 1019-1028.

Mitchell, D. and Wyndham, C. H. (1969) Comparison of weighting formulas for calculating mean skin temperature. **Journal of Applied Physiology,** 26 (5), 616-22.

Montain, S. J. and Coyle, E. F. (1992) Influence of graded dehydration on cardiovascular drift and hyperthermia during exercise. **Journal of Applied Physiology,** 73 (4), 1340-50.

Morris, M., Lamb, K., Hayton, J., Cotterrell, D. and Buckley, J. (2010) The validity and reliability of predicting maximal oxygen uptake from a treadmill-based sub-maximal perceptually regulated exercise test. **European Journal of Applied Physiology,** 109 (5), 983-988.

Nevill, M. E. and Greenhaff, P. L. (1999) Skeletal muscle metabolism during high intensity exercise in humans. In: Whipp, B. J. and Sargeant, A. J. (eds.) **Physiological determinants of exercise tolerance in humans.** London, Portland Press, pp.49-60.

Newsholme, E. A., Acworth, I. N. and Blomstrand, E. (1987) Amino acids, brain neurotransmitters and a functional link between muscle and brain that is important in sustained exercise. In: Benzi, G. (ed.) **Advances in myochemistry.** London, John Libbey, pp.p. 127–33.

Nielsen, B., Hales, J. R., Strange, S., Christensen, N. J., Warberg, J. and Saltin, B. (1993) Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. **The Journal of Physiology,** 460 (1), 467-485.

Nielsen, B. and Nielsen, M. (1962) Body temperature during work at different environmental temperatures. **Acta Physiologica Scandinavica,** 56, 120-129.

Nielsen, M. (1938) Die regulation der kopertemperateur bei muskelarbeit. **Skandinavisches Archiv für Physiologie,** 79, 193.

Noakes, T. D. (1997) 1996 J.B. Wolffe Memorial Lecture. Challenging beliefs: ex Africa semper aliquid novi. **Medicine & Science in Sports & Exercise,** 29 (5), 571-90.

Noakes, T. D. (2008a) How did A V Hill understand the VO2max and the "plateau phenomenon"? Still no clarity? **British Journal of Sports Medicine,** 42 (7), 574-80.

Noakes, T. D. (2008b) Testing for maximum oxygen consumption has produced a brainless model of human exercise performance. **British Journal of Sports Medicine,** 42 (7), 551-5.

Noakes, T. D., Lambert, M. I. and Hauman, R. (2009) Which lap is the slowest? An analysis of 32 world mile record performances. **British Journal of Sports Medicine,** 43 (10), 760-764.

Noakes, T. D. and Marino, F. E. (2009a) Last Word on Point:Counterpoint: Maximal oxygen uptake is/is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 347.

Noakes, T. D. and Marino, F. E. (2009b) Point: maximal oxygen uptake is limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 338-9.

Noakes, T. D. and St Clair Gibson, A. (2004) Logical limitations to the "catastrophe" models of fatigue during exercise in humans. **British Journal of Sports Medicine,** 38 (5), 648-649.

Noakes, T. D., St Clair Gibson, A. and Lambert, E. V. (2004) From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans. **British Journal of Sports Medicine,** 38 (4), 511-514.

Noakes, T. D., St Clair Gibson, A. and Lambert, E. V. (2005) From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. **British Journal of Sports Medicine,** 39 (2), 120-124.

Noakes, T. D., St Clair Gibson, A. and Lambert, E. V. (2006) Is fatigue all in your head? A critical review of the central governor model - Commentary. **British Journal of Sports Medicine,** 40 (7), 586.

Noble, B. J., Borg, G. A. V., Jacobs, I., Cecil, R. and Kaiser, P. (1983) A category-ratio perceived exertion scale: relationship to blood and muscle lactates and heart rate. **Medicine & Science in Sports & Exercise,** 15 (6), 523-528.

Nowicky, A., Burdett, R. and Horne, S. (2005) The impact of ergometer design on hip and trunk muscle activity patterns in elite rowers:an electromyographic assessment. **Journal of Sports Science and Medicine,** 4, 18-28.

Nybo, L. and Nielsen, B. (2001a) Hyperthermia and central fatigue during prolonged exercise in humans. **Journal of Applied Physiology,** 91 (3), 1055-1060.

Nybo, L. and Nielsen, B. (2001b) Perceived exertion is associated with an altered brain activity during exercise with progressive hyperthermia. **Journal of Applied Physiology,** 91 (5), 2017-23.

O'Brien, C., Hoyt, R. W., Buller, M. J., Castellani, J. W. and Young, A. J. (1998) Telemetry pill measurement of core temperature in humans during active heating and cooling. **Medicine & Science in Sports & Exercise,** 30 (3), 468-72.

Ottenbacher, K. J. and Tomchek, S. D. (1994) Measurement variation in method comparison studies: an empirical examination. **Archives of Physical Medicine and Rehabilitation,** 75 (5), 505-12.

Panjkota, A. and Music, J. (2005) Muscle activity during ergometer rowing. In: **Proceedings of the IASTED International Conference, Innsbruck, Austria.** 652-656

Pearsall, J. (ed.) (1999) **The concise Oxford dictionary.** Oxford, Oxford University Press.

Pedersen, T. H., Nielsen, O. B., Lamb, G. D. and Stephenson, D. G. (2004) Intracellular acidosis enhances the excitability of working muscle. **Science,** 305 (5687), 1144-1147.

Poole, D., Wilkerson, D. and Jones, A. (2008) Validity of criteria for establishing maximal O2 uptake during ramp exercise tests. **European Journal of Applied Physiology,** 102 (4), 403-410.

Prampero, P. (1981) Energetics of muscular exercise. **Reviews of Physiology, Biochemistry and Pharmacology,** 89, 143-222.

Pyne, D. B., Boston, T., Martin, D. T. and Logan, A. (2000) Evaluation of the Lactate Pro blood lactate analyser. **European Journal of Applied Physiology,** 82 (1), 112-116.

Ramanathan, N. L. (1964) A new weighting system for mean surface temperature of the human body. **Journal of Applied Physiology,** 19, 531-533.

Robergs, R. A., Ghiasvand, F. and Parker, D. (2004) Biochemistry of exercise-induced metabolic acidosis. **American Journal of Physiology - Regulatory, Integrative and Comparative Physiology,** 287 (3), R502-R516.

Roberts, C. L., Wilkerson, D. P. and Jones, A. M. (2005) Pulmonary O2 uptake on-kinetics in rowing and cycle ergometer exercise. **Respiratory Physiology & Neurobiology,** 146 (2-3), 247-258.

Robertson, R. J. (1982) Central signals of perceived exertion during dynamic exercise. **Medicine & Science in Sports & Exercise,** 14 (5), 390-6.

Rossiter, H. B., Kowalchuk, J. M. and Whipp, B. J. (2006) A test to establish maximum O2 uptake despite no plateau in the O2 uptake response to ramp incremental exercise. **Journal of Applied Physiology,** 100 (3), 764-70.

Saltin, B. and Hermansen, L. (1966) Esophageal, rectal, and muscle temperature during exercise. **Journal of Applied Physiology,** 21, 1757.

Saunders, A. G., Dugas, J. P., Tucker, R., Lambert, M. I. and Noakes, T. D. (2005) The effects of different air velocities on heat storage and body temperature in humans cycling in a hot, humid environment. **Acta Physiologica Scandinavica,** 183 (3), 241-55.

Sawka, M. N. and Wenger, C. B. (1988) Physiological responses to acute exercise-Heat stress. In: Pandolf, K., Sawka, M. and Gonzalez, R. (eds.) **Human Performance Physiology and Environmental Medicine at Terristial Extremes.** Indianapolis, Benchmark Press.

Schabort, E., Hopkins, W. and Hawley, J. (1998) Reproducibility of self-paced treadmill performance of trained endurance runners. **International Journal of Sports Medicine,** 19 (1), 48-51.

Schabort, E. J., Hawley, J. A., Hopkins, W. G. and Blum, H. (1999) High reliability of performance of well-trained rowers on a rowing ergometer. **Journal of Sports Sciences,** 17 (8), 627-32.

Schlader, Z., Simmons, S., Stannard, S. and Mundel, T. (2010a) Skin temperature as a thermal controller of exercise intensity. **European Journal of Applied Physiology**, 1-9.

Schlader, Z. J., Stannard, S. R. and Mundel, T. (2010b) Human thermoregulatory behavior during rest and exercise - a prospective review. **Physiology & Behavior,** 99 (3), 269-75.

Secher, N. (1983) The physiology of rowing. **Journal of Sports Sciences,** 1, 23-53.

Secher, N. (1993) Physiological and biomechanical aspects of rowing. Implications for training. **Sports Medicine,** 15 (1), 24-42.

Sharp, R. L., Costill, D. L., Fink, W. J. and King, D. S. (1986) Effects of eight weeks of bicycle ergometer sprint training on human muscle buffer capacity. **International Journal of Sports Medicine,** 7, 13-17.

Shephard, R. J. (1998) Science and medicine of rowing: A review. **Journal of Sports Sciences,** 16, 603-620.

Shephard, R. J. (2009a) Comments on Point:Counterpoint: Maximal oxygen uptake is/is not limited by a central nervous system governor. **Journal of Applied Physiology,** 106 (1), 343.

Shephard, R. J. (2009b) Is it time to retire the 'Central Governor'? **Sports Medicine,** 39 (9), 709-721.

Shephard, R. J. (2010) Is it time to retire the Central Governor? A philosophical and evolutionary perspective: Response. **Sports Medicine,** 40 (3), 268-270.

Shimojo, N., Naka, K., Uenoyama, H., Hamamoto, K., Yoshioka, K. and Okuda, K. (1993) Electrochemical assay system with single-use electrode strip for measuring lactate in whole blood. **Clinical Chemistry,** 39 (11), 2312-2314.

Skinner, J. S., Hutsler, R., Bergsteinova, V. and Buskirk, E. R. (1973) The validity and reliability of a rating scale of perceived exertion. **Medicine & Science in Sports,** 5 (2), 94-6.

Sleivert, G. (2003) Anaerobic Assessment. In: Bishop, B. and Hume, P. A. (eds.) **Guidelines for Athlete Assessment in New Zealand Sport.** Wellington, SESNZ.

Smith, B. (2000) Rowing New Zealand. In: Bishop, B. and Hume, P. A. (eds.) **Guidelines for Athlete Assessment in New Zealand Sport.** Wellington, SESNZ.

Snell, P. G., Stray-Gundersen, J., Levine, B. D., Hawkins, M. N. and Raven, P. B. (2007) Maximal oxygen uptake as a parametric measure of cardiorespiratory capacity. **Medicine & Science in Sports & Exercise,** 39 (1), 103-7.

Soper, C. and Hume, P. A. (2004) Reliability of power output during rowing changes with ergometer type and race distance. **Sports Biomechanics,** 3 (2), 237-48.

Sparling, P. B., Snow, T. K. and Millard-Stafford, M. L. (1993) Monitoring core temperature during exercise: ingestible sensor vs. rectal thermistor. **Aviation Space & Environmental Medicine,** 64 (8), 760-3.

St Clair Gibson, A., Lambert, E. V., Rauch, L. H., Tucker, R., Baden, D. A., Foster, C. and Noakes, T. D. (2006) The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. **Sports Medicine,** 36 (8), 705-722.

St Clair Gibson, A., Lambert, M. I. and Noakes, T. D. (2001a) Neural control of force output during maximal and submaximal exercise. **Sports Medicine,** 31 (9), 637-650.

St Clair Gibson, A. and Noakes, T. D. (2004) Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. **British Journal of Sports Medicine,** 38 (6), 797-806.

St Clair Gibson, A., Schabort, E. J. and Noakes, T. D. (2001b) Reduced neuromuscular activity and force generation during prolonged cycling. **American Journal of Physiology - Regulatory, Integrative and Comparative Physiology,** 281 (1), R187-R196.

Steinacker, J. M. (1993) Physiological aspects of training in rowing. **International Journal of Sports Medicine,** 14 (Suppl 1), S3-10.

Storer, T. W., Davis, J. A. and Caiozzo, V. J. (1990) Accurate prediction of VO2max in cycle ergometry. **Medicine & Science in Sports & Exercise,** 22 (5), 704-12.

Swart, J., Lamberts, R. P., Lambert, M. I., Lambert, E. V., Woolrich, R. W., Johnston, S. and Noakes, T. D. (2009) Exercising with reserve: exercise regulation by perceived exertion in relation to duration of exercise and knowledge of endpoint. **British Journal of Sports Medicine,** 43 (10), 775-781.

Temple, O. and Temple, R., (Translators). (1998) **The complete fables by Aesop.** London, Penguin Classics.

Thoden, J. S. (1991) Testing aerobic power. In: MacDougall, J. D., Wenger, H. A. and Green, H. J. (eds.) **Physiological testing of the high performance athlete.** Vol. 2nd ed Champaign, Human Kinetics, pp.107-73.

Thomas, J., Nelson, J. and Silverman, S. (2005) **Research methods in physical activity.** Champaign, Human Kinetics.

Thomas, K., Stone, M., Thompson, K., St Clair Gibson, A. and Ansley, L. (2010) Reproducibility of pacing and performance during 20-km laboratory-simulated time trials. In: **'Challenging the Dogma' 2010 BASES Annual Conference, Glasgow, UK.** S156

Townshend, A. D., Worringham, C. J. and Stewart, I. B. (2010) Spontaneous pacing during overground hill running. **Medicine & Science in Sports & Exercise,** 42 (1), 160-169.

Tucker, R. (2009) The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance. **British Journal of Sports Medicine,** 43 (6), 392-400.

Tucker, R., Bester, A., Lambert, E. V., Noakes, T. D., Vaughan, C. L. and St Clair Gibson, A. (2006a) Non-random fluctuations in power output during self-paced exercise. **British Journal of Sports Medicine,** 40 (11), 912-917.

Tucker, R., Lambert, M. I. and Noakes, T. D. (2006b) An analysis of pacing strategies during mens world-record performances in track athletics. **International Journal of Sports Physiology and Performance,** 1 (3), 233-45.

Tucker, R., Marle, T., Lambert, E. V. and Noakes, T. D. (2006c) The rate of heat storage mediates an anticipatory reduction in exercise intensity during cycling at a fixed rating of perceived exertion. **The Journal of Physiology,** 574 (3), 905-15.

Tucker, R. and Noakes, T. D. (2009) The physiological regulation of pacing strategy during exercise: a critical review. **British Journal of Sports Medicine,** 43 (6), e1-.

Tucker, R., Rauch, L. G. H., Harley, Y. X. and Noakes, T. D. (2004) Impaired exercise performance in heat is associated with an anticipatory reduction in skeletal muscle recruitment. **European Journal of Applied Physiology,** 48 (4), 422-430.

Ueda, T. and Kurokawa, T. (1995) Relationships between perceived exertion and physiological variables during swimming. **International Journal of Sports Medicine,** 16 (6), 385-9.

Ulmer, H. V. (1996) Concept of an extracellular regulation of muscular metabolic rate during heavy exercise in humans by psychophysiological feedback. **Experientia,** 52 (5), 416-20.

Vincent, W. (2005) **Statistics in kinesiology.** 3rd ed. Champaign, Human Kinetics.

Vogler, A. J., Rice, A. J. and Withers, R. T. (2007) Physiological Responses to Exercise on Different Models of the Concept II Rowing Ergometer. **International Journal of Sports Physiology and Performance,** 2 (4), 360-370.

Walker, C., Lamb, K. L. and Marriott, H. E. (1996) the validity of using ratings of perceived exertion to estimate and regulate exercise intensity during stepping ergometry. **Journal of Sports Sciences,** 14 (2), 102-103.

Weir, J. P. (2005) Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. **Journal of Strength & Conditioning Research,** 19 (1), 231-40.

Weir, J. P., Beck, T. W., Cramer, J. T., Housh, T. J., Noakes, T. D., St Clair Gibson, A. and Lambert, E. V. (2006) Is fatigue all in your head? A critical review of the central governor model. **British Journal of Sports Medicine,** 40 (7), 573-586.

Whipp, B. J. (2010) The Peak vs Maximum oxygen uptake issue. **CPX International Perspectives** [Internet], Available from: <http://www.cpxinternational.com/attachments/045_VO2PeakVsMax.pdf> [Accessed 04/07/2010].

Wiener, S. P., Garber, C. E. and Manfredi, T. G. (1995) A comparison of exercise performance on bicycle and rowing ergometers in female master recreational rowers. **Journal of Sports Medicine and Physical Fitness,** 35 (3), 176-80.

Winter, E. M. (2006) **Sport and exercise physiology testing guidelines: The BASES guide. Sport Testing.** London, Routledge.

Wright, R. (1996) Brehm's theory of motivation as a model of effort and cardiovascular response. In: Gollwitzer, P., Bargh, J (ed.) **The psychology of action: Linking cognition and motivation to behavior.** New York, Guilford, pp.424-453.

Wyss, C. R., Brengelmann, G. L., Johnson, J. M., Rowell, L. B. and Niederberger, M. (1974) Control of skin blood flow, sweating, and heart rate: role of skin vs. core temperature. **Journal of Applied Physiology,** 36 (6), 726-733.

Zhang, P. and Tokura, H. (1999) Thermoregulatory responses in humans during exercise after exposure to two different light intensities. **European Journal of Applied Physiology and Occupational Physiology,** 79 (3), 285-9.

Appendices

1.0

Ethical approval.

THIS SECTION HAS BEEN REDACTED DUE TO SENSITIVE INFORMATION

2.0

Information provided to participants.

2.1 Participant information sheet used in studies 1 and 2.

UCOL

Participant Information Sheet

You are invited to participate in this study following consideration of the information provided on this sheet and the satisfactory completion of the Pre-test Questionnaire.

STUDY TITLE: Physiological heat stress responses to self-paced and directed-pace rowing ergometry exercise in a thermo-neutral environment at the same relative intensity of effort.

LOCATION: The Human Performance Laboratory situated in block 6, 3rd floor, Human Performance Department of Universal College of Learning

PRINCIPAL RESEARCHER: Patrick Lander - Emergency contact (021 0540362)

RESEARCH SUPERVISOR: Dr Andrew Edwards
Emergency contact (021 2636231)

APPROVAL: This study has been approved by the Central Regional Ethics Committee.

Background –

The main aim of the study is to compare the heat stress responses at the same relative intensity of maximal effort, and at a maximal effort, across self-paced and directed-pace rowing ergometry exercise in normal conditions. The comparison of responses in these conditions will provide further information about the acute physical responses to heat stress and how we control our bodies to prevent becoming too hot during exercise.

Previous research has shown that heat stress is related to aerobic capacity (VO_2 max) and individual differences in thermoregulation (Havenith et al. 1990). Exercise performed at intensities based on each individual's maximal aerobic power is well known to be an effective strategy for normalising effort (Edwards et al. 2003, Edwards & Cooke 2004), but an individual's ability to self-regulate effort is also a powerful means of avoiding physical harm.

In this study, we would like to examine your ability to accurately judge pacing strategies and consequent physiological responses to: 1) 5000m of high intensity (power output equivalent to 80% $\dot{V}O_2$ peak) self-paced rowing (approximately 20-25 min) exercise using a Borg scale of perceived exertion and receiving only stroke rate feedback and 2) compare this with a directed-pace trial designed to elicit a similar level of work based on a fixed percentage of maximal effort, with feedback of stroke rate and power per stroke. To observe the effects of these factors have during maximal exercise we would also like to examine your ability to pace and consequential physiological responses to an all out maximal 5000m effort with 3) feedback of power per stroke and stroke rate and 4) feedback of stroke rate only.

The accurate quantification of thermal stress can now be measured dynamically during exercise through the use of a thermometer pill system which works through close range radio telemetry. This enables the real-time measurement of core temperature where, previously, only pre- and post-exercise measures were possible (Edwards and Clark 2006).

2.1 Participant information sheet used in studies 1 and 2 (cont).

Procedures

Should you agree to participate in this study then you will be asked to complete the following:

Preliminary Physiological Tests

Maximum Oxygen Uptake ($VO_{2\,max}$) in normal and warm conditions

This is a test which determines the ability of your body to take oxygen from the air, deliver it to your working muscles and utilise the oxygen in the muscle. In this test you will be asked to row on the ergometer to exhaustion (approx 10 minutes). Following a 5 min warm up, you will be asked to row at a wattage of 100 watts and increase your power output by 30 watts each minute. Your expired air will be obtained constantly throughout the test and used to evaluate exercise intensity & criteria of aerobic capacity. When you feel that you can't maintain the required intensity any longer the testing will cease. This test will be performed on one occasion only.

Familiarisation

To familiarise yourself with the protocol you will be asked to complete 2 sessions of 22 minutes on the ergometer which will correspond to the intensities you will be asked to maintain for a distance of 5000m in the main trial. These sessions will familiarise you with the protocol, equipment, and intensities to be used in the main trials. Using short bursts of exercise at different levels of intensity, you will asked to pre-estimate a 30-min constant pace for yourself at a hard (but not maximal) intensity using the Borg Scale of Perceived Exertion.

Main Trial Measures

Heart rate and Oxygen Uptake assessment

Heart rate will be measured throughout the test using a Polar chest strap. Oxygen uptakes will be assessed breath by breath using Cortex portable gas analyser which consists of a mouth and nose mask attached to a small pouch to be worn around the chest and shoulders. The mask will be fitted immediately prior to testing and removed as soon as the test has finished.

Core temperature assessment

A silicone coated core temperature 'pill' should be swallowed 4-6 hrs prior to exercise. The thermometer pill has been used in numerous International research publications (Edwards and Clark 2006 among others) and passes naturally through the digestive system. The pill emits a small electrical signal that can be used to accurately monitor core temperature in real-time. The pill is for single use only and it typically passed with the faeces after approximately 24 hr. You will be contacted to confirm this pill has been passed in the faeces 48hrs after testing.

If you have a history of gastrointestinal illness you should not participate in this study.

2.1 Participant information sheet used in studies 1 and 2 (cont).

Skin temperature assessment

Skin temperature will be assessed from 4 sites; chest, arm, thigh and calf using a Grant Squirrel data logger. In order to maintain a good connection each area will be cleaned and may be shaved before the skin thermistors are taped securely in place

Muscle EMG assessment

Muscle electromyography sensors will be placed at 5 locations on the skin; 2 on the thigh, 2 on the bicep, and 1 on the wrist. In order to maintain a good connection each area will be cleaned and may be shaved before the sensors are taped securely in place

Blood and urine samples

Capillary blood samples (100 μl) will be required pre- and post-testing in both the self-paced and directed pace conditions (8 samples in total). Blood will be drawn from the fingertip by well-trained sports scientists. The blood samples will only be used to measure your hydration levels and the build up of lactic acid.

Main Trial Exercise Tests

On 4 occasions you will asked to arrive at the laboratory and complete an exercise test that will commence with a 10-min warm up and which will then lead into a 5000m rowing ergometry test. The following 4 tests will be completed in a randomised order. The following tests should take between 17-35 min depending on your individualised pacing.

Test 1) You will be directed to row for 5000m maintaining a constant effort based on a power output equivalent to 80% of your peak $\dot{V}O_2$ attained previously in the preliminary test. This intensity has previously been shown to broadly correspond with level 15 (hard effort) on the Borg Rating of Perceived Exertion (RPE) scale. You will have knowledge of your power output per stroke and stroke rate. You will be informed when each 1000m of the 5000 metres has elapsed. This trial will be at a hard, but not maximal intensity.

Test 2) You will be asked to maintain a self paced level of effort (RPE of 15) for 5000m of rowing exercise corresponding to 'hard' on the Borg scale. You will have no knowledge of power output per stroke but you will have knowledge of your stroke rate. You will be informed when each 1000m of the 5000 metres has elapsed. This trial will be at a hard, but not maximal intensity.

Test 3) You will be asked to complete the 5000m rowing exercise at an all-out maximal pace. You will have knowledge of stroke rate and power output per stroke so as to judge how to pace yourself maximally for the duration of the test. You will be informed when each 1000m of the 5000 metres has elapsed.

Test 4) You will be asked to complete the 5000m rowing exercise at an all-out maximal pace. You will have no knowledge of power output per stroke. but you will have knowledge of your stroke rate. You will be informed when each 1000m of the 5000 metres has elapsed.

Core temperature, heart rates, skin temperatures, muscle EMG and oxygen uptake will be measured constantly throughout the exercise tests in both trials.

2.2 Informed consent sheet used in studies 1 and 2.

UCOL

Sports Physiology Laboratory
Informed Consent

Research Title: Physiological heat stress responses to self-paced and directed-pace rowing ergometry exercise in a thermo-neutral environment at the same relative intensity of effort

Principal Researcher: Patrick Lander

Research Supervisor: Dr Andrew Edwards

The full details of the test(s) have been explained to me. I am clear about what will be involved and I am aware of the purpose of the tests, the potential benefits and the potential risks.

I know that I am not obliged to complete the tests. I am free to stop the test at any point of the study and for any reason.

The tests results are confidential and will only be communicated to others if agreed in advance.

I have no injury or illness that will affect my ability to successfully complete the tests.

I consent to weighing myself nude immediately before and after each trial.

I consent to giving capillary blood samples for the assessment of blood lactate, red blood cell concentration and osmolality in both the directed pace and self paced trials.

I am aware that all my blood samples will be destroyed immediately following the analyses specified in the information sheet.

I consent to attaching skin thermistors and EMG monitors to the areas of my body as described in the information sheet. I am aware that these areas may need to be cleaned and shaved as required prior to testing on two separate occasions.

I consent to swallow a thermometer 'pill' for the assessment of real-time core temperature during exercise in both trials and to wear a heart rate monitor and mouthpiece for the continuous assessment of exercise heart rates and energy expenditure i.e. swallowing a thermometer pill on two separate occasions.

I understand the ACC compensation provisions for this study outlined on the Participant Information Sheet.

I have had time to consider whether to take part.

Signature of participant...

Date..

Signature of test supervisor..

2.3 Pre-test questionnaire used in studies 1 and 2.

Pre-Test Questionnaire

Name.. Date of Birth..................... Age............

As you are to be a participant in this laboratory, would you please complete the following questionnaire. Your co-operation in this is greatly appreciated.

ANY INFORMATION CONTAINED HEREIN WILL BE TREATED AS CONFIDENTIAL.

Note: A 'yes' answer to questions 1-5 will represent exclusion criteria from this study. All remaining answers will enable the researchers to determine your suitability for participation in the study. In some cases, further medical evidence may be required to confirm participation.

*** Please delete where appropriate.**

1. Do you have any history of gastrointestinal illness? Yes/no*
2. Do you suffer, or have you ever suffered from, any form of heart complaint? Yes/no*
3. Are you taking any medication for a heart complaint, such as beta blockers? Yes/no*
4. Do you currently have any form of muscle or joint injury? Yes/no*
5. Do you suffer from asthma and/or diabetes? Yes/no*
6. Is there a history of heart disease in your family? Yes/no*
7. Have you had any cause to suspend your normal training in the last two weeks? Yes/no*
8. Is there anything to your knowledge that may prevent you from successfully completing the tests that have been outlined to you? Yes/no*

9. How would you describe your present activity level?
   Sedentary/moderately active/highly active*. Give an example of a typical week's exercise.

2.3 Pre-test questionnaire used in studies 1 and 2 (cont).

10. How would you describe your present level of fitness?
    very unfit/moderately fit/ highly trained*
11. How would you consider your present body weight?
    underweight/ideal weight/slightly overweight/very overweight*
12. Smoking habits:
    Currently non-smoker Yes/no*
    A previous smoker Yes/no* .... per day
    If previous smoker, how long since stopping? .... years
    A regular smoker Yes/no* .... per day
    An occasional smoker Yes/no* .... per day

13. Consumption of alcohol:
    Do you drink alcoholic drinks? Yes/no*
    If yes, then do you:
        Have the occasional drink? Yes/no*
        Have a drink every day? Yes/no*
        Have more than one drink a day? Yes/no*
    Please indicate the type of alcoholic beverage you consume, i.e. beer, spirits, shandy.
14. Have you had to consult your doctor within the last 6 months? Yes/no*
    If yes please give relevant details to the test supervisor.

15. Are you presently taking any form of medication? Yes/no*
    if yes please give details to the test supervisor.

16. Do you suffer, or have you ever suffered, from
    Asthma? Yes/no*
    Diabetes? Yes/no*
    Bronchitis? Yes/no*
    Epilepsy? Yes/no*

Signature of subject...

Date...

Signature of test supervisor..

2.4 Participant information sheet used in studies 3 and 4.

Participant Information

Please consider the information provided on this sheet and complete the Pre-test Questionnaire and Informed consent. On satisfactory completion of these documents you will be invited to participate in the following study.

STUDY TITLE: Physiological and performance responses to self-paced rowing ergometry exercise: impact of radiant heat on pacing dynamics.

LOCATION: The Human Performance Laboratory situated in block 6, 3rd floor, Human Performance Department of Universal College of Learning

PRINCIPAL RESEARCHER: Patrick Lander ext 64704
Emergency contact (021 0540362)

RESEARCH SUPERVISOR: Dr Andrew Edwards ext 70612
Emergency contact (021 2636231)

APPROVAL: This study has been approved by the Central Regional Ethics Committee.

Background –

The main aim of the study is to compare physiological responses and concomitant pacing strategies during submaximal exercise in response to varied heat exposure. The comparison of responses in these conditions will provide further information about the impact of radiant heat on pacing strategies during exercise.

Previous research has shown that individuals preselect a pacing strategy at the start (Foster et al 1994) or within the first four minutes (St Clair et al, 1996) of exercise. Numerous authors have also suggested that pacing strategies are altered as part of a complex control mechanism which balances feedforward and feedback from a range of physiological mechanisms' in order to avoid the disruption of homeostasis (Noakes 2008). It is known that core temperature is a defended variable in exercise (Noakes et al 2005) and recent findings (Lander et al 2008 Unpublished data) have identified significant correlations between skin temperature and power output during submaximal self paced exercise.

Thus in this study, we would like to examine your physiological responses and concomitant changes in pacing strategies in conditions of varied heat exposure completing 5,000m of "hard" intensity (RPE 15) self-paced rowing (approximately 20-30 min) exercise whilst: 1) being continuously warmed 1 infrared lamps. 2) not being continuously warmed using infrared lamps and 3) being warmed every alternating 1000m using infrared heat lamps.
In addition to these main trials you will be asked to perform 2 traditional maximum oxygen uptake trials, and 2 self paced maximum oxygen uptake trials.

Any changes in pacing in the main trials may suggest the body takes a more dynamic approach to pacing than previously identified and given the importance of defending core temperature varied heat exposure provides an excellent methodology to do this.

2.4 Participant information sheet used in studies 3 and 4 (cont).

Procedures

Should you agree to participate in this study then you will be asked to complete the following:

Preliminary Physiological Tests

Familiarisation

To familiarise yourself with the protocol you will be asked to complete 2 sessions of 10 minutes on the ergometer which will correspond to the intensities you will be asked to maintain for a distance of 5,000m in the main trials. These sessions will familiarise you with the protocol, equipment, and intensities to be used in the main trials.

Maximum Oxygen Uptake ($VO_{2\,max}$)

This is a test which determines the ability of your body to take oxygen from the air, deliver it to your working muscles, and utilise the oxygen in the muscle. In this test you will be asked to row on the ergometer to a point of exhaustion (approx 10 minutes). Following a 5 min warm up, you will be asked to row at a power output of 150 watts for 3 minutes and then increase your power output by 25 watts each subsequent minute until exhaustion. Your expired air will be monitored constantly throughout the test and used to evaluate exercise intensity & criteria of aerobic capacity. When you feel that you can't maintain the required intensity any longer the testing will cease. This test will be performed on two occasions and will utilise the equipment described in the section below titled Heart rate and Oxygen Uptake assessment.

You will be asked to complete this test twice.

Self Paced Maximum Oxygen Uptake ($VO_{2\,max}$)

This is a novel protocol designed to determine your self paced maximum ability of your body to take oxygen from the air, deliver it to your working muscles, and utilise the oxygen in the muscle. In this test you will be asked to row on the ergometer to a self paced point of exhaustion in 10 mins. Following a 5 min warm up, you will be asked to row at self paced perceived incremental rates of perceived intensity which will increase by 2 RPE points per 2 minutes starting from RPE 11 (Light) and ending with a maximal power output within the final 2 minute stage rated RPE 20 (Maximal exertion). Your expired air will be monitored constantly throughout the test and used to evaluate exercise intensity & criteria of aerobic capacity. This test will cease 10 minutes from the start and will utilise the equipment described in the section below titled Heart rate and Oxygen Uptake assessment.

You will be asked to complete this test twice

Main Trial Measures

Heart rate and Oxygen Uptake assessment

Heart rate will be measured throughout the trials using a Polar chest strap. Oxygen uptakes will be assessed breath by breath using Cortex portable gas analyser which consists of a mouth and nose mask attached to a small pouch to be worn around the chest and shoulders. The mask will be fitted immediately prior to exercise and removed as soon as the trial has finished.

Core temperature assessment

A silicone coated core temperature 'pill' should be swallowed 4-6 hrs prior to exercise. The thermometer pill has been used in numerous International research publications (Edwards et al 2007 among others) and passes naturally through the digestive system. The pill emits a small electrical signal that can be used to accurately monitor core temperature in real-time. The pill is for single use only and it typically passed with the faeces after approximately 24 hr. You will be contacted to confirm this pill has been passed in the faeces 48hrs after each trial.

If you have a history of gastrointestinal illness you should not participate in this study.

2.4 Participant information sheet used in studies 3 and 4 (cont).

Skin temperature assessment
Skin temperature will be assessed from 4 sites; chest, arm, thigh and calf using a Grant Logistics SQ400 data logger. In order to maintain a good connection each area will be cleaned and may be shaved before the skin thermistors are taped securely in place

Muscle EMG assessment
Muscle electromyography sensors will be placed at 5 locations on the skin; 2 on the thigh, 2 on the upper arm, and 1 on the wrist. In order to maintain a good connection each area will be cleaned and may be shaved before the sensors are taped securely in place

Blood samples
Capillary blood samples (100 μl) will be required pre- and post-testing in each of the four conditions (6 samples in total). Blood will be drawn from the fingertip by well-trained sports scientists.

Main Trial Exercise Tests
On 3 further occasions additional to your $\dot{V}O_{2max}$ trials you will be asked to arrive at the laboratory rested and ready to complete an exercise test that will commence with a 10-min warm up and which will then lead into a 5,000m rowing ergometry test. The following 3 tests will be completed in a randomised order. The following tests should take between 20-30 min depending on your individualised pacing.

Condition 1) You will be directed to row for 5,000m maintaining a constant self paced effort based on an RPE of 15 which corresponds to "Hard" on the Borg RPE Scale. You will have no knowledge of your power output per stroke or stroke rate but will be informed when you complete every 1000m. Throughout this trial you will be warmed to an ambient temperature of 35°C using infrared heat lamps.

Condition 2) You will be directed to row for 5,000m maintaining a constant self paced effort based on an RPE of 15 which corresponds to "Hard" on the Borg RPE Scale. You will have no knowledge of your power output per stroke or stroke rate but will be informed when you complete every 1000m. Throughout this trial you will be not be warmed.

Condition 3) You will be directed to row for 5,000m maintaining a constant self paced effort based on an RPE of 15 which corresponds to "Hard" on the Borg RPE Scale. You will have no knowledge of your power output per stroke or stroke rate but will be informed when you complete every 1000m. Throughout this trial you will be warmed to an ambient temperature of 35°C for each alternate 1000m using infrared heat lamps.

Core temperature, heart rate, skin temperatures muscle EMG and oxygen uptake will be measured constantly throughout the exercise trials.

You will be asked to complete each condition once only.

Summary
To complete this study you will be required to participate in a total of 7 trials
(2 x Self paced $\dot{V}O_{2max}$; 2 x $\dot{V}O_{2max}$; 3 x 5000m at RPE 15)

2.4 Participant information sheet used in studies 3 and 4 (cont).

Possible Risks/Discomforts

The trial protocols used in this study should not represent metabolic challenges beyond those of your regular gymnasium training; however, you should note that strenuous exercise carries a minor risk of sudden death due to heart failure in those with undiagnosed medical conditions and/or family history of such conditions. The incidence of such diseases in the exercising population is extremely low with estimated cases varying from 1 per 10,000 active exercisers to 1 per 200,000 in children and young adults. If you or we have any reason to suspect that this may apply to you a doctor's certificate will be required before participation in any testing.

During the VO_{2max} test you will reach your maximal ability to extract oxygen and this will require maximum effort for 1 to 2 minutes. You should recover fully within 5 minutes.

During the trials you will work at a self paced hard intensity over approximately 20-25 minutes. You should recover fully within 15 minutes.

Please note that you are able to withdraw from this study at any stage.

If you have any queries or concerns regarding your rights as a participant in this study you may wish to contact a Health and Disability Advocate, telephone

- Ben Harvey Palmerston North PH – 3537236

In the unlikely event of a physical injury as a result of your participation in this study, you may be covered by ACC under the Injury Prevention, Rehabilitation and Compensation Act. ACC cover is not automatic and your case will need to be assessed by ACC according to the provisions of the 2002 Injury Prevention Rehabilitation and Compensation Act. If your claim is accepted by ACC, you still might not get any compensation. This depends on a number of factors such as whether you are an earner or non-earner. ACC usually provides only partial reimbursement of costs and expenses and there may be no lump sum compensation payable. There is no cover for mental injury unless it is a result of physical injury. If you have ACC cover, generally this will affect your right to sue the investigators.

If you have any questions about ACC, contact your nearest ACC office or the investigator.

For further information on this study please contact:
Patrick Lander
E-mail: p.lander@ucol.ac.nz
Tel: 06 965 3800 ext 64704 or 021 0540362

Dr Andrew Edwards
E-mail: a.m.edwards@ucol.ac.nz
Tel: 06 952 7000 ext 70612 or 021 2636231

2.5 Informed consent sheet used in studies 3 and 4.

Informed Consent

Research Title: Physiological and performance responses to self-paced rowing ergometry exercise: impact of radiant heat on pacing dynamics.

Principal Researcher: Patrick Lander

Research Supervisor: Dr Andrew Edwards

The full details of the trials have been explained to me. I am clear about what will be involved and I am aware of the purpose of the tests, the potential benefits and the potential risks.

I know that I am not obliged to complete the trials. I am free to stop the test at any point of the study and for any reason.

I understand my trial results are confidential and will only be communicated to others if agreed by me in advance.

I have no injury or illness that will affect my ability to successfully complete the trials.

I consent to weighing myself nude immediately before and after each trial.

I consent to giving capillary blood samples for assessment in all trials.

I am aware that all my blood samples will be destroyed immediately following the analyses specified in the information sheet.

I consent to attaching skin thermistors and EMG monitors to the areas of my body as described in the information sheet. I am aware that these areas may need to be cleaned and shaved as required prior to each of the trials.

I consent to swallow a thermometer 'pill' for the assessment of real-time core temperature during exercise in each of the trials and to wear a heart rate monitor and mouthpiece for the continuous assessment of exercise heart rates and energy expenditure.

I understand the ACC compensation provisions for this study outlined on the Participant Information Sheet.

I have had time to consider whether to take part.

Signature of participant..

Date...

Signature of test supervisor...

2.6 Pre-test questionnaire used in studies 3 and 4.

Pre-Test Questionnaire

UCOL
UNIVERSAL COLLEGE OF LEARNING

Name.. Date of Birth.................... Age............

Height............................ Weight............

Prior to any exercise would you please complete the following questionnaire. Your co-operation in this is greatly appreciated.

ANY INFORMATION CONTAINED HEREIN WILL BE TREATED AS CONFIDENTIAL.

Note: A 'yes' answer to questions 1-5 will represent <u>exclusion criteria</u> from this study. All remaining answers will enable the researchers to determine your suitability for participation in the study. In some cases, further medical evidence may be required to confirm participation.

*** Please delete where appropriate.**

1. Do you have any history of gastrointestinal illness? Yes/no*
2. Do you suffer, or have you ever suffered from, any form of heart complaint? Yes/no*
3. Are you taking any medication for a heart complaint, such as beta blockers? Yes/no*
4. Do you currently have any form of muscle or joint injury? Yes/no*
5. Do you suffer from diabetes? Yes/no*
6. Do you suffer from uncontrolled asthma? Yes/no*

7. Is there a history of heart disease in your family? Yes/no*
8. Have you had any cause to suspend your normal training in the last two weeks? Yes/no*
9. Is there anything to your knowledge that may prevent you from successfully completing the tests that have been outlined to you? Yes/no*

10. How would you describe your present activity level?

    Sedentary/moderately active/highly active*.

    Give an example of a typical week's exercise.

11. How would you describe your present level of fitness?

    very unfit/moderately fit/ highly trained*

2.6 Pre-test questionnaire used in studies 3 and 4 (cont).

12. Smoking habits:

Currently non-smoker	Yes/no*
A previous smoker	Yes/no*
	.... per day
If previous smoker, how long since stopping?	.... years
A current smoker	Yes/no*
	.... per day

13. Consumption of alcohol:

Do you drink alcoholic drinks?	Yes/no*
If yes, then do you:	
Have the occasional drink?	Yes/no*
Have one or more alcoholic drinks a day?	Yes/no*

14. Have you had to consult your doctor within the last 6 months? Yes/no*

If yes please give relevant details below.

15. Are you presently taking any form of medication? Yes/no*

If yes please give relevant details below.

16. Do you suffer, or have you ever suffered, from

Asthma?	Yes/no*
Bronchitis?	Yes/no*
Epilepsy?	Yes/no*
Any other controlled condition that may affect this trial?	Yes/no*

If yes please give relevant details below.

Signature of subject.. Date................................

Signature of test supervisor..

3.0

Technical specifications of equipment.

3.1 Technical specifications of Concept 2 Model D rowing ergometer.

concept 2

CONCEPT2 INDOOR ROWER SPECIFICATIONS - Models D and E

Description: Institutional grade rowing exercise machine with air-resistance flywheel, sliding seat, and self-calibrating electronic performance monitor.

Construction: Frame: extruded aluminum I-beam monorail with stainless steel seat track.

Flywheel: Fully-enclosed chain driven flywheel is steel with glass reinforced ABS squirrel cage fan attached. The flywheel enclosure is made of hi-impact, ABS Thermo-plastic. The "Quiet Cog" system significantly softens the sound of rowing by damping the chain noise with a urethane washer on each side of the cog. The idler pulleys and travelling pulley are made of a Thermo-plastic elastomer for increased durability and noise reduction.

PM Monitor (PM3 and PM4): Battery powered LCD digital display features time/distance rowed; calories burned; power produced (watts); stroke rate; stroke output (watts, calories, meters); average pace (time per 500 meters); library of preset workouts (timed, distance, timed interval, distance interval); projected finish (time or distance); split memory recall function; optional heart rate monitor interface. Choose from a variety of units and graphic display options including Force Curve, Paceboat and Bar Chart. On board games provide video game-like competition. C2 LogCard easily and automatically records workouts and tracks progress without separate paper record of each workout. PC-interface to transfer LogCard data to your personal computer. Power generation feature extends the life of the batteries by providing operating power to the PM while rowing. Monitor is powered by 2 D batteries (PM3) or a rechargeable battery pack (PM4) and are included. No external power source is needed. Wireless heart rate monitoring and PM to PM racing is standard on the PM4.

Misc: Adjustable air resistance; Flexfoot(TM) adjustable footboard system; impact-resistant, glass-reinforced Nylon, ergonomically-designed handle with overmolded soft rubber grips; molded rubber foot pads; anatomically designed seat top; built in caster wheels; quick disconnect feature for compact storage.

Benefits: The Concept2 Indoor Rower is the rowing machine of choice for all on water rowing programs as well as health clubs, cardiac rehabilitation centers and corporate fitness centers. The smooth, fluid feel of each stroke and the proper balance of momentum and drag are unsurpassed by any other rowing machine in the simulation of the on water rowing stroke. The rugged institutional grade construction assures minimal maintenance and years of trouble-free use. The self-calibrating electronic performance monitor is unique. Its' accuracy allows for objective comparison between workouts, as well as allowing measured competition between individuals.

Space Requirements: The Concept2 Indoor Rower measures 8' long by 24" maximum width. An area of 9' by 4' is required for operation of the machine. Storage requirement for two upright pieces is 27" x 47 x 54.5"H (Model E) and 25" x 33" x 53"H (Model D) .

Spare Parts and Service: Spare parts are available direct from the factory. Machines are user serviceable. Initial assembly takes approximately 30 minutes and subsequent installation of the most common spare parts is not difficult. Technical assistance is available during regular business hours (M-F 7:30 a.m.-5:00 p.m. ET) on our toll-free customer service line 800.245.5676.

Warranty: Covers defective parts for a 2 - 5 year period from date of shipment. Copy of warranty is available upon request.

Concept2, Inc. 105 Industrial Park Drive, Morrisville, VT USA 05661-8532 Toll Free: 800.245.5676 (USA & Canada)
Fax: 802.888.4791 rowing@concept2.com concept2.com

Concept2 is the sole manufacturer and factory direct sales source for the Concept2 Indoor Rower. All prices are factory direct. Prices are subject to change without notice.
10/10

3.2 Technical specifications of MetaMax 3B gas analyser.

CORTEX

MetaMax® 3B

Extent of Supply

- MetaMax® 3B Portable CPX System
- DVT or Triple® Volume Transducer with Temperature Sensor
- Sample Line with Nafion® Drying Tube
- CORTEX Face Mask Set
- Head Cap
- „MaxBelt" Shoulder Mounts or "MaxSport" Jackets
- Earphone for Audio Feedback
- Polar® Heart Rate Transmitter Belt with Strap
- Batteries & Battery Charger
- Telemetry Receiver with Cable
- PC Connection Cable
- Power Supply and Power Cord
- MetaSoft® CPX Software
- User Manual
- Carrying Case

Options

Hardware

- CardioLyzer 12 for bike or treadmill testing in the lab:
  - PC-Based 12-Channel Rest/Stress Test ECG
  - Motion-Tolerant NIBP
  - Pulse Oximetry
  - 10-Lead Suction Electrode System
- CBP 2000 Portable NIBP System
- 3-Channel Monitoring ECG (stationary/portable)

Software

- Ergometer / Treadmill Control
- Spirometry
- Indirect Calorimetry
- Non-invasive Cardiac Output

Accessories

- MetaMax® 3B "Aqua Fitness Set"
- Battery Power Packs (Sprint, Medium, Marathon)
- Battery Charger for Battery Power Packs
- Calibration Kits
- PC / Notebook
- Color Printer
- Multi-Function Trolley

Safety

Standards	EN 60601-1 (1996) EN 60601-1-1 (1994) EN 60601-1-1/A1 (1996)
Class	Class II, Type BF
EMC	EN 60601-1-2 (1994)
Conformity	Class II a (93/42/EWG; Appendix IX)

Design Award iF Winner 2001

CORTEX Biophysik GmbH
Nonnenstr. 39
04229 Leipzig/Germany
Phone: +49 341 48 74 9-0
Fax: +49 341 48 74 9-50
email: info@cortex-medical.de
http://www.cortex-medical.de

Technical Specifications

Portable Cardiopulmonary Exercise System

Base System

Method	Breath-by-breath	
Size (L/W/H)	2 x 120 x 110 x 45 mm	
Weight	650g, including battery	
CPU	16bit processor, 20 MHz, Flash memory	
Data storage	8 MB	

Environmental Specifications

Temperature	-20° - +40 °C	
Pressure	500 - 1050 mbar	
Humidity	0 - 99%	
Battery	Type:	Lithium ion
	Capacity:	1350 mAh
	Time:	approx. 2 hrs.
	Voltage:	7.2 V nominal
	Size:	70(L) x 38(W) x20(H) mm
	Weight:	80g

Analyzers

Volume transducer DVT	Type:	turbine, digital
	Range:	0.1 - 12 l/s
	Resolution:	7 ml
	Accuracy:	2 %
Volume transducer Triple® V	Type:	turbine, digital
	Range:	0.05 - 20 l/s
	Resolution:	7 ml
	Accuracy:	2 %
O_2 analyzer	Type:	electro-chemical cell
	Range:	0 - 35% O_2
	t_{90}:	≤ 100 ms
	Accuracy:	0.1 Vol %
CO_2 analyzer	Type:	Infrared
	Range:	0 - 13% CO_2
	t_{90}:	≤ 100 ms
	Accuracy:	0.1 Vol. %
Pressure	Type:	Silicon
	Range:	200 – 1050 mbar
	Accuracy:	1.8 %
Temperature	Type:	NTC-Thermistor
	Range:	-55°C - +155°C
	Accuracy:	1°C
Heart rate	POLAR® or ECG (optional)	

Telemetry

Type	bi-directional, 19.6 kBaud, 64 channels
Frequency	433 - 434 MHz; manual or automatic frequency selection
Range	up to max. 1,000 m

3-Channel ECG (optional)

Channels:	3
Leads:	Einthoven, Wilson, Nehb, Goldberger
Frequency:	100 Hz
Amplification:	5, 10, 20 mm/mV

Telemetry Receiver

Type	bi-directional, 19.66 kBaud
Frequency	433 - 434 MHz; manual or automatic frequency selection
Interface	RS232 for PC / notebook connection
Size	150 (L) x 80 (W) x 45 (H) mm
Weight	200g

Quality

ISO 9001, EN 46001, CE 0124

CORTEX. Pioneers in Metabolic Stress Testing.

3.3 Technical specifications of Lactate Pro analyser.

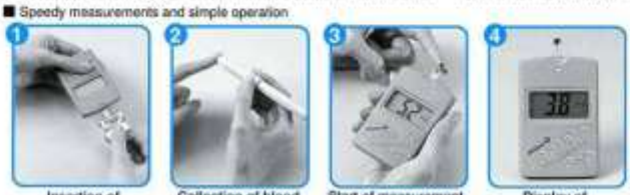
Lactate Pro™ LT-1710

Simplified Blood Lactate Test Meter

With only 5μL of blood and simple operation, "Lactate Pro" provides accurate blood lactate level in 60 seconds.

"Lactate Pro" adopts the electrochemical measurement method utilizing enzyme reaction. The operation has been further simplified. As little as 5μL of blood is enough for a measurement. Furthermore, the wiping of excess blood and other troublesome preparation are not required. Measurements are completed in a mere 60 seconds. The automatic aspiration of blood greatly reduces the risk of human error, and thus provides accurate blood lactate level without involving any manual operation.

■ Speedy measurements and simple operation



1 Insertion of the test strip. 2 Collection of blood. 3 Start of measurement. 4 Display of blood lactate level.

1 Insert the test strip into the strip inlet of the meter.
2 Before collecting 5μL of blood from your finger, wash and dry your hands.
3 Blood is automatically aspirated and measurement begins.
4 The measurement result is displayed in 60 seconds.

High data precision of C.V. 3% satisfies the needs of clinical testing.

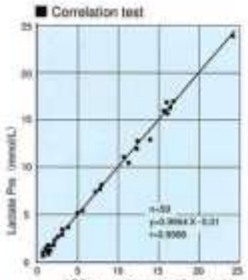
With the high repeatability of C.V.3%, "Lactate Pro" is able to be used not only in physical training but also useful for clinical testing. Thus, "Lactate Pro" provides reliably precise data equivalent to that of large-scale testing equipment and also maintains good correlation with conventional lactate test meters.

■ Repeatability test

n	Sample1	Sample2
1	2.1	11.2
2	2.3	11.4
3	2.3	11.4
4	2.1	11.4
5	2.2	11.3
6	2.2	11.7
7	2.3	11.4
8	2.2	11.4
9	2.2	11.5
10	2.2	12.0
11	2.1	11.4
12	2.2	12.0
13	2.1	12.1
14	2.2	11.8
15	2.2	11.8
mean	2.2	11.6
S.D.	0.07	0.30
C.V.	3.2	2.6

mmol/L

■ Correlation test



A credit card size meter is very convenient for mobile use.

Measuring 83.8 x 55.0 x 14.5 mm, the smallest of its kind in the world, "Lactate Pro" requires only a limited space. Further, weighing only 50g, it is easy to carry about. Whenever and wherever necessary, accurate blood lactate levels can be obtained.

Memory function for the benefit of data management. Up to 20 measurement results can be stored.

From the latest test result, up to 20 previous measurements can be recorded. Furthermore, the average of the past 20 measurement results can be displayed for the benefit of better data management and analysis.

Specifications

●Meter

Test	Lactate in whole blood
Sample size	Approximately 5μL
Test strip	Exclusive Lactate Pro™ Test Strip
Measuring range	0.8~23.3mmol/L
Measuring time	60 seconds
Temperature compensation	Automatic compensation using a built-in sensor
Calibration	Automatically selects the appropriate calibration curve by using a calibration strip
Power source	Two 3-volt lithium batteries(DL or CR2032)
Battery life	Approximately 1000 tests
Operating environment	Temperature range 10°-40°C(50°-104°F), Humidity 20-80%RH
Dimensions	83.8(L)×55.0(W)×14.5(H)mm
Weight	50g

●Test Strip

Storage	Store at room temperature lower than 30°C
Expiry	1 year after production
Package unit	25 strips/box

Design and specifications may be subject to change without notice.

ARKRAY, Inc.
KYOTO MIYUKI Bldg. 10F, 689 Takanna-cho, Nakagyo-ku,Kyoto 604-8153,JAPAN
TEL.: +81-75-662-8967, FAX: +81-75-662-8973,
http://www.arkray.co.jp/english

3.4 Technical specifications of Squirrel 400 datalogger.

V2 Oct-2004

9. Technical data

9.1 Inputs, ranges and resolutions

Note that not all ranges are available on all models. Please consult a brochure for details.

Input type	Available ranges		Resolution
Thermistor temperature U,Y,S	-50 to 150°C	-58 to 302°F	0.05°C
Thermocouple temperature K	-200 to 200°C	-328 to 392°F	0.1°C
Impedance: 100kΩ	-200 to 450°C	-328 to 842°F	0.2°C
	-200 to 1200°C	-328 to 2192°F	0.5°C
	0 to 950°C	32 to 1742°F	0.25°C
Thermocouple temperature T	-200 to 200°C	-328 to 392°F	0.1°C
Impedance: 100kΩ	-200 to 350°C	-328 to 662°F	0.2°C
PT100 temperature (P3/P4)	-200 to 100°C	-328 to 212°F	0.1°C
Max line resistance 100Ω	-200 to 400°C	-328 to 752°F	0.2°C
	-200 to 600°C	-328 to 1112°F	0.3°C
DC voltage	0 to 50mV	-25 to 25mV	50µV
Impedance: 1MΩ	0 to 100mV	-50 to 50mV	50µV
	0 to 200mV	-100 to 100mV	50µV
	0 to 500mV	-250 to 250mV	0.5mV
	0 to 1V	-500 to 500mV	0.5mV
	0 to 2V	-1 to 1V	0.5mV
	0 to 5V	-2.5 to 2.5V	5mV
	0 to 10V	-5 to 5V	5mV
	0 to 20V	-10 to 10V	5mV
DC current	4 to 20mA (as 0 to 100%)		0.05%
Impedance: 10Ω	0 to 20mA		10µA
Pulse count	0 to 65,000		1
Impedance: 1MΩ	0 to 650,000		10
State or	00000000 to	11111111	1
Digital	0 to 255		1

Accuracy Voltage: ±0.1% of reading ±0.1% of range
Temperature/current: ±0.2% of reading ±0.1% of range

Analogue/Digital Converter The SQ400/800 and 1000 Series dataloggers have a 12 bit A/D converter; most ranges therefore offer a 12 bit resolution. Some short ranges or those with nonlinear responses offer only a 10 or 11 bit resolution.

47

3.5 Technical specifications of Philips Partytone (placebo) bulb.

19/5/2010

PARTYTONE 80W E27 240V PAR38 RE 1CT

Product family description

Coloured pressed-glass 121 mm diameter reflector lamp

Product Feature

- Weatherproof silicon lacquer coating on the refractor face in a choice of colours
- Flood beam width

Product Benefit

- Gives striking decorative effects, both indoors and outdoors
- 20% lower power consumption compared with conventional coloured PAR lamps

Application

- Parks, public and private gardens
- Festive illumination
- Restaurants, bars, dance halls, nightclubs
- Show-window displays, fountains and 'Son et Lumiere' spectacles
- Can be installed outdoors without any protection, provided they are used in a watertight lampholder
- For outdoor use, a heat-resistant rubber ring must be fitted between the lamp and the lampholder

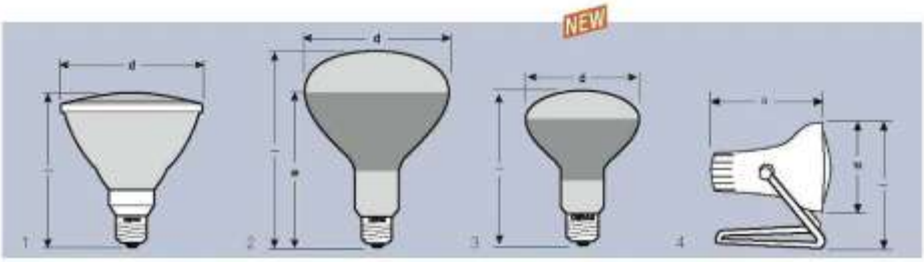
Product data	
Commercial Code	PAR38FLRE80W240VES
Full product name	PARTYTONE 80W E27 240V PAR38 RE 1CT
Order product name	PARTY 80W E27 240V PAR38 RE 1CT/6
Packing type	1 Lamp in a Folding Carton
Pieces per pack	1
Packing configuration	6
Packs per outerbox	6
Bar code on pack - EAN1	8711500045119
Bar code on intermediate packing - EAN2	
Bar code on outerbox - EAN3	8710163073507
Logistic code(s) - 12NC	9238 112 45580
ILCOS code	IPAR/R-80-240-E27-121
Net weight per piece	0.350 KG
Successor order code	
Cap-Base	E5 [E5]

PHILIPS

1

3.6 Technical specifications of Osram Siccatherm (warming) bulb.

TECHNICAL DATA



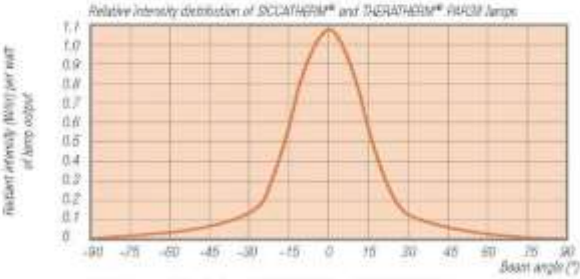
Product reference	EAN	Wattage (W)	Average life (h)	Diameter d max (mm)	Length l (mm)	Length a (mm)	Bulb shape	Base	Fig.no	Glass
SICCATHERM®, PAR bulb										
SICCA PAR38 Red 100W	4050300**010984**	100	5000	122.5	139	–	Red filter	E27	1	Pressed glass
SICCA PAR38 Red 175W	4050300**010991**	175	5000	122.5	139	–	Red filter	E27	1	Pressed glass
SICCATHERM®, R125 bulb										
SICCA R125 Red 150W	4050300**790060**	150	5000	127.5	185	150	Red filter	E27	2	Soft glass
SICCA R125 Red 250W	4050300**007946**	250	5000	127.5	185	150	Red filter	E27	2	Hard glass
SICCA R125 FR 250W	4050300**014029**	250	5000	127.5	185	150	Frosted	E27	2	Soft glass
SICCA R125 CL 250W	4050300**278414**	250	5000	127.5	185	150	Clear	E27	2	Hard glass
SICCA R125 CL 375W	4050300**206912**	375	5000	127.5	185	150	Clear	E27	2	Hard glass
E27 base to IEC/EN 60061-1, Sheet 7004-21, maximum base edge temperature 250 °C										
THERATHERM®										
THERA PAR38 Red 150W	4050300**003122**	150	5000	122.5	139	–	Red filter	E27	1	Pressed glass
THERA R125 Red 250W	4050300**003115**	250	5000	127.5	185	150	Red filter	E27	2	Hard glass
NEW THERA R95 Red 100W	4008321**131508**	100	600	95	140	–	Red filter	E27	3	Soft glass
THERATHERM® DE LUXE 0172										
20400	4050300**003856**	150	–	138	180	180	–	E27	4	–

Please note:

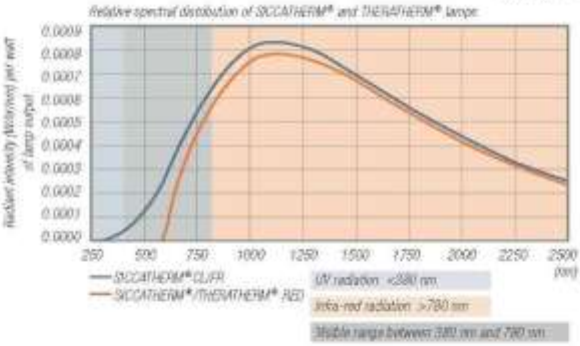
This unit is not a medical product. You should consult your doctor if you have any medical problems. Only your doctor will be able to suggest suitable treatment for your symptoms.

Because of the heat that these lamps generate you should use them only in suitable heat-resistant equipment. Protect the lamps (made from soft glass) against moisture and splashes.

Relative intensity distribution of SICCATHERM® and THERATHERM® PAR38 lamps



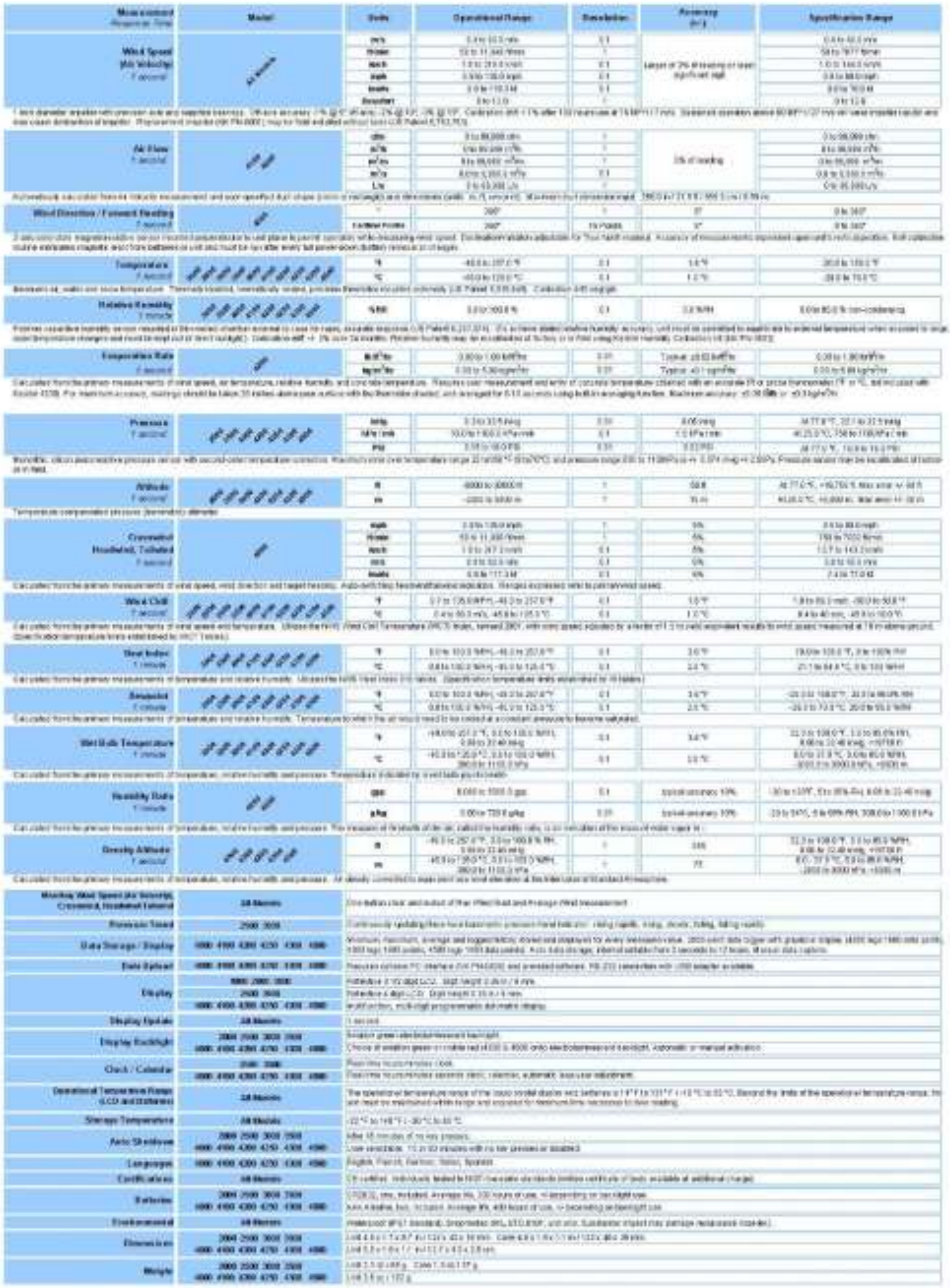
Relative spectral distribution of SICCATHERM® and THERATHERM® lamps



member of voltimum.com

SEE THE WORLD IN A NEW LIGHT OSRAM

3.7 Technical specifications of Kestrel 2000 windmeter.



4.0

Recording sheets used in studies.

4.1 Recording sheet used for study 1 familiarisation and max trials.

Familiarisation and $\dot{V}O_2$ Test

UCOL

Research Title: Physiological heat stress responses to self-paced and directed-pace rowing ergometry exercise in a thermo-neutral environment at the same relative intensity of effort

Subject Name ____________________ **Date** __________ **Coding** __________

DOB __________ **Height** __________ **Weight** __________

Time __________ **Temp** __________ **BP** __________

Time	RPE	Average Stroke Rate	Power Output
0-4	11		
4-7	13		
7-9	15		
9-10	19		

Time	Power Output	Average Stroke Rate	$\dot{V}O_2$
0-3	80		
3-4	105		
4-5	130		
5-6	155		
6-7	180		
7-8	205		
8-9	230		
9-10	255		
10-11	280		
11-12	305		
12-13	330		
13-14	355		
14-15	380		
15-16	405		
16-17	430		
17-18	455		
18-19	480		
19-20	505		

$\dot{V}O_2$ Peak __________

4.2 Recording sheet used for studies 1 and 2.

Main Trial

Subject Name ____________________ Date __________ Coding __________

Time (min)	Time (s)	Core T
0.0	0	
0.5	30	
1.0	60	
1.5	90	
2.0	120	
2.5	150	
3.0	180	
3.5	210	
4.0	240	
4.5	270	
5.0	300	
5.5	330	
6.0	360	
6.5	390	
7.0	420	
7.5	450	
8.0	480	
8.5	510	
9.0	540	
9.5	570	
10.0	600	
10.5	630	
11.0	660	
11.5	690	
12.0	720	
12.5	750	
13.0	780	
13.5	810	
14.0	840	
14.5	870	
15.0	900	
15.5	930	
16.0	960	
16.5	990	
17.0	1020	
17.5	1050	
18.0	1080	
18.5	1110	
19.0	1140	
19.5	1170	
20.0	1200	
20.5	1230	
21.0	1260	
21.5	1290	
22.0	1320	
22.5	1350	
23.0	1380	
23.5	1410	
24.0	1440	
24.5	1470	
25.0	1500	
25.5	1530	
26.0	1560	
26.5	1590	
27.0	1620	
27.5	1650	
28.0	1680	
28.5	1710	
29.0	1740	
29.5	1770	
30.0	1800	

Pre Weight	
Pre Lactate	

EMG	Metres
2 strokes from the full extension	0
to prompt	1000
to prompt	2000
to prompt	3000
to prompt	4000
to prompt	5000

Post Weight	
Post Lactate	

4.3 Recording sheet used for study 3.

Heat Trial

UCOL UNIVERSAL COLLEGE OF LEARNING

Subject Name ____________ Date ________ Coding ________

Time (min)	Time (s)	Core Temp
0.0	0	
0.5	30	
1.0	60	
1.5	90	
2.0	120	
2.5	150	
3.0	180	
3.5	210	
4.0	240	
4.5	270	
5.0	300	
5.5	330	
6.0	360	
6.5	390	
7.0	420	
7.5	450	
8.0	480	
8.5	510	
9.0	540	
9.5	570	
10.0	600	
10.5	630	
11.0	660	
11.5	690	
12.0	720	
12.5	750	
13.0	780	
13.5	810	
14.0	840	
14.5	870	
15.0	900	
15.5	930	
16.0	960	
16.5	990	
17.0	1020	
17.5	1050	
18.0	1080	
18.5	1110	
19.0	1140	
19.5	1170	
20.0	1200	
20.5	1230	
21.0	1260	
21.5	1290	
22.0	1320	
22.5	1350	
23.0	1380	
23.5	1410	
24.0	1440	
24.5	1470	
25.0	1500	
25.5	1530	
26.0	1560	
26.5	1590	
27.0	1620	
27.5	1650	
28.0	1680	
28.5	1710	
29.0	1740	
29.5	1770	
30.0	1800	

Pre Core Temp	
Pre Weight	
Pre Lactate	
PC Trial Start Time	

Heat	
Humidity	

Warm Up	
Time	RPE
0-4	11
4-7	13
7-9	15
9-10	19

EMG	Metres
3 strokes full extension	0
to prompt	1000
to prompt	2000
to prompt	3000
to prompt	4000
to prompt	5000

PC Trial End Time	
Post Lactate	
Post Weight	
Perceived RPE	

Notes:

4.4 Recording sheet used for study 4.

Maximum Oxygen Uptake ($\dot{V}O_2$) Test

UCOL Universal College of Learning

Research Title: Physiological and performance responses to self-paced rowing ergometry exercise: impact of radiant heat on pacing dynamics.

Subject Name ____________________

DOB __________

Height __________ **Weight** __________

Date __________ **Time** __________

Heat __________ **Humidity** __________

Coding __________

Warm Up

Time	RPE
0-4	11
4-7	13
7-9	15
9-10	19

Time	RPE
0-4	11
4-7	13
7-9	15
9-10	19

Sporting Experience:

Trial

Time	Power Output
0-3	150
3-4	175
4-5	200
5-6	225
6-7	250
7-8	275
8-9	300
9-10	325
10-11	350
11-12	375
12-13	400

Time	RPE	Statement
0-2	11	Light
2-4	13	Somewhat Hard
4-6	15	Hard
6-8	17	Very Hard
8-10	20	Maximal Exertion

Notes:

Pre Lactate __________ **Post Lactate** __________ **$\dot{V}O_2$ Peak** __________

5.0

Presentations and publications derived from this research.

5.1 Lander, P. J., Butterly, R. J., Edwards, A. M. and Zanker, C. (2007) Dynamic characteristics of physiological responses, power output, and concomitant pacing strategies during 5000m all-out rowing ergometry. Proceedings of the New Zealand Sports Medicine+Science Conference, pg 54. Abstract only.

Dynamic characteristics of physiological responses, power output, and concomitant pacing strategies during 5000m all-out rowing ergometry.

PJ Lander[1,2], *AM Edwards*[1,2], *R Butterly*[1], *C Zanker*[1]

[1]Leeds Metropolitan University, Carnegie Research Institute, Leeds, UK
[2]UCOL Institute of Technology, Department of Human Performance, Palmerston North, NZ

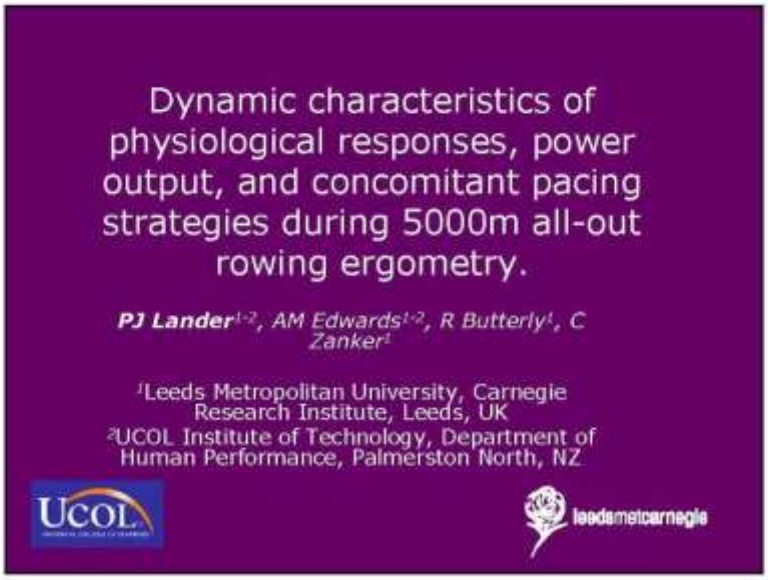
Introduction: The aim of this study was to describe the dynamic physiological response characteristics to all-out rowing exercise in which numerical knowledge of performance was altered by manipulating the presence of visual feedback. Several recent studies have suggested that when free to vary power output during high intensity exercise, humans will subconsciously adjust external work (pacing) in a dynamically fluctuating pattern via a centrally regulated teleoanticipatory mechanism which influences feedback and feed forward mechanisms in an effort to defend homeostasis (Lambert et al. 2005, Tucker et al. 2006). It was hypothesised that the dynamic physiological responses between feedback (FB) and no-feedback (NFB) conditions would reflect condition-dependent pacing strategies whilst trial performances at completion would be unaffected. **Methods:** Seven well-trained male participants (age: 32.0 ± 6.5 years, body mass: 78.5 ± 9.4 kg, $\dot{V}O_2$ peak: 51.0 ± 2.0 ml·kg·min^{-1}) performed three exercise trials (VO_2 peak, 5000 m all-out FB, 5000 m all-out NFB) with trials 2-3 performed in a randomised order. Breath-by-breath gas exchange, heart rates, core and skin temperatures, and stroke-by-stroke power outputs were monitored continuously throughout trials 2-3. Dynamic responses were batched into 30-sec bins (mean) for statistical comparisons between conditions. **Results:** 5000m all-out trial performance times were not significantly different between FB (20 min 15 s ± 01 min 05 s) and NFB (20 min 15 s ± 54 s) conditions (P= 0.983). At trial completion core and mean skin temperatures were also similar between conditions however the dynamic characteristics of oxygen uptake, external power output, and temperature regulation all demonstrated condition-dependent differences during the trial. **Conclusion:** Overall 5000 m all-out rowing performance is unaffected by numerical knowledge of performance, whilst the dynamic responses of participants during the trials demonstrate condition-specific differences. The results of this study support the role of a central processor in the determination of pacing during exercise performances in which external work is free to vary, thus favouring the co-ordination of exercise completion with a critical core temperature over any other preceding performance fluctuation.

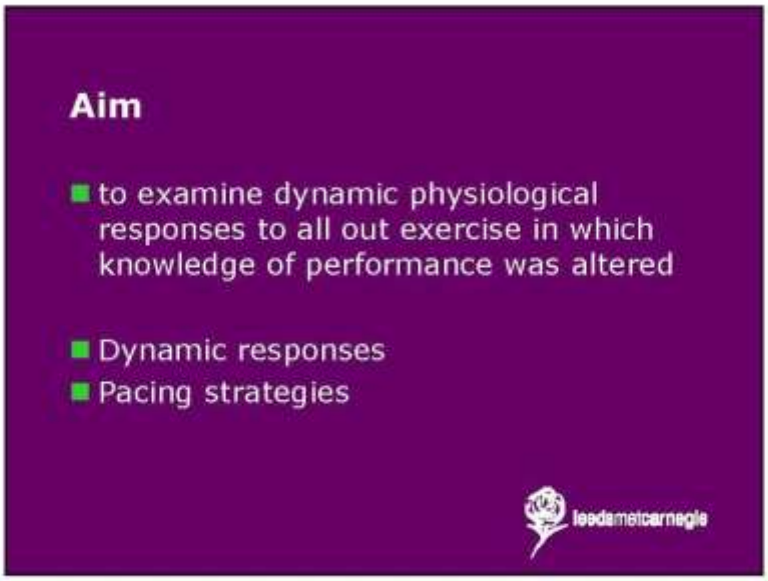
References:

Lambert EV, St Clair Gibson A, Noakes TD. Complex systems model of fatigue: integrative homoeostatic control of peripheral physiological systems during exercise in humans. Br J Sports Med 2005; 39: 52-62.

Tucker RA, Bester A, Lambert E, Noakes TD, Vaughan C, Gibson A. Non-random fluctuations in power output during self-paced exercise. Br J Sports Med 2006; 40: 912-917.

5.2 Presentation slides from SESNZ 2007.



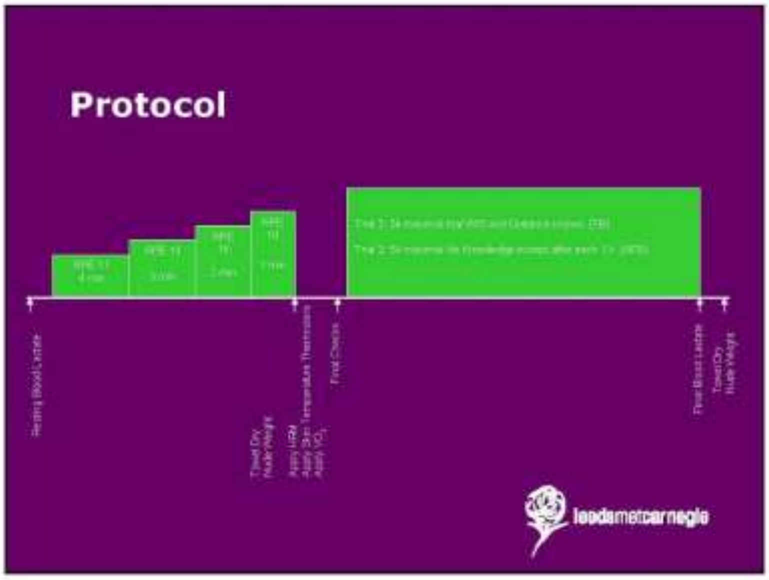


1

5.2 Presentation slides from SESNZ 2007 (cont).

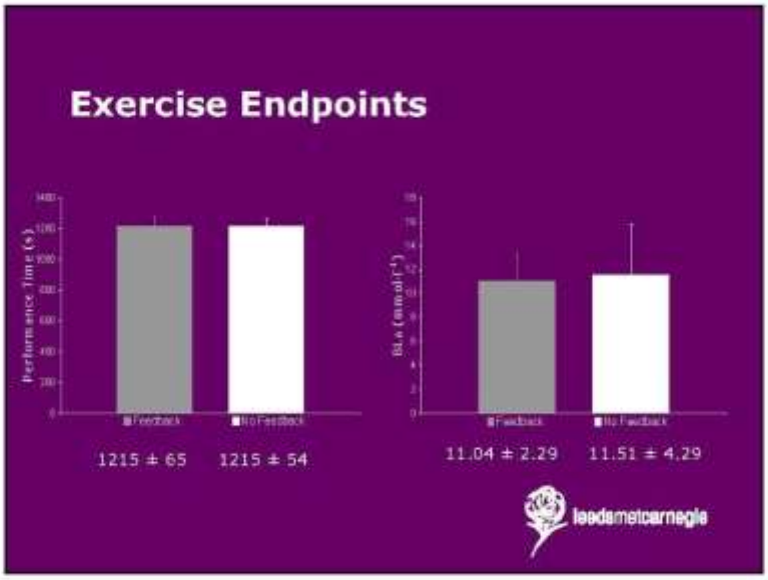
2

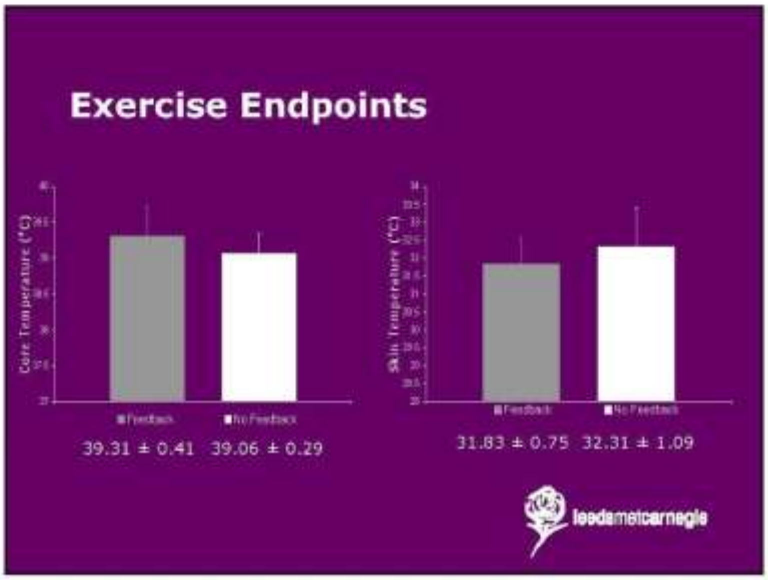
5.2 Presentation slides from SESNZ 2007 (cont).



3

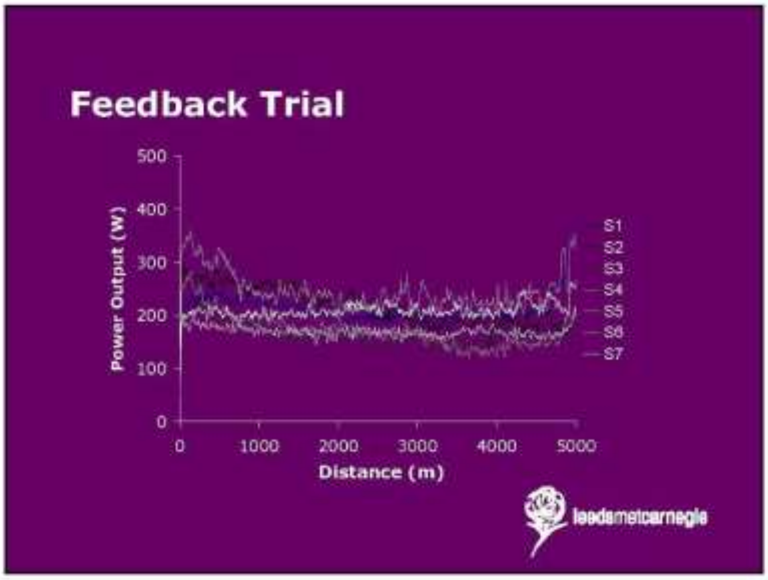
5.2 Presentation slides from SESNZ 2007 (cont).

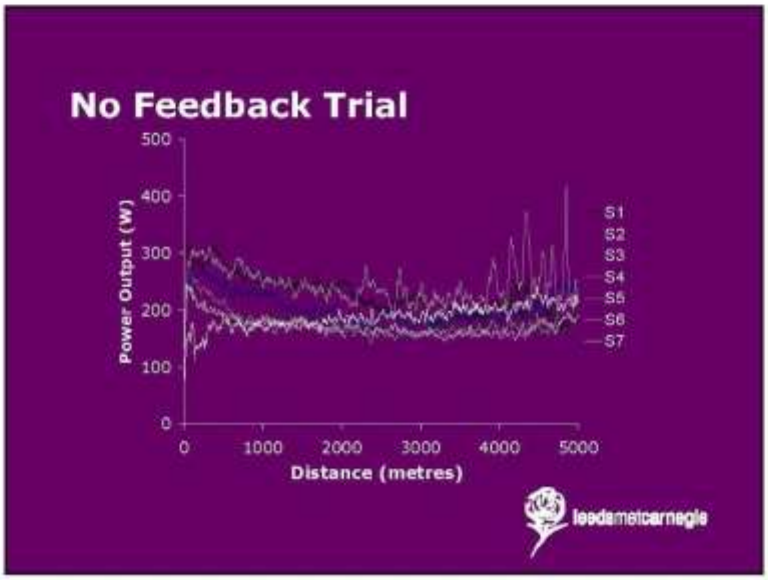




4

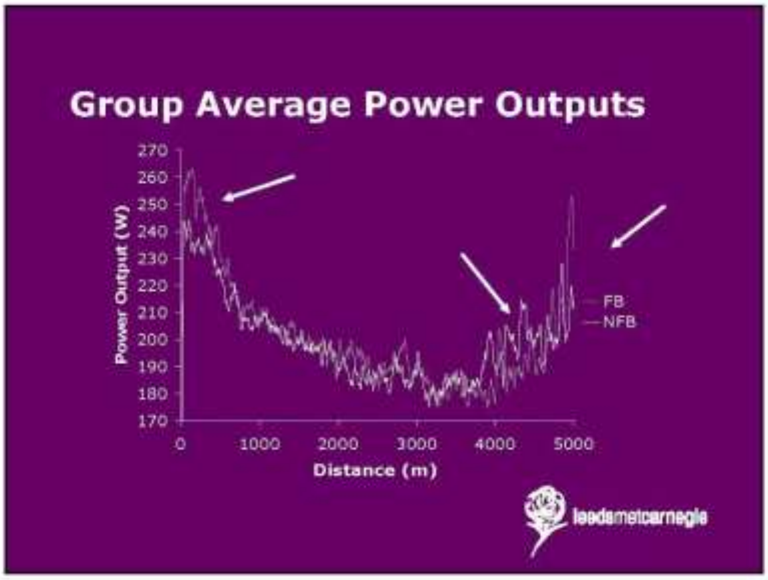
5.2 Presentation slides from SESNZ 2007 (cont).

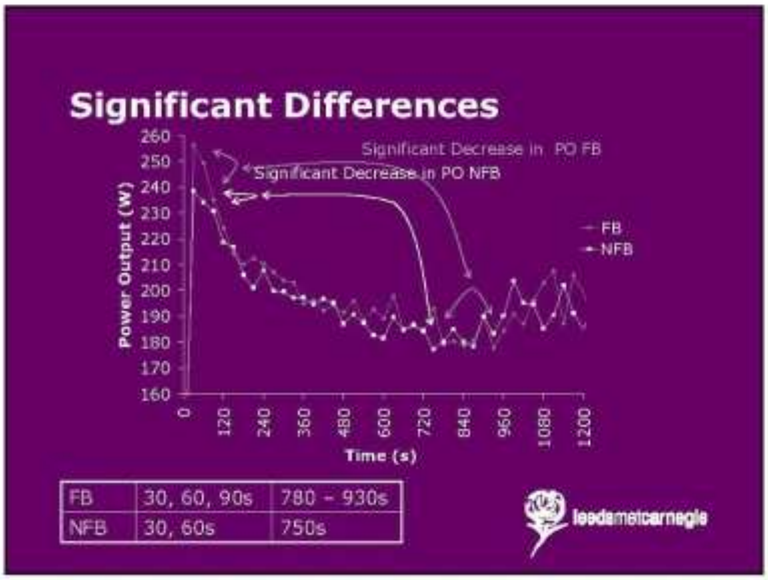




5

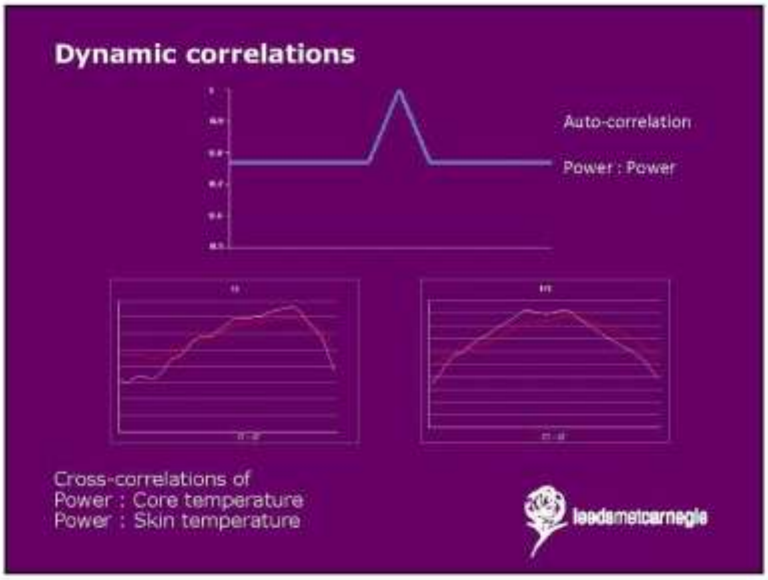
5.2 Presentation slides from SESNZ 2007 (cont).

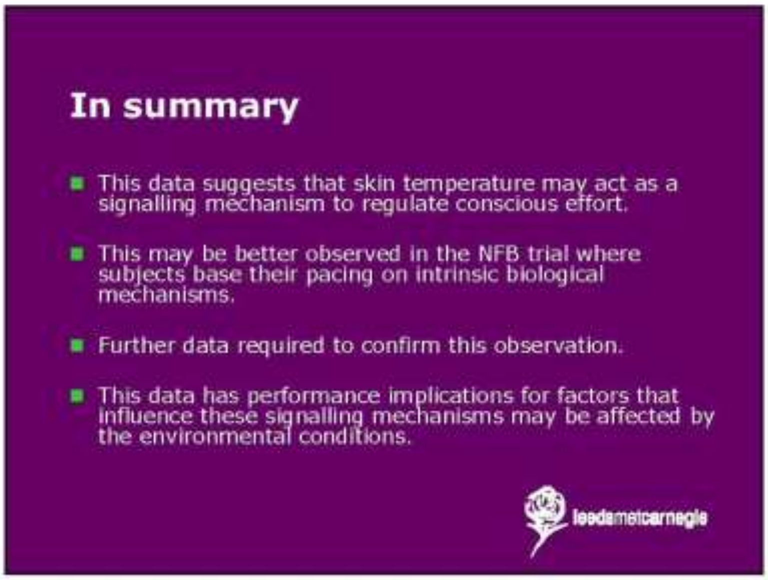




6

5.2 Presentation slides from SESNZ 2007 (cont).





7

5.2 Presentation slides from SESNZ 2007 (cont).

8

5.3 Lander, P. J., Butterly, R. J. and Edwards, A. M. (2009) Self paced exercise presents a reduced metabolic challenge compared to matched intensity enforced pace exercise: Use of an RPE Clamp in submaximal rowing. Proceedings of the New Zealand Sports Medicine+Science Conference, pg 54. Abstract only.

Self paced exercise presents a reduced metabolic challenge compared to matched intensity enforced pace exercise: Use of an RPE Clamp in submaximal rowing.

***PJ Lander*[1,2], *R Butterly*[1], *AM Edwards*[1,3]**

[1]Leeds Metropolitan University, Carnegie Research Institute, Leeds, UK
[2]UCOL Institute of Technology, Exercise Sport Science, Palmerston North, NZ
[3]James Cook University, Institute of Sport and Exercise Science, Queensland Australia

Introduction: The aim of this study was to compare the dynamic physiological response characteristics of 5000m rowing ergometry exercise, in self paced, and matched intensity enforced pace exercise. Recent studies have suggested that when individuals are free to voluntarily vary power output during high intensity exercise, subconscious adjustments are made to external work (pacing) in a dynamically fluctuating pattern. It has previously been hypothesised that a centrally regulated teleoanticipatory mechanism controls this behaviour via feedback and feed forward mechanisms in an effort to defend homeostasis (Lander et al. 2009, Tucker 2009). In this study, it was hypothesised that by matching enforced pace exercise to a self paced effort using an RPE clamp that dynamic physiological responses would result in meaningful non random fluctuations of power output, which reflected condition-dependent pacing strategies.

Methods: Nine well-trained male participants (age: 29 ± 6 years, body mass: 77.1 ± 8.1 kg, VO_2 peak: 51.6 ± 2.7 ml·kg·min^{-1}) performed three exercise trials (VO_2 peak, 5000 m RPE clamped at RPE 15 (SP), 5000 m enforced pace matched intensity (EP)) subjects were deceived to believe that the EP intensity was equivalent to ventilatory threshold in order to prevent pacing similar to that of the previous self-paced trial. Breath-by-breath gas exchange, heart rates, core and skin temperatures, iEMG, and stroke-by-stroke power outputs were monitored continuously throughout trials 2-3. Dynamic responses were batched into 30-sec bins (mean) for statistical comparisons between conditions.

Results: Performance times for the 5000m matched intensity trials were not significantly different between the EP (1298.67 ± 71.59s) and SP (1300.11 ± 77.53 s) conditions ($P>0.05$). T_C ($P<0.01$), post-test BLa ($P<0.05$) and iEMG ($P<0.05$) were all significantly elevated in EP compared to SP. There were no differences in the dynamics of HR, VO_2, T_{sk} between EP and SP. The intra-test stroke-to-stroke variability (ttv) of power output was significantly lower in the EP condition compared to SP ($P<0.01$).

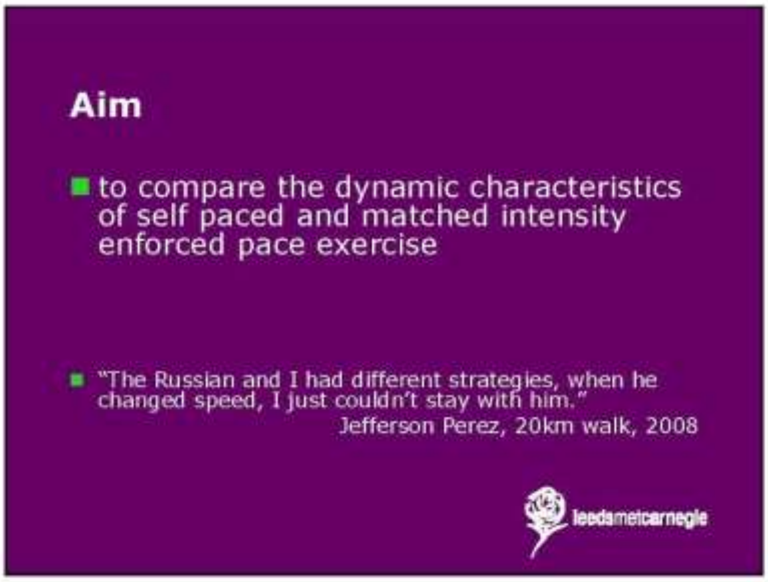
Conclusion: In matched paced submaximal exercise, similar performance outcomes are achieved despite differing dynamic physiological responses. Self paced exercise presents a significantly reduced metabolic challenge when compared to matched intensity enforced pace exercise. The ability to voluntarily fluctuate effort in self paced exercise is therefore a conscious behavioural response to a subconscious homeostatic challenge such as increased core temperature and blood lactate concentration.

References:

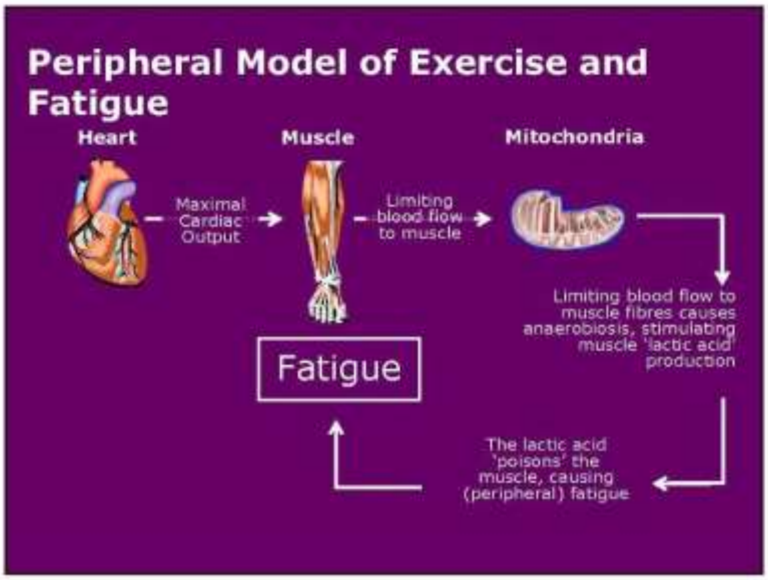
Lander PJ, Butterly RJ, Edwards AM. Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control 10.1136/bjsm.2008.056085. *Br J Sports Med* 2009:bjsm.2008.056085

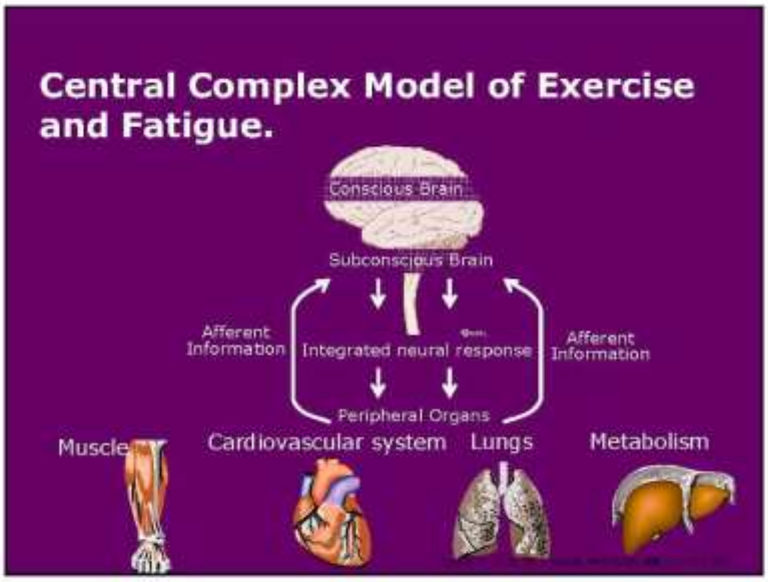
Tucker R. The anticipatory regulation of performance: the physiological basis for pacing strategies and the development of a perception-based model for exercise performance *Br J Sports Med* 2009;43(6):392-400

5.4 Presentation slides from SESNZ 2009.

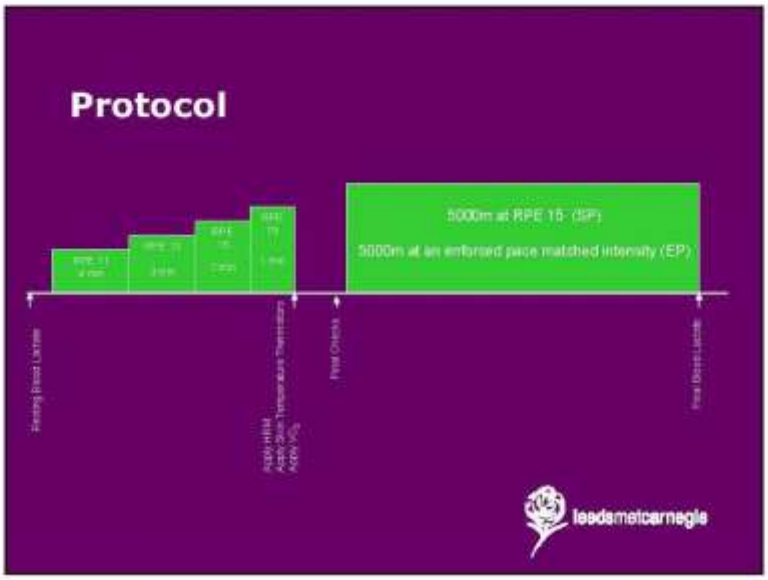


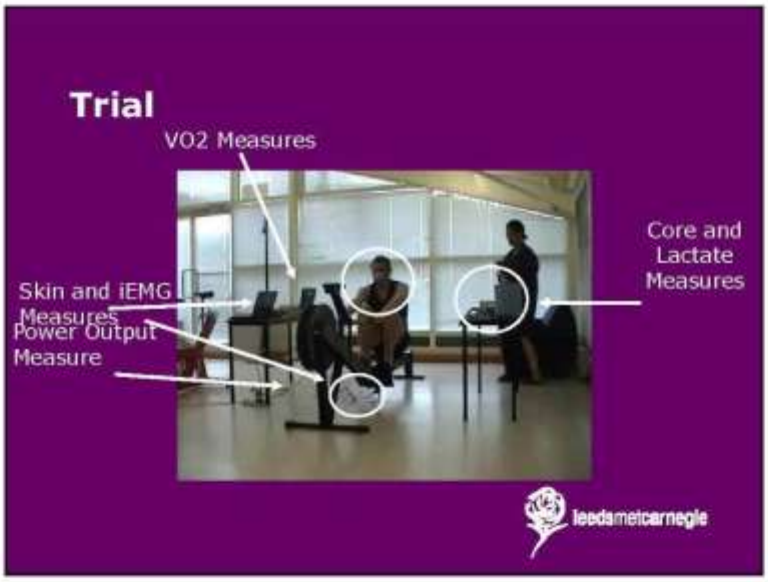
5.4 Presentation slides from SESNZ 2009 (cont).



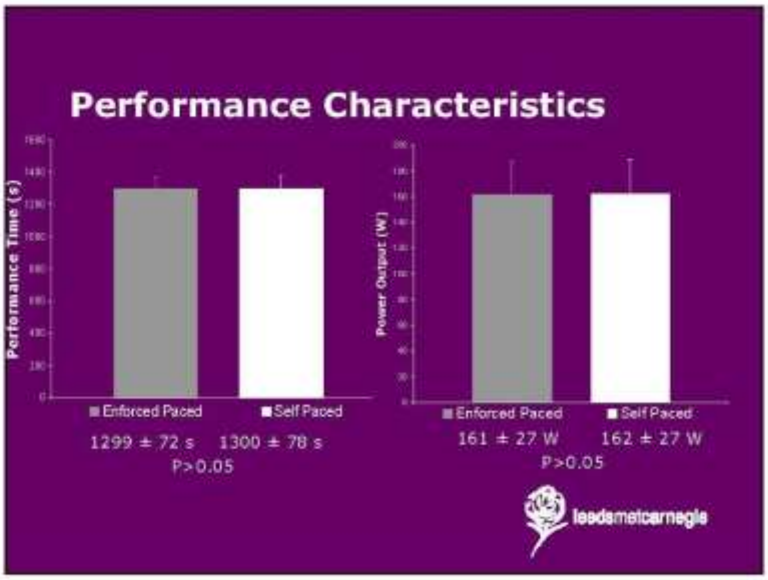


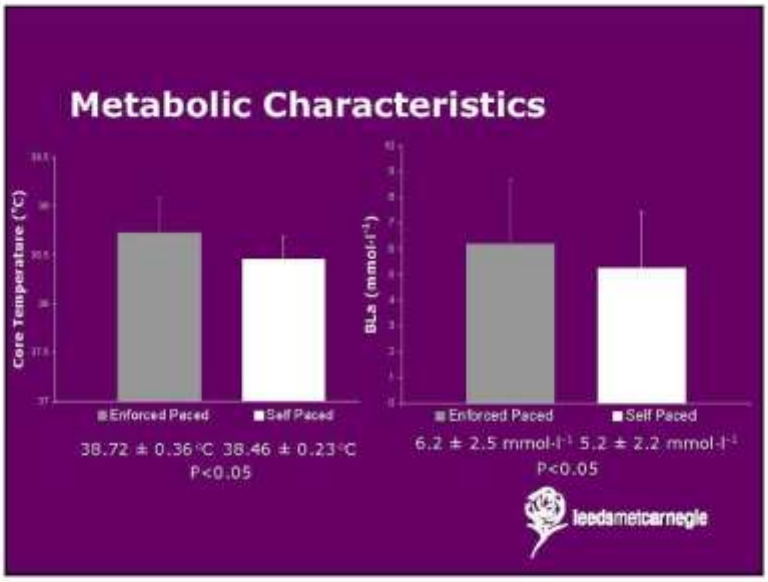
5.4 Presentation slides from SESNZ 2009 (cont).



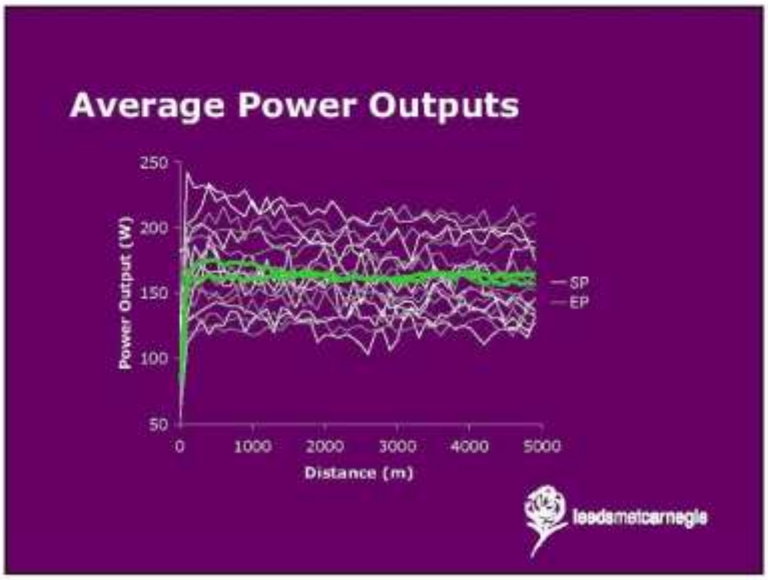


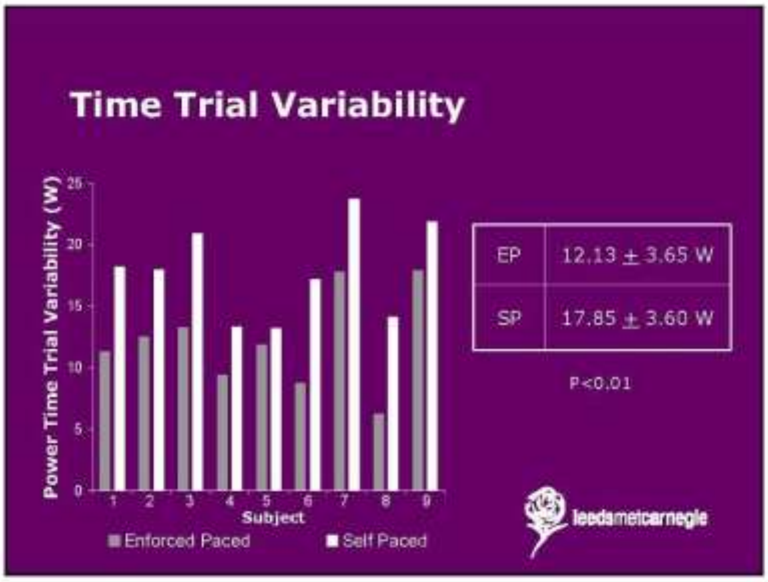
5.4 Presentation slides from SESNZ 2009 (cont).





5.4 Presentation slides from SESNZ 2009 (cont).





5.4 Presentation slides from SESNZ 2009 (cont).

5.5 Publication article 2009

Lander, P. J., Butterly, R. J. and Edwards, A. M. (2009) Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. British Journal of Sports Medicine, 43 (10), 789-795.

Original article

EDITOR'S CHOICE

Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control

P J Lander,[1,2] R J Butterly,[2] A M Edwards[3]

[1] UCOL Institute of Technology, Palmerston North, New Zealand; [2] Leeds Metropolitan University, Carnegie Faculty of Sport & Education, Leeds, UK; [3] Institute of Sport & Exercise Science, James Cook University, Cairns, Australia

Correspondence to: Dr A M Edwards, Institute of Sport & Exercise Science, James Cook University, Cairns, Queensland, Australia; andrew.edwards@jcu.edu.au

Accepted 29 January 2009
Published Online First 5 February 2009

ABSTRACT

Objective: To examine whether self pacing reduces the physiological challenge of performing 5000 m rowing ergometry exercise in comparison with a matched-intensity exercise condition in which a constant effort pacing strategy is enforced.

Methods: Nine healthy well-trained male participants volunteered to participate in three 5000 m rowing conditions (two submaximal and one maximal conditions) in an individualised order. In the submaximal conditions, participants were required to (1) perform 5000 m at a constant rating of perceived exertion (RPE 15-Hard) (SubRPE) or (2) perform 5000 m at an enforced constant pace equivalent to the mean power output (PO) of the SubRPE condition (SubEXT). A maximal condition (MaxTT) was included to disguise the purpose of the study and to facilitate an element of randomisation in the test sequence. Dynamic intratest responses were assessed every 30s: PO, Vo_2, iEMG, core (T_c) and skin temperatures (T_{sk}).

Results: There was no difference between performance times of the two submaximal trials. The mean PO represented 83.83 (SD 8.88)% (SubRPE) and 83.40 (8.84)% (SubEXT) of the mean MaxTT power output. T_c (SubRPE:38.46 (0.23)°C, SubEXT:38.72 (0.36)°C, $p<0.01$), post-test BLa (SubRPE:5.24 (2.18), SubEXT:6.19 (2.51) mmol/l; $p<0.05$) and iEMG ($p<0.05$) were significantly elevated in SubEXT compared with SubRPE. There were no differences in the dynamics of HR or Vo_2 between SubEXT and SubRPE. The intratest stroke-to-stroke variability of power output was significantly greater in the SubRPE condition compared with SubEXT ($p<0.01$).

Conclusions: Enforced constant paced exercise presents a significantly greater physiological challenge than self-paced exercise. The ability to dynamically self-pace effort via manipulations of power output during exercise is an important behavioural response to homeostatic challenges and thus forms an integral part of a complex central regulatory process.

The ability to accurately self pace an exercise bout is an important feature of race and time trial performances.[1-6] Self-paced exercise bouts are known to demonstrate considerable intratrial fluctuations of power output,[4] and it is unlikely that this is simply due to random misjudgements of pace. It is probable that these fluctuations of power output are important behavioural responses during exercise at times when homeostasis is challenged.[7] However, the importance of this observation requires researchers to consider the brain as a (central) feature of pacing and the development of fatigue.

Until recently,[6 8] it had commonly been viewed that exercise of maximal intensity progressively induced a decrease in force production towards a terminal endpoint of fatigue at which the immediate cessation of exercise was a necessary consequence.[9] This theory has often been used to attribute fatigue to impaired peripheral muscle contractile function, through either excessive accumulation of metabolic acidosis or the depletion of intramuscular fuels.[10] However, such peripheral fatigue cannot easily explain all observations during endurance exercise,[11] in particular those where performance improves in the end stages of a self-paced exercise bout.[12-14]

Several contemporary research studies have suggested that discreet alterations in pace are mediated through central neural control, by which muscle recruitment is manipulated as part of a regulatory process to maintain a reserve of motor units and thus avoid catastrophic fatigue.[6 8] According to this central (governor) model, the regulation of exercise intensity (power output) is a behavioural response to both feedback information from peripheral receptors and feedforward (anticipatory) mechanisms which regulate exercise intensity to avoid the development of bodily harm.[8 11] Consequently, fluctuations in power output during exercise may be an important feature of a regulatory process, based on information from various peripheral systems (eg, muscle, respiratory, metabolic receptors) within a complex metabolic control system.

Previous work has shown biological variation to be an important feature in submaximal exercise.[15] However, relatively few studies have thoroughly examined both the dynamic physiological and thermoregulatory responses to exercise in relation to the concept of pacing.[1 2 4] With the development of fast-response technologies, it is now feasible to examine the concept of pacing in more dynamic experimental conditions than was previously practical. For example, it is possible that thermoregulatory factors such as core and skin temperatures are dynamically related to the perception of effort during exercise through which alterations in pacing are linked to temperature regulation and/or muscle recruitment patterns. Nevertheless, there currently remains a lack of empirical data in which dynamic responses have been evaluated.

5.5 Publication article 2009

Lander, P. J., Butterly, R. J. and Edwards, A. M. (2009) Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. British Journal of Sports Medicine, 43 (10), 789-795. (cont).

We propose that the inter-relationship between conscious perceptions of effort (RPE) and subconscious metabolic control (mediating muscle recruitment) will result in physiologically meaningful non-random fluctuations of power output[4] in self-paced exercise, while enforced matched-intensity constant paced exercise will result in adverse physiological responses. The aim of this study was consequently to compare physiological responses to a 5000 m rowing exercise at a matched intensity in which the participants were (1) able to voluntarily fluctuate power output (self-paced) while performing exercise at a fixed rating of perceived exertion (RPE) or (2) were required to maintain a matched-intensity (enforced) constant power output.

METHODOLOGY

Participants

Nine healthy, well-trained male participants agreed to take part in this study (table 1). All were informed of the procedures in advance, and informed consent was provided prior to any data collection. The study was approved by the Central Regional Ethics Committee of New Zealand. All participants were recreational gymnasium users, and each received technical advice from a qualified rowing coach on using the rowing ergometer during a 2-week familiarisation period.

Preliminary testing

At the beginning of the study, all participants performed a standardised familiarisation trial which consisted of a four-stage incremental protocol. The initial stage required participants to work for 4 min at RPE 11 (light), and each subsequent stage increased in intensity and decreased in time (3 min: RPE 13 (moderate), 2 min: RPE 15 (hard), 1 min: RPE 19 (very very hard)). This familiarisation protocol was subsequently used as a standardised priming exercise in each of the trials (fig 1).

Rowing ergometry was selected as a useful exercise modality for this study, as the power output attained (and effort) from each rowing stroke during the bout can be easily influenced by sensations of fatigue through up- and downregulation of effort when pulling the rowing handle. It is therefore highly sensitive to fluctuations in power during the test.

In all conditions, the air resistance of the ergometer flywheel was standardised by using the damper lever to apply a predetermined drag factor 130 (10^{-6} Nms^2).[16 17]

On a separate and subsequent occasion all participants performed an incremental exercise test to volitional exhaustion on a Concept II rowing ergometer (Model D: Concept II, Tauranga, New Zealand) in our exercise laboratory for the determination of maximal aerobic power ($\dot{V}O_2$ max). Oxygen uptake (Cortex MetaMax 3B, Cortex Biophysik, Leipzig, Germany) and power output (RowPro v2.006 software; Digital Rowing, Boston, Massachusetts) were continuously monitored stroke-to-stroke. Power output was visible via the Concept II display unit at all times.

Experimental procedures

Each subject completed three 5000 m rowing trials in three different experimental conditions in an individualised order. Condition 1 (Submaximal Self-paced using RPE scale; SubRPE) required the participants to complete 5000 m at a constant rating of perceived exertion (RPE: 15—Hard). Condition 2 (Submaximal Externally paced; SubEXT) required the participants to perform 5000 m at a constant power output equivalent to the mean power output attained in the SubRPE condition. No visual feedback was provided in the SubRPE condition to ensure subjects self-paced, while only stroke-to-stroke power output was visible during the SubEXT condition, and participants received continual reinforcement to ensure the required power output was attained. A further experimental condition (Maximal Time Trial; MaxTT) was included to disguise the importance of the two submaximal conditions and to compare intensity of efforts, while also facilitating an element of randomisation in the test sequence. In the MaxTT condition, participants were instructed to perform 5000 m as fast as possible, while stroke-to-stroke power output was visible at all times (fig 1).

In the SubEXT condition, participants were deceived to believe that the required exercise intensity was based on a constant power output equivalent to that of ventilatory threshold attained in the baseline $\dot{V}O_2$max test. This deception was conducted in an attempt to avoid participants realising that the two submaximal efforts in the three test series were matched for mean intensity and thus pacing the SubEXT trial on their previous SubRPE efforts.

The exercise trials were held at the same time of the day on each of the three occasions to avoid diurnal variations in body temperature, and were each separated by approximately 1 week. The participants were instructed to refrain from additional organised physical activity during the testing period and to maintain habitual exercise routines. The laboratory temperature was standardised at 18°C across all tests while relative humidity remained consistent (35–45%). All participants consumed a beverage of water 2 h before the start of the test (5 ml of water per kilogram body mass) to ensure comparable euhydration between participants and trials.[18]

Oxygen uptake, heart rate and power output measurement

Gas exchange and minute ventilation were continuously recorded breath by breath (Cortex MetaMax 3B, Cortex Biophysik, Leipzig, Germany). The system was calibrated before and verified after each test with standard calibration gases. Volume expired was measured by a volume measuring turbine, which was calibrated with a 3 l syringe (Hans Rudolph, Kansas City, Missouri).

Whole blood capillary samples were drawn from the finger tip prior to exercise and at the immediate cessation of time-trial performances for the analysis of blood lactate concentration (Lactate Pro, Akray, Kyoto, Japan). Heart rates (HR) were continuously recorded (S610i, Polar, Kempele, Finland) throughout all exercise tests, time-aligned and averaged into 30 s intervals.

Stroke-to-stroke power output was assessed using the RowPro v2.006 software (Digital Rowing) in conjunction with the Concept II interface. After each trial, power output was time-aligned and averaged into 30 s intervals.

Measurement of thermoregulatory factors

Core temperature (T_c) was measured via telemetry from the intestine using a silicon-coated thermometer pill (CorTemp2000, HQ, Palmetto, Florida) which was swallowed by all participants 5 h before exercise to ensure that it would be past the stomach and insensible to swallowed hot or cold liquids.[19] The calibration of the ingestible pills was checked prior to ingestion at four different temperatures against a certified mercury thermometer in a water bath at temperatures ranging from 30°C to 42°C. In accordance with our earlier work, a linear regression equation was then used to adjust pill measurements.[20]

Br J Sports Med 2009;43:789–795. doi:10.1136/bjsm.2008.056085

5.5 Publication article 2009

Lander, P. J., Butterly, R. J. and Edwards, A. M. (2009) Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. British Journal of Sports Medicine, 43 (10), 789-795. (cont).

Table 1 Baseline anthropometric and cardiovascular characteristics of the participants

	Anthropometric characteristics				
	Height (m)	Weight (kg)	Age (years)	$\dot{V}O_2$ peak (ml/kg/min)	HR at $\dot{V}O_2$ peak (b/min)
Mean (SD)	1.77 (0.06)	77.10 (8.11)	29 (6)	51.56 (2.75)	185.41 (7.86)

Skin temperatures (T_{sk}) were measured at four sites using stainless steel surface skin thermistors (Grant Logistics, Cambridge). Temperatures were recorded continuously throughout the trial using a data logger (SQ400 Squirrel Data logger, Grant Logistics). The mean body skin temperature was calculated using the formula previously described by Ramanathan[21] and others.[22 23] Measurements were taken of T_c and T_{sk} continuously throughout the trials in order to assess dynamic responses to exertion, time-aligned and then averaged into 30 s intervals for comparison with other dynamic exercise data sets.

Measurement of surface iEMG

Surface electrodes (Medi-Trace 230 Foam Electrode, Kendall Healthcare, Mansfield, Massachusetts) were placed 20 mm apart on the belly of the biceps brachii and vastus lateralis muscles, and a reference electrode was placed on the lateral aspect of the styloid process of the radius.[24 25] The skin surface was cleaned and shaved prior to electrode application in order to avoid interference and to increase adhesion; all electrodes were additionally fastened with medical adhesive tape. As rowing involves bilateral activation of the muscles,[26] recordings were taken from only one side (right) of the body. Scores were not standardised against a standard isometric maximal voluntary contraction (MVC), as the dynamic nature of the movement pattern involved in rowing has been previously shown to elicit higher peak muscle sEMG in rowing than in the manoeuvre used to produce isolated maximal voluntary contractions.[19] In addition, the plane of movement in rowing is difficult to replicate in MVC conditions, and pretrial evaluations did not support the use of that technique.

iEMG was recorded during the final 100 m of each 1000 m period using the Power Lab data acquisition system (Power Lab AD Instruments, NSW, Australia). Raw scores were digitally filtered (band pass filter; 20 Hz to 480 Hz), digitised (1 kHz sampling rate) and stored (Chart 5 v5.5.5, AD Instruments, NSW, Australia). Each stroke was visually identified and quantified using the root mean square (rms) method, and the mean of three strokes at the end of each 1000 m interval across the three trials was then batched for the purposes of statistical comparisons.

Data analysis

Dynamic variations attributable to pacing were assessed by the measurement of oxygen uptake, heart rate and power output gained from the 30 s time-aligned data series of each outcome measurement.

A simple and effective means of determining time-domain variability is to calculate the standard deviation (SD) of each data point (ie, each 30 s time-aligned interval) as a series. Since variance is mathematically equal to the total power of spectral analysis, the SD of the data series reflects all the cyclic components responsible for variability in the period of recording, in this case the time trial. This method of analysis is frequently used in the study of heart rate variability.[27 28] The standard deviation for each data series was therefore used to provide an overall comparative measure of dynamic time trial variability (ttv) between test conditions using the following outcome measurements: (1) oxygen uptake ($\dot{V}O_{2ttv}$), (2) heart rate (HR_{ttv}) and (3) power output (PO_{ttv}).

Statistical analysis

The statistical software package SPSS (version 11.0, SPSS, Chicago) was used for all statistical analysis. Parametric results were statistically compared using one-way repeated-measures analyses of variance (ANOVA) and post-hoc Tukey tests of

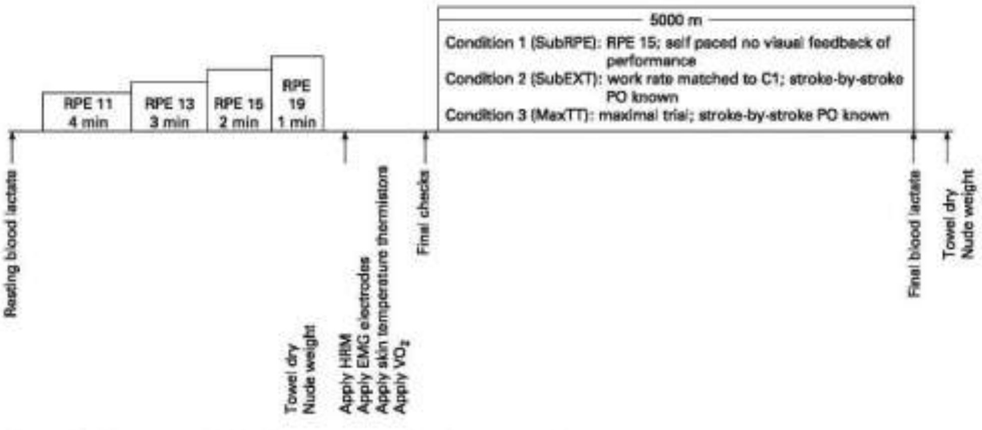


Figure 1 Experiment protocol for the three test sequence of rowing ergometer trials.

5.5 Publication article 2009

Lander, P. J., Butterly, R. J. and Edwards, A. M. (2009) Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. British Journal of Sports Medicine, 43 (10), 789-795. (cont).

Honest Significant Differences as appropriate. Other comparisons were made using paired Student t tests. Non-parametric data were assessed using the Friedman analysis of variance and Mann–Whitney U tests. Probability values of less than 0.05 were considered significant. All results are expressed as mean (SD).

RESULTS

The fastest mean 5000 m performance time was observed in the MaxTT condition, and this was shorter in duration than both SubRPE ($p<0.01$) and SubEXT ($p<0.01$) (table 2). There was no difference in the performance times of the two submaximal matched-intensity trials (SubRPE and SubEXT). The mean performance characteristics of V_{O_2}, HR, and power output were not different between both submaximal conditions, but these were all significantly elevated in MaxTT (tables 2, 3).

There were no differences in mean or dynamics of oxygen uptake or heart rate between the submaximal conditions (table 3). However, the dynamics of power output (PO_{ttv}) across the time-trials showed significantly greater variability in SubRPE compared with SubEXT ($p<0.01$) (table 2). The variability of power output was further elevated in MaxTT condition compared with both the submaximal trials ($p<0.01$) (table 2).

Mean T_{sk} was similar across all three (submaximal and maximal) conditions (fig 2). The mean T_c was significantly lower in SubRPE than in both SubEXT ($p<0.05$) and MaxTT ($p<0.01$). There was no difference in mean T_c between either SubEXT or MaxTT.

BLa concentrations taken immediately post-exercise were significantly elevated in SubEXT (6.2 (SD 2.5) mmol/l) compared with SubRPE (5.2 (2.2) mmol/l) ($p<0.05$). Both submaximal blood lactate responses were significantly lower when compared with the maximal trial (10.9 (2.4) mmol/l) ($p<0.01$).

Mean iEMG activity measured at both the vastus lateralis and biceps brachii was greater at each 1000 m interval in SubEXT when compared with SubRPE ($p<0.05$). The mean iEMG activity of MaxTT was significantly higher than both the submaximal conditions at each 1000 m (fig 3).

Core temperature was not correlated with power output in any exercise condition, while T_{sk} was correlated with power output in both submaximal trials SubRPE ($r=0.67$; $p<0.01$), SubEXT ($r=0.54$, $p<0.01$) but not with MaxEXT. Immediate post-test evaluation of RPE in the SubEXT condition demonstrated a tendency for subjects to perceive that condition (RPE: 16 (1.9); $p=0.08$) to be more challenging than that of the prescribed RPE of 15 in the SubRPE condition. All subjects rated the MaxTT condition to be of maximal perceived effort (RPE: 20 (0)) on the RPE scale.

Scalar evaluation of 30 s power output data identified that all participants demonstrated a spurt of power (identified as a visible upward alteration in the trajectory of power output) at a similar stage of their maximal trial (MaxTT) (89 (5)% trial; range: 81–95% of trial duration).

Table 2 Mean and dynamic responses of performance time and power output in the three experimental conditions

	Performance outcome measurements		
	Performance time	Power output	
	(s)	(W)	(ttv)
SubRPE	1300.11 (77.53)‡	162.16 (26.63)‡	17.85 (3.00)†‡
SubEXT	1298.67 (71.59)‡	161.33 (26.51)‡	12.13 (3.05)*‡
MaxTT	1219.33 (53.92)*†	193.74 (27.12)	29.55 (13.08)*†

Significantly different from Submaximal Self-paced using RPE scale $p<0.01$; *Submaximal Externally paced † $p<0.01$; Maximal Time Trial $p<0.01$‡.
ttv, Time trial variability.

Table 3 Mean and dynamic responses of oxygen uptake and heart rate in the three experimental conditions

	Physiological (oxygen uptake and heart rate) responses			
	Oxygen uptake		Heart rate	
	(ml/kg/min)	(ttv)	(bpm)	(ttv)
SubRPE	36.87 (4.96)‡	4.68 (0.72)‡	156.15 (15.17)‡	11.31 (1.49)
SubEXT	35.88 (5.62)‡	4.30 (0.82)	153.06 (17.42)‡	12.62 (1.56)
MaxTT	43.26 (4.16)	5.12 (0.05)*	172.17 (11.60)	11.84 (2.36)

Significantly different from Submaximal Self-paced using RPE scale $p<0.01$; *Submaximal Externally paced † $p<0.01$; †Maximal Time Trial $p<0.01$.
‡ttv, Time trial variability.

DISCUSSION

The main finding from this study was that, in submaximal exercise, the enforced constant paced condition (SubEXT) posed significantly greater physiological and thermoregulatory challenges to homeostasis than the matched-intensity self-paced trial despite there being no difference in performance. Specifically, the SubEXT condition resulted in elevated mean core temperatures ($p<0.01$), greater post-test blood lactate concentrations ($p<0.05$) and elevated iEMG activity at both biceps brachii ($p<0.05$) and vastus lateralis ($p<0.01$). The most likely explanation for this appears to be that self-paced exercise facilitates the opportunity for individuals to continually modify effort via feedback and feedforward mechanisms in response to frequent homeostatic challenges. Thus, the greater time trial variability of power output (PO_{ttv}) observed in the SubRPE condition compared with SubEXT ($p<0.01$) may indicate the presence of a central regulatory mechanism.

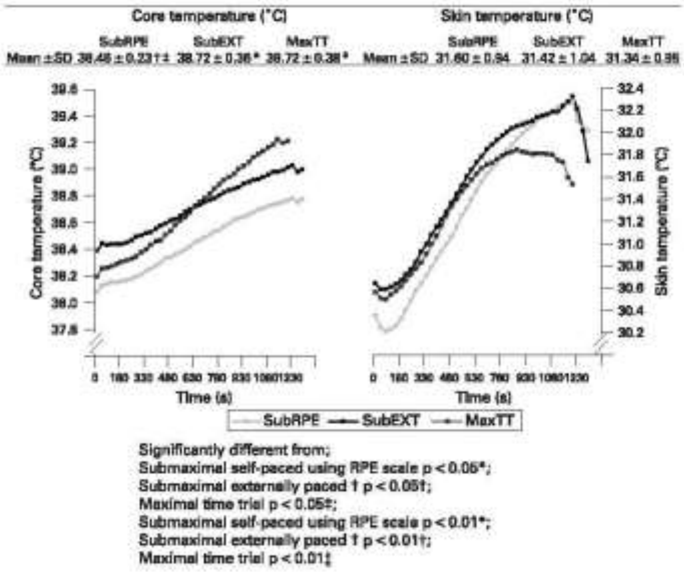
The greater variation of PO_{ttv} in the SubRPE condition compared with SubEXT was not accompanied by greater condition-specific variability in either V_{O_2} or HR. However, the similarity of HR and V_{O_2} between SubRPE and SubEXT is logical, as power output is the variable manipulated as a behavioural response (to transient sensations of fatigue), and alterations in both V_{O_2} and HR are therefore consequent with that behaviour, that is they are both responses to that change in power output. This delay in physiological response can also be explained via common system response times. For example, it is well known that the tau of oxygen uptake in response to dynamic changes in work is approximately 20–25 s among well trained participants,[29] while the tau of heart rate is appreciably slower.[30] Consequently, in self-paced exercise, dynamic variations in power output are probably too small and frequent for either V_{O_2} or heart rate to discreetly follow each alteration. As noted by other authors,[5] the importance of such dynamic responses have often been overlooked, probably due to the relatively recent emergence of fast-response technology. Nevertheless, such minor alterations in power output probably infer a mechanism by which voluntary behaviour (up- or downregulation of effort) maintains a constant metabolic challenge at a sustainable level throughout the bout.[4] Behavioural change (pacing) therefore acts to defend homeostasis (e.g by defending core temperature and blood pH) and this process is compromised where self-pacing is not facilitated.

The greater variability of power output observed in the maximal trial ($p<0.01$) compared with the submaximal trials was a likely consequence of the greater freedom to alter pace in that condition in comparison with the restricted conditions (fixed RPE or fixed power output) of the submaximal trials. It is therefore

5.5 Publication article 2009

Lander, P. J., Butterly, R. J. and Edwards, A. M. (2009) Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. British Journal of Sports Medicine, 43 (10), 789-795. (cont).

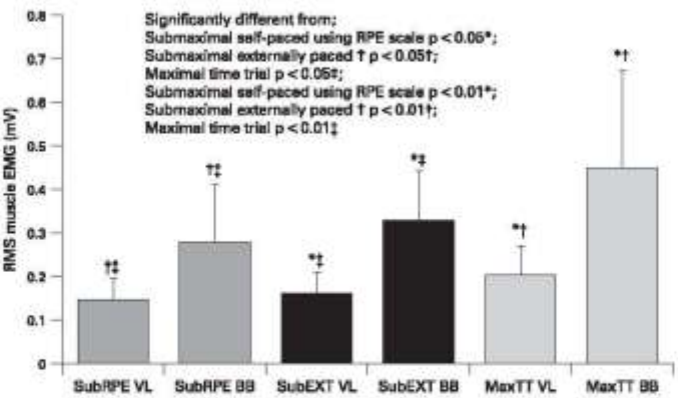
Figure 2 Mean thermoregulatory responses to the matched intensity submaximal exercise trials (SubRPE, SubEXT) and the maximal condition (MaxTT).



predictable that the maximal trial would demonstrate greater variability than the two submaximal conditions. Evaluation of the post-test RPE scores demonstrated that subjects tended to perceive the SubEXT condition (RPE: 16 (1).9) to be more challenging than the SubRPE condition (seven of the nine subjects rated it higher than SubRPE condition) but this did not reach statistical significance (p = 0.08). Two of the subjects did not rate the SubEXT condition to be more challenging than SubRPE although their metabolic responses (blood lactate concentrations and T_c) were elevated in the SubEXT condition. Our conclusion from this observation was that these two subjects were not able to verbally express their perceptions of effort as finely as their bodies were able to distinguish between the two submaximal conditions. The MaxTT condition produced a clear (and more obvious) distinction in RPE evaluation from the two submaximal conditions (p<0.01) whereby all subjects rated their efforts as being at the top of the scale. The maximal trial was included in this study for several comparative purposes but most usefully to identify whether participants were able to distinguish between working at different levels of exertion in response to a 5000 m rowing exercise test. Participants in this experiment were clearly able to accomplish this task.

Previous studies[12 14] have identified that an end spurt in performance tends to occur at 90% of task completion, and the maximal condition in this study was consistent with those observations. This appears to confirm that the increased final

Figure 3 Mean EMG bar chart for each of three experimental conditions. BB, biceps brachii; VL, vastus lateralis.



5.5 Publication article 2009

Lander, P. J., Butterly, R. J. and Edwards, A. M. (2009) Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. British Journal of Sports Medicine, 43 (10), 789-795. (cont).

What is already known on this topic

- It is widely acknowledged that the ability to accurately self pace is an important feature of race and time trial performances.
- Non-random fluctuations of power output have recently been observed during self-paced exercise, which may be associated with system control mechanisms.
- A central (brain) governor model has been proposed to regulate both afferent and efferent physiological mechanisms to defend homeostasis via pacing during exercise and consequently avoid the development of bodily harm.

What this study adds

- This study demonstrates that self-pacing exercise poses a reduced metabolic challenge when compared with matched-intensity enforced constant paced submaximal exercise.
- The greater voluntary time trial variability of power output observed in a self-paced condition appears to be a behavioural response to metabolic disturbance, thereby resulting in greater up- and downregulation of effort with no net loss in performance compared with a matched intensity enforced constant paced submaximal condition.
- Use of modern fast-response technologies allows a higher capture rate of both dynamic physiological and thermoregulatory responses to exercise which are fundamental to the investigation of pacing during an exercise bout.

effort in maximal trials is representative of scalar rather than absolute pacing[8] and provides little support for the concept that maximal intensity exercise progressively induces decreases in force production toward a terminal endpoint of fatigue.

No differences were seen in T_{sk} across submaximal and maximal trials (fig 2), although the T_{sk} of both SubRPE and SubEXT were correlated with power output (SubRPE: r = 0.67, p<0.01; SubEXT: r = 0.54, p<0.01). As the trajectories of T_{sk} for both submaximal trials were similar (and also distinct from MaxTT), it is possible that T_{sk} may have acted in some way as a regulatory mechanism in the submaximal conditions, but this was ineffectual for the maximal condition, whereby an optimal temperature (plateau) was reached at an earlier stage due to the greater physical cost of working in that condition. The most likely explanation for the similarity of skin temperatures between all conditions is probably that T_{sk} progresses towards an optimal level during laboratory exercise and in the absence of further opportunities for convective cooling becomes ineffectual as a regulatory system when a steady state is attained. Further research needs to be conducted to confirm this observation.

It was anticipated that the MaxTT condition would result in significantly faster performances compared with the submaximal trials, but the similarity of physiological responses between SubEXT and MaxTT provides further evidence of the greater metabolic challenge of externally paced submaximal work in comparison with self-paced exercise. Indeed, where the ability to self pace is denied, the metabolic challenge progresses toward a similar level to that of maximal exercise.

CONCLUSIONS

This study demonstrates that self-pacing exercise poses a reduced metabolic challenge when compared with matched-intensity enforced constant paced submaximal exercise. It is likely that this is attributable to the ability to voluntarily fluctuate power output in accordance with transient sensations of fatigue during the exercise bout. The voluntary behavioural change to fluctuate pace is therefore a conscious decision based on subconscious physiological feedback from an array of peripheral receptors. Externally paced (enforced pacing) submaximal exercise thereby forces an individual to abandon their own pacing plan and minimises opportunities for self-managing the conscious signs of fatigue. This suggests that pacing is an important physiological mechanism to minimise the adverse conscious sensations of fatigue experienced during exercise which enables homeostasis to be defended during exercise.

To our knowledge, this study is the first to thoroughly examine both the cardiorespiratory and thermoregulatory responses to rowing performance in relation to matched-intensity self- and externally paced conditions. Further work is now required to establish whether this effect is consistent across more dynamic exercise challenges.

Competing interests: None.

Ethics approval: Ethics approval was provided by Central Regional Ethics Committee of New Zealand.

Patient consent: Obtained.

Provenance and peer review: Not commissioned; externally peer reviewed.

REFERENCES

1. **Abbiss CR,** Laursen PB. Describing and understanding pacing strategies during athletic competition. *Sports Med* 2008;**38**:239–52.
2. **Foster C,** Schrager M, Snyder A, *et al*. Pacing strategy and athletic performance. *Sports Med* 1994;**17**:77–85.
3. **St Clair Gibson A,** Noakes TD. Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans. *Br J Sports Med* 2004;**38**:797–806.
4. **Tucker R,** Bester A, Lambert EV, *et al*. Non-random fluctuations in power output during self-paced exercise. *Br J Sports Med* 2006;**40**:912–17.
5. **St Clair Gibson A,** Lambert EV, Rauch LH, *et al*. The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort. *Sports Med* 2006;**36**:705–22.
6. **St Clair Gibson A,** Schabort EJ, Noakes TD. Reduced neuromuscular activity and force generation during prolonged cycling. *Am J Physiol Regul Integr Comp Physiol* 2001;**281**:R187–96.
7. **St Clair Gibson A,** Lambert MI, Noakes TD. Neural control of force output during maximal and submaximal exercise. *Sports Med* 2001;**31**:637–50.
8. **Noakes TD,** St Clair Gibson A, Lambert EV. From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans: summary and conclusions. *Br J Sports Med* 2005;**39**:120–4.
9. **Hulleman M,** De Koning JJ, Hettinga FJ, *et al*. The effect of extrinsic motivation on cycle time trial performance. *Med Sci Sports Exerc* 2007;**39**:709–15.
10. **Kirkendall DT.** Mechanisms of peripheral fatigue. *Med Sci Sports Exerc* 1990;**22**:444–9.
11. **Lambert EV,** St Clair Gibson A, Noakes TD. Complex systems model of fatigue: integrative homoeostatic control of peripheral physiological systems during exercise in humans. *Br J Sports Med* 2005;**39**:52–62.
12. **Catalano JF.** Effect of perceived proximity to end of task upon end-spurt. *Percept Mot Skills* 1973;**36**:363–77.
13. **Catalano JF.** End-spurt in addition of numbers. *Percept Mot Skills* 1974;**39**:121–2.
14. **Catalano JF.** End-spurt following simple repetitive muscular movement. *Percept Mot Skills* 1974;**39**:763–6.
15. **McLellan TM,** Cheung SS, Jacobs I. Variability of time to exhaustion during submaximal exercise. *Can J Appl Physiol* 1995;**20**:39–51.
16. **Smith B.** Rowing New Zealand. In: Bishop B, Hume PA, eds. *Guidelines for athlete assessment in New Zealand sport*. Wellington: SESNZ, 2000.
17. **Dudhia A.** *The physics of ergometers: measuring the damping*. Available at: http://www.atm.ox.ac.uk/rowing/physics/ergometer.html#section7. (Accessed 7 May 2008).
18. **Montain SJ,** Coyle EF. Influence of graded dehydration on cardiovascular drift and hyperthermia during exercise. *J Appl Physiol* 1992;**73**:1340–50.
19. **Sparling PB,** Snow TK, Millard-Stafford ML. Monitoring core temperature during exercise: ingestible sensor vs. rectal thermistor. *Aviat Space Environ Med* 1993;**64**:760–3.

Br J Sports Med 2009;**43**:789–795. doi:10.1136/bjsm.2008.056085

5.5 Publication article 2009

Lander, P. J., Butterly, R. J. and Edwards, A. M. (2009) Self-paced exercise is less physically challenging than enforced constant pace exercise of the same intensity: influence of complex central metabolic control. British Journal of Sports Medicine, 43 (10), 789-795. (cont).

20. **Edwards AM,** Clark NA. Thermoregulatory observations in soccer match play: professional and recreational level applications using an intestinal pill system to measure core temperature. *Br J Sports Med* 2006;**40**:133–8.
21. **Ramanathan NL.** A new weighting system for mean surface temperature of the human body. *J Appl Physiol* 1964;**19**:531–3.
22. **Marsh D,** Sleivert G. Effect of precooling on high intensity cycling performance. *Br J Sports Med* 1999;**33**:393–7.
23. **Mitchell D,** Wyndham CH. Comparison of weighting formulas for calculating mean skin temperature. *J Appl Physiol* 1969;**26**:616–22.
24. **Basmajian JV,** De Luca CJ. *Muscles alive: their functions revealed by electromyography.* 5th edn. Baltimore: Williams & Wilkins, 1985.
25. **De Luca CJ.** *Surface electromyography: detection and recording.* Boston: Delsys, 2002.
26. **Nowicky A,** Burdett R, Horne S. The impact of ergometer design on hip and trunk muscle activity patterns in elite rowers: an electromyographic assessment. *J Sports Sci Med* 2005;**4**:18–28.
27. **Achten J,** Jeukendrup AE. Heart rate monitoring: applications and limitations. *Sports Med* 2003;**33**:517–38.
28. **Aubert AE,** Seps B, Beckers F. Heart rate variability in athletes. *Sports Med* 2003;**33**:889–919.
29. **Edwards AM,** Cooke CB. Oxygen uptake kinetics and maximal aerobic power are unaffected by inspiratory muscle training in healthy subjects where time to exhaustion is extended. *Eur J Appl Physiol* 2004;**93**:139–44.
30. **Hughson RL.** Exploring cardiorespiratory control mechanisms through gas exchange dynamics. *Med Sci Sports Exerc* 1990;**22**:72–9.

6.0

Research Training Programme completion.

6.1 Evidence of research training programme completion.

Patrick Lander

Loughborough
Leicestershire

Mrs Sarabjit Bissas on Behalf of Professor Carlton Cooke
Carnegie Faculty
Leeds Metropolitan University
Room G04 Macauley Hall
Leeds, UK
LS6 3QS
Tel: 0044 (0)113 8120000 extn: 26621
E-mail Address: s.bissas@leedsmet.ac.uk
Fax: 0044 (0) 113 2745966

19th October 2010

Dear Patrick

Faculty Research Committee
Outcome: Application for Approval of Research Training Programme - APPROVED
Held: Wednesday 13th October 2010

I write to inform you that the Faculty Research Committee duly considered Paper FRCA-2010-010, this being your application for approval of the Research Training Programme which you have undertaken alongside your doctoral studies.

Following due consideration the Committee resolved to **APPROVE** your Research Training Programme. The Committee further noted that a good location of evidence to support your application which you have presented to Dr Athanassios Bissas, Research Awards Co-ordinator who has considered this and duly signed the Assessment Record sheets.

A copy of the Research training Programme: Assessment Record is enclosed for your file.

Should you have any concerns please do not hesitate to contact the Chair, Professor Richard Light or the Committee Secretary Mrs Sarabjit Bissas.

Yours sincerely

Professor Carlton Cooke
Chair of Faculty Research Committee

Cc:
Director of Study: Dr Ron Butterly
File: 19/10/2010