

**THE INFLUENCE OF PROTOCOL ON THE ASSESSMENT OF ECONOMY OF
MOVEMENT.**

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ABSTRACT

It is suggested that only data below gas exchange threshold (GET) should be used in regressions to calculate economy of movement. The purpose of this study was to compare the accuracy of the prediction from sub-GET only data (incremental_{sub}) and the sub & supra GET data (incremental_{full}) with a fixed work rate (WR) at an intensity typical of endurance performance. Twelve physically active male participants volunteered of age 29 ± 9 years, height 1.81 ± 0.07 m and body mass 81.4 ± 10 kg.

The participants completed four separate tests each on a separate day. Initially performing a maximal ramp test ($20 \text{ W} \cdot \text{min}^{-1}$) to volitional exhaustion at approximately 12 min. The other three tests included an incremental_{sub} and incremental_{full} and a fixed WR and were counterbalanced for potential order and carryover effects. All tests were carried out on an electronically braked cycle ergometer and the cadence maintained at approximately of $80 \text{ rev} \cdot \text{min}^{-1}$. The data from the maximal test was used to determine peak power, the highest $\dot{V}\text{O}_2$ over a 15 s sequential period ($\dot{V}\text{O}_{2\text{peak}}$) and GET. The incremental_{sub} method consisted of five stages six min in duration with equal transitions from 50 W to 95% GET. The incremental_{full} method consisted of five stages six min in duration with equal transitions from 50 W to 85% Δ . The data collection period was set at 4-6 min for these tests. The criterion fixed WR consisted of ten min duration at a WR of 75% Δ and had two data collection periods set at 4-6 and 8-10 min. The data collection period of 8-10 min was used in all further analysis; as at the 4-6 min data collection period steady state had not been attained. A linear regression was conducted on the mean oxygen uptake ($\dot{V}\text{O}_2$) kinetic response at each data collection stage of the five WRs in the two predictive tests and the calculation of $\dot{V}\text{O}_2$ requirement at 75% Δ performed. These two calculated and the measured $\dot{V}\text{O}_2$ values of economy of movement at 75% Δ were then entered into repeated measures ANOVA to identify differences in the oxygen uptake ($\text{L} \cdot \text{min}^{-1}$).

The ANOVA showed a significant effect of the method on $\dot{V}\text{O}_2$ at 75% Δ ($p < 0.001$). Post hoc analysis showed that both the incremental_{sub} and the incremental_{full} underestimated the $\dot{V}\text{O}_2$ requirement in the fixed WR ($2.90 \pm 0.40 \text{ L} \cdot \text{min}^{-1}$ ($p < 0.001$) and $3.21 \pm 0.47 \text{ L} \cdot \text{min}^{-1}$ ($p = 0.012$) vs. $3.43 \pm 0.45 \text{ L} \cdot \text{min}^{-1}$). Furthermore, the incremental_{sub} was significantly lower than the $\dot{V}\text{O}_2$ estimated from the incremental_{full} ($p = 0.037$).

Economy of movement should not be estimated using sub-GET data points only as this significantly underestimated the measured $\dot{V}\text{O}_2$ requirement. The use of regressions from incremental tests that use a full range of WR data will reduce this error but still underestimate the measured $\dot{V}\text{O}_2$ requirement. The impact of incremental designs on $\dot{V}\text{O}_2$ kinetics requires further investigation to fully understand this effect.

DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of the University of Gloucestershire and is original except where indicated by specific reference in the text. No part of this thesis has been submitted as part of any other academic award. The thesis has not been presented to any other education institution in the United Kingdom or overseas.

Any views expressed in the thesis are those of the author and in no way represent those of the University.

Mark Tabrett

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ABBREVIATIONS

$\dot{V}O_{2max}$	-	Maximal oxygen uptake
%	-	Percentage
$\dot{V}O_2$	-	Oxygen uptake
GET	-	Gas exchange threshold
WR	-	Work rate
SC	-	Slow component
$\dot{V}O_{2peak}$	-	Peak oxygen uptake
O_2	-	Oxygen
ATP	-	Adenosine TriPhosphate
$v\dot{V}O_{2max}$	-	Velocity at maximal oxygen uptake
AT	-	Anaerobic threshold
L_B	-	Blood lactate
LT	-	Lactate threshold
FE_{O_2}	-	Fraction of expired oxygen
CO_2	-	Carbon dioxide
\dot{V}_E	-	Pulmonary ventilation
VT	-	Ventilatory threshold
V-slope	-	Ventilatory slope
$\dot{V}CO_2$	-	Volume of carbon dioxide
MLSS	-	Maximum lactate steady state
CP	-	Critical power
RCP	-	Respiratory compensation point

PCO_2	-	Partial carbon dioxide
Δ	-	Delta
BxB	-	Breath by breath
τ	-	Time delay
Q	-	Cardiac output
(a-v) O_2 diff	-	Difference in oxygen content between arterial-to-venous
δ	-	Time constant
MRT	-	Mean response time
FT	-	Fast twitch fibres
BASES	-	British Association of Sport and Exercise Sciences
RER	-	Respiratory exchange ratio

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Chapter 1: Introduction

Introduction

There are a number of functional physiological determinants that integrate to control the highest race pace that can be maintained for the duration of that race (Coyle *et al.*, 1988). These parameters determine the intensity of exercise that can be sustained and also interact to produce a successful distance performance: (a) a high maximal oxygen uptake ($\dot{V}O_{2\max}$) (Hill *et al.*, 1924, Foster, 1983); (b) the ability to sustain a high % of $\dot{V}O_{2\max}$; (c) the energy requirement to perform at a particular WR (economy of movement) (Conley and Krahenbuhl, 1980, DiPrampo, 1993, Jones and Carter, 2000).

The most important physiological factor determining endurance performance has traditionally been considered to be $\dot{V}O_{2\max}$ (Costill, 1967, Saltin and Astrand, 1967, Costill *et al.*, 1971, Costill *et al.*, 1973, Foster, 1983). When dealing with a heterogeneous group of athletes, $\dot{V}O_{2\max}$ has a strong correlation with performance (Hill *et al.*, 1924), as does % $\dot{V}O_{2\max}$ (Costill *et al.*, 1973); however, when dealing with a homogeneous group (e.g. elite athletes), the correlation between $\dot{V}O_{2\max}$ and performance is poor (Conley and Krahenbuhl, 1980). A high $\dot{V}O_{2\max}$ is a prerequisite for successful endurance performance. Therefore, in elite athletes economy of movement is a stronger predictor of elite level performance (Bassett and Howley, 2000, Saunders *et al.*, 2004).

There are three approaches for the assessment of economy of movement. Firstly, by measuring the $\dot{V}O_2$ required at fixed WR (Joyner, 1991). Secondly, a series of incremental WR stages using a full range (e.g. sub & supra GET termed incremental_{full})

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of intensities lasting four to ten minutes, starting with a WR where a steady state $\dot{V}O_2$ is clearly discernible and finishing at a WR where maximal lactate steady state is thought to occur to extrapolate using the linear regression of the $\dot{V}O_2 - WR$ relationship to given WR (Zoladz *et al.*, 1998a). Thirdly, the Foster and Lucia (2007) method of assessment which utilises a minimum of three sub GET only incremental intensities ($\text{incremental}_{\text{sub}}$) and extrapolates to a given WR.

All three approaches have limitations in their assessment of economy. A criticism of the fixed WR approach is that it is difficult to determine the most appropriate WR to measure across subjects; as differences occur in the relative exercise intensity ($\% \dot{V}O_{2\text{max}}$) and therefore, measured oxygen uptake (Fletcher *et al.*, 2009). Meaningful comparisons using absolute WRs, can be difficult, because participants work at differing relative intensities of their individual $\% \dot{V}O_{2\text{max}}$ (Morgan *et al.*, 1989, Sherman and Jackson, 1998). A criticism of the regression approach that utilises both sub and supra GET WRs; is that above the GET the $\dot{V}O_2$ response becomes more complex (Barstow and Mole, 1991). During these exercise intensities the exponential increase in $\dot{V}O_2$ has a delayed additional phase (termed slow component (SC)) that raises the $\dot{V}O_2$ over and above that predicted from the sub-threshold only intensities (Hansen *et al.*, 1988, Xu and Rhodes, 1999, Berger and Jones, 2007). The Foster and Lucia's method only uses sub-threshold WR's to eliminate contamination by the SC; which can add up to $800 \text{ ml} \cdot \text{min}^{-1}$ over ten minutes causing an elevated $\dot{V}O_2$ and reduction of the value of economy of movement (Henson *et al.*, 1989). Therefore, the omittance of SC leads to an underestimation of the measured $\dot{V}O_2$ requirement at heavy intensity WR's.

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The impact of the emergence of the SC after GET demonstrates that the $\dot{V}O_2$ - WR relationship is nonlinear above the GET (Zoladz *et al.*, 1995). The slope of the $\dot{V}O_2$ - WR relationship becomes steeper above the threshold (Hansen *et al.*, 1988). Despite the fact that the $\dot{V}O_2$ - WR relationship is the most often applied criterion of human tolerance to exercise, surprisingly little attention has been paid to the non-linear increase in $\dot{V}O_2$ occurring during exercise at intensities above threshold (Zoladz *et al.*, 1998b).

Foster and Lucia (2007) state that the present consensus is that the standard method for measuring economy of movement, is to measure steady state $\dot{V}O_2$ at three or four discrete sub-threshold intensities only, to stop the SC contaminating the $\dot{V}O_2$ response and extrapolating the linear $\dot{V}O_2$ - WR relationship to estimate the value of $\dot{V}O_2$ for a given WR at supra-threshold. Foster and Lucia (2007) also state that at supra-threshold intensities the delayed additional phase SC will dictate that steady state conditions are unlikely to be achieved. The above statements and the fact that economy of movement can only be accurately measured at speeds or power outputs that elicit steady state $\dot{V}O_2$ is important when determining the $\dot{V}O_2$ requirement at a given WR. However, steady state is only delayed during heavy intensity exercise therefore allowing measurement of economy of movement to be undertaken (Zoladz *et al.*, 1998a).

The fact that training and competition occur at intensities above the GET means that a SC will always be incurred and will, therefore, incur an addition to the predicted $\dot{V}O_2$ requirement from the sub-GET only regression. Therefore, protocols that only include sub-threshold intensities and extrapolate using a linear regression may underestimate the true economy. Helgerud (2010) states that the most appropriate protocol for

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measuring economy of movement as a means of determining race performance capacity would be to actually include measurements of $\dot{V}O_2$ at race WR's. Daniels & Daniels (1992) suggest that economy of movement data should be collected up to 95% $\dot{V}O_{2peak}$ to ensure replication of race and training WR's.

As yet, no study has empirically investigated the comparison of the predictive methods of the $incremental_{sub}$ and $incremental_{full}$ regressions to the criterion of the fixed WR to identify which is the most accurate method to predict the economy of movement. The aim of the present study was to compare the two predictive methods with the criterion of the fixed WR of 75% Δ to determine the most accurate method of predicting the economy of movement at a given heavy exercise intensity.

2.0 Literature Review

2.1 Determinants of performance in endurance events

Physiological testing is widely used to study physical performance (Leaf, 1985); assess training interventions (Dufour *et al.*, 2006); evaluate the effects and/or state of cardiopulmonary or neuromuscular disease (Myers *et al.*, 2007); and, assess the response to rehabilitation (Markovitz *et al.*, 2004). Sport Scientists are interested in standard laboratory measures that can be used to assess the potential for exercise or the attained performance level.

Endurance is defined as the capacity to sustain a given WR for the longest possible time. Endurance events are those lasting more than 10 min and require a substantial and sustained energy transfer from oxidative pathways (Coyle, 1995, Lucia *et al.*, 2006). Therefore, successful endurance performance can be evaluated by the amount of time required to complete a given amount of work or by the length of time that a given power output can be maintained (Coyle, 1999).

Models of human endurance are based on three physiological determinants of performance (Hill *et al.*, 1924). These determinants are; the maximal rate of oxygen uptake ($\dot{V}O_{2max}$); ability to sustain a high percentage (%) of $\dot{V}O_{2max}$ and economy of movement. The maximal rate of oxygen uptake is the highest rate at which oxygen can be consumed during maximal intensity work (Wasserman *et al.*, 1987). The sustainable percentage of $\dot{V}O_{2max}$ is the highest % of $\dot{V}O_{2max}$ that can be sustained during a run. (Costill *et al.*, 1973). Economy of movement is a measure of energy requirement

commonly identified from oxygen uptake ($\dot{V}O_2$) (e.g. steady state oxygen consumption) relative to a given power output or speed (Conley and Krahenbuhl, 1980, Coyle, 1995).

2.1.1 The significance of $\dot{V}O_{2\max}$ as determinant of endurance performance

Maximal oxygen uptake is defined as the highest rate at which oxygen can be consumed and utilized by the body in one minute during maximal or predicted from submaximal exercise (Wasserman *et al.*, 1987) and is often considered the gold standard measurement of aerobic performance (Davison *et al.*, 2009). The traditional recommendation for determining $\dot{V}O_{2\max}$ is to utilise an incremental protocol of typically 8 to 12 min in duration (Buchfuhrer *et al.*, 1983, Pierce *et al.*, 1999, Brickley *et al.*, 2007). The units in which $\dot{V}O_{2\max}$ is expressed needs consideration. The value can be expressed as an absolute rate in litres of oxygen per minute ($L \cdot \text{min}^{-1}$) or as a relative rate in millilitres of oxygen per kilogram of body mass per minute ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$).

As $\dot{V}O_{2\max}$ is such an important requisite for endurance performance it is important to mention the physiological factors that could hinder the attainment of a high maximum. There are a number of central limiting factors associated with attainment of high $\dot{V}O_{2\max}$, including: pulmonary diffusion capacity for oxygen; maximal cardiac output; and the oxygen (O_2) carrying capacity of the blood. A peripheral limiting factor is the metabolic capacity of the skeletal muscles. The metabolic capacity of the skeletal muscles is determined by peripheral diffusion gradients, mitochondrial density, mitochondrial enzyme levels and capillary density. Each and every step in the O_2 pathway contributes in an integrated way to determining the rate of $\dot{V}O_2$ kinetics and

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any reduction in the transport capacity of any of the steps will reduce $\dot{V}O_{2\max}$ (Wagner, 1992, Wagner, 2008).

In endurance events, performance and $\dot{V}O_{2\max}$ are positively correlated. The $\dot{V}O_{2\max}$ intensity cannot be sustained during competition for greater than 5-10 min (Sjodin *et al.*, 1982, Joyner, 1991). The performance time in a 10-mile run has an inverse correlation ($r = -0.91$) with $\dot{V}O_{2\max}$ (Costill *et al.*, 1973). These investigations used subjects heterogeneous for $\dot{V}O_{2\max}$ (54.8 to 81.6 ml·kg⁻¹·min⁻¹) to examine this relationship. Thus, demonstrating that $\dot{V}O_{2\max}$ has a strong correlation with performance in heterogeneous groups of athletes (Costill *et al.*, 1973, Farrell *et al.*, 1979).

However, when a homogeneous group of athletes were studied the correlation between $\dot{V}O_{2\max}$ and performance was weak (DiPrampero *et al.*, 1986). This weak relationship between $\dot{V}O_{2\max}$ and performance has been depicted in homogeneous groups of middle-distance runners ($r = 0.28$) (Kenney and Hodgson, 1985); 10,000 m runners ($r = -0.12$) (Conley and Krahenbuhl, 1980) and marathon runners ($r = 0.15$) (Sjodin and Svendenhag, 1985). These findings demonstrate that within a homogeneous group of athletes, $\dot{V}O_{2\max}$ becomes weakly correlated with endurance performance.

The highest $\dot{V}O_{2\max}$ currently reported is 94 ml·kg⁻¹·min⁻¹ and most elite level performers have values of 70-85 ml·kg⁻¹·min⁻¹; compared to sedentary population with values of 30- 45 ml·kg⁻¹·min⁻¹ which is nearly two-fold greater aerobic power (Saltin and Astrand, 1967).

Assessing athletes for $\dot{V}O_{2\max}$, even when homogeneous for $\dot{V}O_{2\max}$, is still important due to the fact that high values of $\dot{V}O_{2\max}$ are identified as a prerequisite for entry into the elite class performers. Therefore, a prerequisite for any success in endurance events (Brandon, 1995). This indicates that $\dot{V}O_{2\max}$ alone does not adequately predict a winning performance among homogeneous groups with similar aerobic power (Fletcher *et al.*, 2009). In elite athletes $\dot{V}O_{2\max}$ has been shown to have reached a value greater than $65 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ early in their careers and, thereafter, further training interventions do not show substantial improvements (Lucía *et al.*, 2000, Coyle, 2005). Additionally, in these athletes there is evidence that $\dot{V}O_{2\max}$ is relatively insensitive to continued training (e.g. after three years) and therefore becomes a weaker correlation with performance capability (Conley and Krahenbuhl, 1980, Coyle, 1995, Jones, 1998).

2.1.2 The significance of sustainable percentage as a determinant of endurance performance

Once an elite level of $\dot{V}O_{2\max}$ had been attained, it was recognised that the ability to sustain a high % of $\dot{V}O_{2\max}$ throughout a race was important (DiPrampero *et al.*, 1986, DiPrampero, 1993). This enabled an alternative description of an athlete's training status, as the fractional utilisation of $\dot{V}O_{2\max}$ reflects the metabolic characteristics of the working muscles and their capacity for aerobic metabolism. An athlete can operate at a given fraction of $\dot{V}O_{2\max}$ that decreases as race duration increases. Sustainable % becomes increasingly important therefore in races of greater than 30 min duration (Coetzer *et al.*, 1993, Coyle, 1995, Lucia *et al.*, 2002); i.e. can sustain ~92% for 10 km but only ~78% for a marathon on average. In order to maximise performance athlete's

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must, therefore, be able to sustain a pace as close as possible to their $\dot{V}O_{2\max}$ especially in long distance. This is paramount as small differences in % $\dot{V}O_{2\max}$, i.e. 1-2%, can have a significant effect on race performance (Coyle, 1995).

There are a number of factors that will influence the sustainable % including the aerobic capacity of the active muscles and the % of type 1 muscle fibres (Coyle *et al.*, 1991a, Coyle, 1995); muscle capillary density (Coyle *et al.*, 1988); the LT (Coetzer *et al.*, 1993); and, the actual $\dot{V}O_2$ at LT (Coyle *et al.*, 1988). This sustainable level can vary widely between individuals and has been used to explain differences in race performance. Coyle (1988) indicated that athlete's exercising at 79% $\dot{V}O_{2\max}$ varied more than twofold in performance. This finding can be criticised on the fact that this intensity could actually be bridging two different exercise intensities, i.e. heavy and severe, and therefore would incur very different performance levels (see section 2.2.4 and 2.8).

The sustainable % $\dot{V}O_{2\max}$ can be evaluated under laboratory conditions, previously examined using two different methods; either by measuring the exercise time to exhaustion at a given % $\dot{V}O_{2\max}$ (Hardman, 1982) or by estimating the highest % $\dot{V}O_{2\max}$ sustainable during a given period of time from measurements of the average WR (Mayes *et al.*, 1985).

2.1.3 The significance of economy of movement on endurance performance

In groups homogeneous for performance or $\dot{V}O_{2max}$, there must be other subtle variables that account for the differences in performance or the ability to perform at the same level with a lower $\dot{V}O_{2max}$ value; which has been shown to be economy of movement. The ability of an athlete to translate their aerobic capabilities into performance depends on a concept known as economy. The term economy of movement is defined as the steady-state oxygen requirement for exercise at a given WR or distance travelled (Daniels, 1985, Morgan *et al.*, 1989). The oxygen requirement of endurance running at a given WR can vary by as much as 30-40 % among athletes (Farrell *et al.*, 1979, Conley and Krahenbuhl, 1980). Therefore, an athlete with better economy of movement can be considered to have an advantage in endurance performance due to the fact that they will utilise a lower % of their $\dot{V}O_{2max}$ during exercise at a given WR than a less economical athlete (Pate *et al.*, 1992). Early research comparing elite distance runners with good distance runners indicated that the elite runners had better economy of movement (Pollock, 1977).

Economy is expressed by plotting oxygen requirement versus WR or by simply expressing economy as the oxygen required per unit mass to cover a horizontal distance (e.g. 1 km) (Bassett and Howley, 2000). However, economy is more commonly calculated from the relationship between $\dot{V}O_2$ and WR by measuring across a range of WRs (Daniels and Daniels, 1992). The calculation of the $\dot{V}O_2$ -WR relationship is central to the calculation of many important physiological variables.

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It is important to note that economy of movement can only be accurately assessed at sub-maximal WRs where $\dot{V}O_2$ attains a steady state (Daniels and Daniels, 1992, Davison *et al.*, 2009). The conceptual basis is that the assessment of energy requirement must assess the balance of aerobic and anaerobic metabolic contributions to the overall energy requirement of exercise, particularly during heavy intensity exercise (Brooks and Fahey, 1984). In contrast to the problems inherent in quantifying the energy requirement of heavy intensity exercise, the economy of movement can be obtained by measuring the steady state $\dot{V}O_2$ for a fixed WR. A major assumption of this is that Adenosine TriPhosphate (ATP) requirement is derived wholly from cell respiration and not from anaerobic pathways (Margarita *et al.*, 1963, Whipp and Wasserman, 1970, Brooks and Fahey, 1984). However, during heavy intensity exercise an influential portion of the total energy requirement of active muscles is from anaerobic sources. The fact that SC of $\dot{V}O_2$ kinetics is not considered in the sub-GET only method questions whether the assumption that a steady state $\dot{V}O_2$ exists at the predicted level or whether it is delayed and elevated during heavy intensity exercise (Whipp, 1994). Consequently, the aerobic requirement of exercising at heavy intensity WRs may underestimate the true $\dot{V}O_2$ requirement (Bransford and Howley, 1977).

There is considerable interindividual variability in the oxygen requirement of submaximal exercise at a given WR (Morgan *et al.*, 1995); even in individuals of similar $\dot{V}O_{2max}$ or performance capability (Conley and Krahenbuhl, 1980, Bassett and Howley, 1997). Within elite athletes 65.4% of race performance variation can be explained by differences in economy of movement (Morgan and Craib, 1992). Elite cyclists exercising at the same power output have been demonstrated to require different

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$\dot{V}O_2$ requirements to achieve this (Horowitz *et al.*, 1994). Interindividual comparison between subjects trained in endurance and untrained counterparts demonstrated that trained runners are more economical (Kyrolainen *et al.*, 2001). A strong correlation ($r = 0.82$) between economy of movement and performance in a 10-km run was found in a group of runners, homogeneous for $\dot{V}O_{2max}$, but with a range of 10-km times of 30.5–33.5 min (Conley and Krahenbuhl, 1980). However, as Noakes (1998) pointed out when one examines the fastest four runners (10 km in 30.5–31 min) there was considerable variability in the economy of movement ($45 - 49 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ at $16 \text{ km}\cdot\text{h}^{-1}$), which suggests a lack of association between the variables. However, whenever the heterogeneity of a group is reduced (i.e. performance) the correlation between economy and performance will diminish in accordance.

Investigations have also shown that a relatively low $\dot{V}O_{2max}$ can be compensated for by exceptional economy of movement (Morgan *et al.*, 1995). Indeed, an inverse relationship between $\dot{V}O_{2max}$ and running economy has been reported in samples of well-trained runners (Morgan and Daniels, 1994). Daniels (1985) showed that one athlete was able to match another athlete's performance, in spite of 17.6 % lower $\dot{V}O_{2max}$ due to superior economy of movement. While acknowledging the comparatively small difference in economy between elite and untrained athletes, it should be noted that a 1% reduction in the aerobic requirement would potentially translate into a one min improvement in elite marathon race performance (Morgan *et al.*, 1995).

It can be speculated therefore that good exercise economy is somehow related to the total volume of endurance training performed in elite athletes (Conley and Krahenbuhl,

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1980, Jones and Carter, 2000). This is because the best economy values are often found in older or more experienced athletes, or those who complete a large weekly training mileage (Jones, 1998). Consequently, a reduction in the requirement of muscle glycogen utilisation and therefore, potentially less reliance on O₂-independent metabolism which results in a reduced metabolic acidosis state, i.e. fatigue (Jones, 1998). A female marathon world record holder displayed a remarkable 14% improvement in economy over 5 years of training (Jones, 1998). Also, cycling economy was observed to increase 8% over the course of 7 years in an elite endurance cyclist (Coyle, 2005).

Furthermore, an athletes' most economical WR tends to be those at which they habitually train (Jones and Carter, 2000). However, it is not clear whether the habitual training levels makes this the most economical WR or vice versa. A champion roadracer was tested during a period of 18 weeks training. The athletes economy at 18 km.h⁻¹ improved from 58.7 to 53.5 ml.min⁻¹.kg⁻¹ and $\dot{V}O_{2max}$ increased from 70.2 to 75.1 ml.min⁻¹.kg⁻¹. An elite cyclist, over a 7 yr period, managed an 8% improvement in their economy of movement; defined as the power output relative to energy requirement, i.e. calculated from $\dot{V}O_2$ requirement (Coyle, 2005). This would indicate that athletes should train over a broad range of WRs if they wish to lower the slope of the $\dot{V}O_2$ -WR relationship. Therefore, it would make sense to test economy over the broad range of WRs utilised or directly at the fixed race pace of the individual athlete.

Economy is therefore a key factor in continued performance improvements in elite athletes (Coyle, 1995, Jones, 1998). However, measurement of economy at race pace in

practice is complicated by the existence of the SC of $\dot{V}O_2$ at WRs exceeding GET (Jones *et al.*, 1999). From a practical standpoint it is essential to reliably measure economy continually after training interventions to measure the influence this may have on improving race performance.

2.1.4 The significance of composite measures as determinant of endurance performance

Composite measures of $\dot{V}O_{2max}$ and economy, e.g. peak speed and velocity at maximal oxygen uptake ($v\dot{V}O_{2max}$), have also been shown to be an important determinant of endurance performance (Daniels, 1985, Scrimgeour *et al.*, 1986, Noakes *et al.*, 1990).

Peak speed is the highest speed that can be maintained for 60 s during an incremental maximal test and has been demonstrated to correlate strongly ($r = 0.91$) with distances 10-90 km (Scrimgeour *et al.*, 1986, Noakes *et al.*, 1990). However, the highest speed attained at exhaustion, in such a test, will be higher than peak speed due to the incorporation of a contribution from anaerobic metabolism following a plateau in $\dot{V}O_2$.

Running velocity at $\dot{V}O_{2max}$ strongly predicted 10km running performance in a group of well-trained male runners with homogeneous $\dot{V}O_{2max}$ values ($\sim 65 \text{ ml.kg}^{-1}.\text{min}^{-1}$) (Morgan and Daniels, 1994). The minimum velocity needed to elicit $\dot{V}O_{2max}$, i.e. $v\dot{V}O_{2max}$, is reported to be based upon the linear relationship between running velocity and $\dot{V}O_{2max}$ to determine (Daniels, 1985). A comprehensive battery of physiological tests was carried out on 13 trained runners heterogeneous for $\dot{V}O_{2max}$ (i.e. 53 - 67 $\text{ml.kg}^{-1}.$

$^1 \cdot \text{min}^{-1}$). During an 8 km run, $v\dot{V}O_{2\text{max}}$ has been demonstrated to be strongly correlated ($r = 0.93$) with performance (Jones and Doust, 1998).

2.2 The domains of exercise intensity

2.2.1 Overview

The nature of $\dot{V}O_2$ response to exercise has been shown to be a function of exercise intensity and, therefore, demonstrates differences in its trace dependent on the intensity of the exercise performed (Whipp and Mahler, 1980). Before discussing the $\dot{V}O_2$ kinetic response to the various exercise intensities, a summary of current exercise intensity domain definitions and what physiological parameters demarcate the lower and upper boundaries of each must be made. In order for comparisons it is important to identify the discrepancies that exist, between authors, in their terminology.

Categorisation of the domains of exercise intensity is often problematic since the definition of the upper and lower limits of each domain is uncertain and different laboratory measures are used to calculate them. When percentage of $\dot{V}O_{2\text{max}}$ is used to define exercise intensity, the actual exercise intensity domain the athlete is performing in could vary (Rowland and Rimany, 1995, Wetter *et al.*, 1999, Hill and Stevens, 2001). Uncertainty around the definitions of the exercise intensity domains has led to some less well defined terms being used; such as submaximal (Hughson *et al.*, 1987), sub and supra maximal exercise (Medbo *et al.*, 1988, Sherman and Jackson, 1998, Esposito *et al.*, 2006), exhaustive exercise (Billat *et al.*, 1998b), high intensity exercise (Whipp and

Ward, 1993, Gerbino *et al.*, 1996, Bernard *et al.*, 1998, Obert *et al.*, 2000) or very heavy intensity (Whipp and Ward, 1990).

Within this thesis the terms moderate and heavy intensity exercise are used to describe the intensities that fall below and above GET respectively (discussed further in section 2.2.2). At exercise intensities where the $\dot{V}O_2$ steady state cannot be achieved, i.e. above maximal steady state, are referred to as severe (Draper *et al.*, 2003). However, since the focus of this thesis was to investigate a range of intensities that attained steady state $\dot{V}O_2$, it is safe to assume all the exercise bouts were performed within the moderate and heavy intensity domains.

2.2.2 Demarcation of domains of exercise intensity

During incremental exercise, the ATP is broken down and continuously resynthesized by aerobic and anaerobic processes. As exercise increases, from the lowest WR with discernible response, the initial WRs are characterised by a balance between the production and removal of lactate from and into the muscle and blood.

Wasserman and McIlroy (1964) developed the concept that a critical threshold exists where the metabolic needs for O_2 in the muscle exceed the capacity of the cardiopulmonary system to supply them; a systematic increase in anaerobic metabolism and lactate is formed in the muscle. The term anaerobic threshold (AT) was used to describe this transitional point where there is a systematic rise in blood lactate (L_B) during exercise (Davis *et al.*, 1976, Brooks, 1985). This concept however, has been

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criticised on many fronts. Evidence has amassed that dissociates lactate production from anaerobiosis, suggesting that muscles can release lactate even when the O₂ supply is more than adequate (Brooks, 1991). These issues have led to vast controversy over the definition, and the techniques used for detection and the resultant measurements vary widely.

Despite this controversy the term AT has been used to illustrate the demarcation of moderate to heavy intensity exercise (Gaesser and Poole, 1996, Xu and Rhodes, 1999). Moderate intensities are consequently described as those that do not result in an increased (above resting levels) metabolic acidemia (Whipp, 1994). However, controversy still surrounds the calculation of the AT; as there are various methods used, both from the measurement of blood lactate (Hughson *et al.*, 1987, Green and Dawson, 1993) and from respiratory data (Beaver *et al.*, 1985, Beaver *et al.*, 1986).

Many researchers have adopted the term lactate threshold (LT) which refers to the highest $\dot{V}O_2$ that can be achieved without a sustained increase in L_B and decrease in pH (Wasserman *et al.*, 1994). Invasive techniques for detecting LT have used L_B data. To achieve this blood samples have been drawn from many differing sites; arteries (Yoshida *et al.*, 1987) and capillaries (Billat *et al.*, 1998b, Jones *et al.*, 1999) but in most cases from veins (Poole *et al.*, 1991, Zoladz *et al.*, 1998c, Gonzales and Scheuermann, 2008). All of these invasive studies have failed to consider possible differences in lactate levels among venous, mixed venous, arterial and capillary blood (Bosquet *et al.*, 2002). Also, the onset of L_B accumulation has been detected in different ways; an abrupt increase in venous lactate (Davis *et al.*, 1979), a non-linear rise in venous lactate

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(Sjodin *et al.*, 1982), a slight increase in capillary lactate concentration (Belli *et al.*, 2007), or the onset of an exponential rise in venous lactate (Yoshida *et al.*, 1987). The criterion to define the L_B inflection varies too; a fixed concentration of 4 mmol.L^{-1} (Sjodin *et al.*, 1982), concentration of 2.5 mmol.L^{-1} (Hurley *et al.*, 1984), 2.2 mmol.L^{-1} (LaFontaine *et al.*, 1981) and a 1 mmol.L^{-1} rise above resting levels (Yoshida *et al.*, 1987) or baseline (Coyle *et al.*, 1983). Using a fixed lactate level as the threshold certainly increases objectivity but denies individuality since the non-linear increase does not always occur at a fixed level (Williams *et al.*, 2001). All of these variations, being as much as 13% ($79 - 92 \% \dot{V}O_{2\max}$) on the same data, in methods make identification of LT and any comparisons between studies difficult (Bassett and Howley, 2000).

The majority of research on $\dot{V}O_2$ kinetics has used respiratory methods to estimate LT. Most of the criteria used for this non-invasive detection of AT was introduced by Wasserman, Whipp and Davis. The first suggested detection method was the point of an increase in respiratory gas exchange ratio (RER) (Wasserman and McIlroy, 1964). The traditional methods for non-invasive respiratory data were based on reliance of visual inspection of graphical plots of ventilatory equivalents, end-tidal gas concentrations and RER (Wasserman and McIlroy, 1964, Wasserman *et al.*, 1973, Davis *et al.*, 1979). Further, definitions included, the detection of an abrupt increase in the fraction of expired O_2 (FE_{O_2}) and the increase in ventilatory equivalent (minute ventilation/ O_2 consumption) for O_2 but not in ventilatory equivalent of carbon dioxide (CO_2) (Davis *et al.*, 1979). During incremental exercise pulmonary ventilation (\dot{V}_E) linearly increases with increasing $\dot{V}O_2$, but the increment of ventilatory equivalent has two inflection points. The first inflection point, occurring at the lower $\dot{V}O_2$, is termed ventilatory

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threshold (VT) (Whipp *et al.*, 1981). A computer method has been used to detect the VT from these quantities, by using a data smoothing technique, i.e. cumulative sum (Smith and O'Donnell, 1984). Another computerised method used \dot{V}_E vs. \dot{V}_{O_2} uptake curve to be analysed using a three segment regression to locate the intersection point identified as VT (Orr *et al.*, 1982). Methods relying on \dot{V}_E changes are not effective due to reliance on ventilatory response to metabolic acidosis above VT. There are ventilatory changes which occur that are caused by other factors than accelerated CO_2 production, which can interfere with the determination of VT.

The ventilatory-slope (V-slope) method, uses gas exchange data, relies on an assumption that H^+ ions of lactic acid are released and are buffered by blood bicarbonate (isocapnic buffering) producing additional CO_2 is generated during exercise which in turn increases \dot{V}_E as the concentration of lactate increases. This V-slope method, where \dot{V}_{CO_2} and \dot{V}_{O_2} are plotted against each other, and demonstrates two distinct slopes; the intercept of these slopes are considered to be the gas exchange threshold (GET). This technique is referred to as the V-slope method because it defines the behaviour of \dot{V}_{CO_2} as a function of \dot{V}_{O_2} (Beaver *et al.*, 1986). Before GET the \dot{V}_{O_2} and \dot{V}_{CO_2} tend to rise at roughly the same rate but after GET metabolic acidosis develops causing \dot{V}_{CO_2} to rise at a faster rate than \dot{V}_{O_2} . The onset of excess CO_2 production in response to lactate accumulation is the fundamental event to be detected and can be measured at the mouth (Bearden and Moffatt, 2001a, Burnley *et al.*, 2003, Roberts *et al.*, 2005). The use of VT is an incorrect use of terminology as the V-slope method incorporates gas exchange data, i.e. O_2 and CO_2 , and is therefore more appropriately termed GET. An advantage of these methods using respiratory data for the

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calculation of GET or VT compared to LT, was the far greater number of values used to determine the inflection.

Therefore, the range of WRs that do not incur a sustained metabolic (lactic) acidemia (above resting levels) have been described as moderate intensity (Whipp and Ward, 1990, Whipp, 1994). The GET not only has functional significance for setting the upper limit of moderate intensity domain, but, also, highlights the lower limit of heavy intensity exercise (Whipp, 1994). Therefore, because GET is used as the demarcation point, many researchers have referred to these domains as sub- and supra-threshold (Whipp and Ward, 1990, Womack *et al.*, 1995, Gerbino *et al.*, 1996). The $\dot{V}O_2$ kinetics that these two intensity domains have are different (Linnarsson, 1974, Whipp and Ward, 1990), covered in more detail in section 2.2.3.

The lower limit of heavy intensity domain is well established (even if calculation still disputed), however, the upper limit is perhaps less certain or well established in literature. The demarcation point of the upper limit of heavy exercise intensity is defined as the highest WR that will achieve metabolic steady state in both $\dot{V}O_2$ and lactate production and removal, i.e. maximum lactate steady state (MLSS) (Whipp and Wasserman, 1972, Billat *et al.*, 1998a). Whilst some consensus exists on the point, the disagreement comes about what physiological measure or parameter represents this upper limit. Past studies have suggested that the asymptote of the hyperbolic relationship between WR and time to fatigue for an individual, demarcates the boundary between heavy and severe intensity domains (Whipp and Ward, 1990, Poole *et al.*, 1994, Hill and Stevens, 2001). The value of this asymptote represents a theoretical

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maximum speed or power that can be achieved and maintained without occurrence of fatigue. This theoretical maximum speed or power has been termed critical speed (Hughson *et al.*, 1984) or velocity (Daniels, 1985, Bull *et al.*, 2008) for running and critical power (CP) for cycling (Hill and Stevens, 2001, Wilkerson and Jones, 2007, Zoladz *et al.*, 2008).

Respiratory compensation point (RCP), the point above which the \dot{V}_E augmentation (i.e. hyperventilation) starts to occur inducing a fall in arterial partial carbon dioxide (PCO_2) and severe lactic acidosis (i.e. pH acidic) has been used to demarcate the heavy and severe exercise intensities (Jones *et al.*, 1999, Jones, 2000, Bentley *et al.*, 2007). This is possible because sodium bicarbonate is the major buffer of metabolic acids, therefore, an increase in blood lactic acid causes an obligatory increase in CO_2 production, which may be detected in the breath at the mouth (Wasserman and McIlroy, 1964). However, the RCP is inappropriate for this because the identification can be affected, unlike GET, by the rate at which the WR is incremented (Davis *et al.*, 1982, Buchfuhrer *et al.*, 1983) or by metabolic substrate (Cooper *et al.*, 1989, Yoshida *et al.*, 1995).

Exercise intensities that occur above heavy, that is intensities that a steady state $\dot{V}O_2$ is not attained, are termed severe. Due to the nature of $\dot{V}O_2$ response, it is assumed that steady state cannot be achieved and that exhaustive exercise in this domain will result in attainment of $\dot{V}O_{2max}$, provided the duration is sufficient (Whipp, 1994). The importance of the demarcation between heavy and severe intensity is extremely important both experimentally and practically. The upper boundary of heavy intensity demonstrates a separation between WRs that attain and those that do not attain steady

state conditions (Poole *et al.*, 1988). The key of the demarcation between heavy and severe exercise intensities is the achievement of metabolic steady state in both $\dot{V}O_2$ and lactate production and removal.

As mentioned earlier, there are conceptual issues with the use of % $\dot{V}O_{2max}$ to determine exercise intensity. The popular way of quantifying exercise intensity is to use the difference between $\dot{V}O_2$ at GET and $\dot{V}O_{2max}$ (Koga *et al.*, 1997, Bearden and Moffatt, 2000). This difference is usually referred to as delta (Δ) (Burnley *et al.*, 2000, Carter *et al.*, 2000a, Jones *et al.*, 2006). For example, an individual with power output of 300W at $\dot{V}O_{2max}$ and 100W at GET; 50% Δ would be at an associated power output of 200W.

2.2.3 $\dot{V}O_2$ kinetics response to moderate intensity exercise

The Foster and Lucia (2007) method of calculating economy is based wholly upon the moderate intensity $\dot{V}O_2$ response to exercise. These characteristics of the $\dot{V}O_2$ response in the transition from rest to constant load exercise have been extensively described for upright cycling (Whipp and Wasserman, 1972, Barstow and Mole, 1991). Following the onset of constant-load muscular moderate intensity exercise, there is an exponential increase in pulmonary $\dot{V}O_2$, after an initial delay (Linnarsson, 1974, Whipp *et al.*, 1982). Since the pioneering work in early 1923, it has been recognised that pulmonary $\dot{V}O_2$ rises in an approximately exponential manner during moderate exercise (Hill and Lupton, 1923). However, with the advent of sophisticated gas analysis systems and development of measurement techniques that allowed the calculation of $\dot{V}O_2$ on a breath-by-breath (BxB) basis, it is now possible to examine the response in far greater

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detail. Also, advances in computer software technology have made complex mathematical modelling of physiological data more easily accessible and provided a selection of methods to describe $\dot{V}O_2$ kinetics.

At the onset of moderate intensity exercise the $\dot{V}O_2$ measured at the mouth follows three distinct responses, ending with the attainment of steady state $\dot{V}O_2$, which is normally achieved within approximately three minutes in healthy subjects (Whipp *et al.*, 1982, Casaburi *et al.*, 1989a), giving a time constant (τ) of 25-35s with a time delay (δ) of 15-20s (Whipp and Wasserman, 1986, Burnley *et al.*, 2000, Wilkerson *et al.*, 2004). The $\dot{V}O_2$ response to moderate intensity exercise has three distinct responses: a delay response (also called cardiodynamic), the primary response, and the steady state.

The first response is essentially a time delay (δ) of ~20s which reflects the transit time that pooled deoxygenated blood takes to travel from the working muscles to the lungs, i.e. venous return (Casaburi *et al.*, 1989b, Whipp, 1994, Hughson *et al.*, 2000). The increases in $\dot{V}O_2$ within the early delay component have been attributed principally to augmented cardiac output and the sudden increase in venous return due to increased activation of the muscle pump with a transient overshoot in cardiac volume (Bell *et al.*, 2001, Faisal *et al.*, 2009). Smaller contributions are likely arising from changes in lung gas stores (Barstow and Mole, 1987) and mixed venous O_2 content (Casaburi *et al.*, 1989b). By using direct measurements of blood extracted from a pulmonary arterial catheter, it was demonstrated that mixed venous O_2 saturation began to decrease prior to the expected transient delay, and partial pressure of CO_2 showed signs of an increase in this delay phase and, therefore, constitutes part of the $\dot{V}O_2$ response to onset of

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moderate intensity exercise (Casaburi *et al.*, 1989b). The exact nature of this first phase is not fully understood. This early response is more discernible when commencement of exercise occurs from rest rather than from an unloaded WR (Whipp, 1987). The Fick equation describes $\dot{V}O_2$ at the mouth:

$$\dot{V}O_2 = Q \times (a-v) O_2 \text{ diff}$$

Where Q is cardiac output and (a-v) O_2 diff is the difference in oxygen content between arterial-to-venous. The increased $\dot{V}O_2$ is primarily due to increased Q, with little change in (a-v) O_2 diff. The two temporal components of the transient response in pulmonary gas exchange need the confounding influence of BxB noise eliminated (Lamarra *et al.*, 1987) or at least sufficiently minimised by averaging (Whipp *et al.*, 1982) for them to be clearly identified.

The primary response reflects an exponential rise in $\dot{V}O_2$ and achieves steady state in ~ 3 min (Obert *et al.*, 2000, Deley *et al.*, 2006). This exponential response is initiated by the arrival at the lungs of venous blood from the working muscles and represents augmented muscle O_2 utilisation (which is reflected in (a-v) O_2 diff.) and continued increase in pulmonary blood flow (Whipp, 1994). The time constant (~ 20 - 40 s) for this rise in $\dot{V}O_2$ (τ) is thought to be relatively invariant across the range of moderate intensity WRs (Hagberg *et al.*, 1980, Whipp and Ward, 1990). Although, recent evidence suggests it may be affected by exercise intensity even in this domain (Brittain *et al.*, 2001). Some studies have demonstrated that τ of the exponential function of $\dot{V}O_2$ kinetics is influenced by the level of aerobic performance (Chilibeck *et al.*, 1996). Other

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studies have shown that τ is sensitive to endurance training, with reduced τ as training progresses (Hagberg *et al.*, 1980, Phillips *et al.*, 1995). The notion that pulmonary $\dot{V}O_2$ in this response reflects closely the muscle $\dot{V}O_2$ (Grassi *et al.*, 1996) is supported by the modelling studies (Barstow *et al.*, 1990b) and also the temporal correspondence between $\dot{V}O_2$ changes and those of phosphocreatine breakdown within the working muscle (Rossiter *et al.*, 1999, Whipp *et al.*, 1999).

For moderate intensity exercise, a steady state in both $\dot{V}O_2$ and lactate will be attained within $\sim 2 - 3$ min (Burnley *et al.*, 2000, Koppo *et al.*, 2002). The $\dot{V}O_2$ increases linearly with WR and, therefore, $\dot{V}O_2$ -WR relationship is considered to be a dynamic linear one (Whipp and Wasserman, 1972, Whipp and Mahler, 1980, Whipp, 1987, Henson *et al.*, 1989). This linear dynamic $\dot{V}O_2$ -WR relationship is suggested from the finding that neither the slope of the $\dot{V}O_2$ increase, with respect to WR, nor the $\dot{V}O_2$ time constant ($\tau\dot{V}O_2$) have been found to be a function of WR (Whipp, 1987, Whipp and Ward, 1990, Barstow *et al.*, 1993).

The modelling of $\dot{V}O_2$ kinetics in this exercise intensity domain has been achieved in a number of ways, mainly as a mono exponential function. Since $\dot{V}O_2$ has been shown to behave exponentially following step changes in external WR (Henry and DeMoor, 1956, Whipp and Wasserman, 1972), the amplitude of the response can be expressed as a function of time (Linnarsson, 1974). The mean response time (MRT) represents the time required for the O_2 transport – O_2 utilisation system to reach 63% of the metabolic requirement (asymptote) in step WRs. Therefore, MRT is defined as δ and the τ of the exponential at 63% of the asymptote of the steady state response (Sietsema *et al.*, 1989).

The MRT can therefore be used for comparisons of the overall rate of change between responses (DiPrampero *et al.*, 1970, Cerretelli *et al.*, 1977).

Some investigators have used a monoexponential function, modelled from all data points and including no δ (Sietsema *et al.*, 1989). Others have recognised it is necessary to take account of this transit delay if pulmonary $\dot{V}O_2$ kinetics are to be used to estimate muscle $\dot{V}O_2$ kinetics and, therefore, treated this response as a pure delay (Whipp *et al.*, 1982, Barstow *et al.*, 1994). This recognition has led to a time delay being included, but the cardiodynamic response data points removed (Whipp and Mahler, 1980, Barstow, 1994), or simply to remove the first 20 s of data (Lamarra *et al.*, 1987, Gerbino *et al.*, 1996, Grassi *et al.*, 1996), this effectively time aligns the muscle and pulmonary responses (Krustrup *et al.*, 2004).

2.2.4 $\dot{V}O_2$ kinetics response to heavy intensity exercise

Where an individual is exercising at an intensity that is above their GET, the muscle and pulmonary $\dot{V}O_2$ kinetic response takes on an additional complexity with the delayed emergence of $\dot{V}O_2$ SC (to be discussed in further detail in section 2.3) which delays the attainment of steady state conditions (as seen in Figure 2.1) (Whipp and Wasserman, 1972, Barstow and Mole, 1991, Carter *et al.*, 2002). The characteristics of the on-transient $\dot{V}O_2$ kinetic response to heavy exercise take on a more complicated description than the simple monoexponential model (Whipp and Wasserman, 1970, Linnarsson, 1974, Barstow, 1994). The $\dot{V}O_2$ kinetic responses supra GET are described as a distortion of the sub GET response (Whipp, 1994, Scheuermann *et al.*, 2001). The

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dynamics of $\dot{V}O_2$ are, therefore, considered multifarious and elicit evidence of temporal and an amplitude non-linearity (Ozyener *et al.*, 2001, Wilkerson *et al.*, 2004).

The delayed onset of steady state caused by the slowly developing excess $\dot{V}O_2$, has led to it being termed the SC of $\dot{V}O_2$ (Poole *et al.*, 1994, Sloniger *et al.*, 1996, Billat *et al.*, 1998b). Evidence for the existence of a SC during heavy intensity cycle ergometry exercise has existed since the 1960's (Astrand and Saltin, 1961, Margaria *et al.*, 1963).

Since these findings, Whipp and associates in the 1970's, went on to formally identify the existence of a SC (Whipp and Wasserman, 1970, Whipp and Wasserman, 1972).

The SC of $\dot{V}O_2$ is delayed, but the period after onset of exercise has been measured as 80-100 s (Poole *et al.*, 1994), 90-150 s (Paterson and Whipp, 1991) or more definite 105 s (Barstow and Mole, 1991) and ~120 s (Whipp and Wasserman, 1972). This excess $\dot{V}O_2$ drives the overall $\dot{V}O_2$ requirement over and above that would be predicted from the $\dot{V}O_2$ -WR relationship (discussed further in section 2.4) (Whipp and Ward, 1990, Paterson and Whipp, 1991).

If the protocol used rapid incremental stages or a ramp then the $\dot{V}O_2$ -WR relationship was linear (Astrand and Rodahl, 2003, Wilmore and Costill, 2004). However, these protocols are not appropriate objectively for calculation of economy for endurance athletes. The appropriate protocol for calculating economy uses stages of long duration, which challenges the $\dot{V}O_2$ -WR relationship is linear. The $\dot{V}O_2$ -WR relationship is indeed linear at moderate intensity exercise (Gaesser and Poole, 1996). However, in the heavy intensity exercise domain the $\dot{V}O_2$ -WR relationship has been demonstrated to be non-linear for both cycling (Hansen *et al.*, 1988, Zoladz *et al.*, 1995, Zoladz *et al.*,

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1998b) and treadmill running (Jones *et al.*, 1999). This non-linearity of the relationship has obvious implications for calculating O₂ deficit (Bangsbo, 1996) and economy of movement (Whipp, 1994, Sherman and Jackson, 1998) in what is said to be the traditional manner, which relies on accurate measurement and the assumption of constant $\dot{V}O_2$ requirement.

Barstow *et al.* (1993) found the primary response to be linear even at heavy intensity WR, but the SC of delayed onset resulted in a deviation from linearity at intensities above GET. This non-linearity is often not recognised in incremental tests, as typically a fast ramp rate is used to bring an individual to exhaustion within approximately 10 min (Buchfuhrer *et al.*, 1983), which does not allow sufficient time for the SC to manifest (Davis *et al.*, 1982). A non-linear relationship has also been shown when using a slow incrementation rate (e.g. 15 W.min⁻¹ in cycling) that allows a SC to develop (Whipp and Mahler, 1980, Hansen *et al.*, 1988). The $\dot{V}O_2$ -WR relationship is then not only non-linear but also time dependent. Therefore, an incremental test with one minute stages is likely to produce a more linear relationship to one with five minute stages, where a SC would be manifest.

Research is equivocal as to whether primary response $\dot{V}O_2$ kinetics are slowed (displaying a longer τ), in heavy compared with moderate intensity exercise. This may be a reflection of a greater τ in the primary component, or an additional SC $\dot{V}O_2$ that will reach a delayed steady state at a level above that predicted from a sub GET $\dot{V}O_2$ -WR regression, or both (Paterson and Whipp, 1991). This additional requirement has been shown to slow the MRT (Sietsema *et al.*, 1989). When investigators have

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modelled the heavy intensity exercise $\dot{V}O_2$ response, determining the primary and SC separately; Barstow *et al.* (1993) showed the time constant in heavy intensity exercise was systematically slowed, but was not related to the primary $\dot{V}O_2$ kinetics but rather due to the additional SC. Patterson and Whipp (1991) found that the time constant increased with increasing exercise intensity whereas Barstow and Mole (1991) report no change. The two studies used slightly different mathematical models but both used a two-component model, with phase-1 regarded as a time delay. In the domain of heavy intensity exercise a second exponential term is used to describe the slow component. This term, which tends to a higher asymptote (GAIN2), has a separate time delay (δ_2) and time constant (τ_2) to describe the delayed onset. Whilst Barstow and Mole (1991) did not demonstrate the slowing of kinetics shown by Patterson and Whipp (1991), it is clear from their data that the highest WR resulted in the longest time constant. It may be that a small subject group ($n = 4$) and a large variability in this parameter prevented them from statistically demonstrating the same effect. Recently, Carter *et al.* (2002), using a three-component model, showed that the primary response τ was increased in the heavy compared to the moderate intensity domain but was invariant across all supra GET work rates (Barstow *et al.*, 1990a).

An exponential function has been widely used to describe the SC (Linnarsson, 1974, Camus *et al.*, 1988, Bearden and Moffatt, 2000). However, there is some controversy over whether the SC is an exponential or a linear function (Barstow and Mole, 1991, Paterson and Whipp, 1991). Some studies have modelled the SC rise as a linear function (Armon *et al.*, 1991), whilst others have simply expressed the magnitude of the SC as the difference between final $\dot{V}O_2$ and $\dot{V}O_2$ at three minutes (Billat *et al.*, 1999b,

Jones and McConnell, 1999). The criticism of this simple approach is that it underestimates the magnitude of the SC (Bearden and Moffatt, 2001b). Describing the $\dot{V}O_2$ response with a monoexponential model through the entire duration of exercise (Gerbino *et al.*, 1996) or reporting the MRT (MacDonald *et al.*, 1997) may be misleading if the aim is to establish primary $\dot{V}O_2$ response to heavy exercise.

Therefore, the $\dot{V}O_2$ response to heavy intensity exercise has certain apparent features: 1) the slowing of phase II time course (Paterson and Whipp, 1987); 2) an additional requirement (SC) of delayed onset (Linnarsson, 1974, Paterson and Whipp, 1987) which results in progressively increasing $\dot{V}O_2$, which has not convincingly been shown to be exponential; 3) the SC causes $\dot{V}O_2$ to increase to greater values than that predicted from the extrapolation of sub-GET WRs (Whipp, 1987, Poole *et al.*, 1988).

2.2.5 $\dot{V}O_2$ kinetics response to severe intensity exercise

A key assumption that exists surrounding the $\dot{V}O_2$ response to exercise in the severe intensity domain is that, at a constant WR, a SC will be present and of a greater magnitude than that seen in heavy intensity exercise (Billat *et al.*, 1998b, Hill and Stevens, 2001). The difference in the response, in this domain compared to heavy intensity domain, is that $\dot{V}O_2$ is unable to reach a steady state and instead continues to rise until $\dot{V}O_{2max}$ or exhaustion (Whipp, 1994, Hill *et al.*, 2003). Poole *et al.* (1988, 1990) proposed that, for any exercise intensity above critical power, the SC of $\dot{V}O_2$ will drive $\dot{V}O_2$ to $\dot{V}O_{2max}$ instead of to a delayed steady state. Given this assumption, it is apparent that a maximum steady state, in both blood lactate and $\dot{V}O_2$, would be the

logical lower limit for this exercise intensity domain (Poole *et al.*, 1988, Hill *et al.*, 2002). However, the terms fatigue threshold and critical speed or power has also been used to describe this same division of exercise intensity domains (Poole *et al.*, 1988, Billat *et al.*, 2000).

2.3 How O₂ utilisation and transportation effect the $\dot{V}O_2$ kinetic response

During moderate intensity exercise, the mechanism that limits the rate at which $\dot{V}O_2$ approaches the new steady state is still controversial and debated (Tschakovsky and Hughson, 1999). Investigations into muscle O₂ uptake have proposed two opposing mechanisms to be the rate limiting factor in oxidative phosphorylation; either adaptation of O₂ utilisation (cellular metabolic controllers (Barstow *et al.*, 1994) and/or enzyme activation (Hochachka and Matheson, 1992)) or O₂ transport (convection and diffusion) mechanisms (Hughson, 1984, Hughson, 1990).

The ability to sustain muscular exercise is dependent on the body's ability to transport oxygen from the mouth to be used as the terminal oxidant in the mitochondrial electron chain (Caputo *et al.*, 2003). To support an O₂ extrinsic transport limitation theory, it would be imperative, to illustrate that increasing O₂ delivery accelerated muscle O₂ uptake kinetics. The observation that $\dot{V}O_2$ kinetics are significantly slower in exercise-to-exercise compared to rest-to-exercise transitions has led to the proposal of O₂ transport limitation theory (Hughson and Morrissey, 1982, Hughson, 1990). Proponents of the O₂ extrinsic transport limitation theory have demonstrated that the rate of the rise in $\dot{V}O_2$ kinetics is slowed when muscle O₂ delivery is impaired by inspired hypoxia

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(Engelen *et al.*, 1996) or reduction of arterial O₂ content (Murphy *et al.*, 1989, Hughson and Kowalchuk, 1995); supine posture (Hughson *et al.*, 1993); β -adrenergic receptor blockade (Hughson, 1984); transition from prior exercise (Hughson and Morrissey, 1982) and diseases that impair cardiovascular dynamics and pulmonary function (Poole *et al.*, 2005). It is widely accepted that there are conditions under which O₂ transport can impact upon $\dot{V}O_2$ kinetics, however, controversy remains over the exact nature of these conditions (Tschakovsky and Hughson, 1999). Hughson and Morrissey (1982) investigated different exercise transitions to WRs strictly below GET and demonstrated the $\dot{V}O_2$ kinetics response. The $\dot{V}O_2$ kinetics were shown to be slower during the 40-80% GET transition than from rest to 80% GET transition. Thus, proposing that the slower $\dot{V}O_2$ kinetics in the 40 - 80% GET transition were the consequence of slower O₂-transport kinetics to the exercising muscles.

Proponents of the hypothesis that muscle $\dot{V}O_2$ kinetics is fundamentally determined by intrinsic metabolic inertia base their position on many observations. The most important is the demonstration that muscle O₂-delivery kinetics are appreciably faster than $\dot{V}O_2$ kinetics (Delp, 1999), and it is hard to envisage a faster process limiting a slower one. This means that cellular metabolic controllers (Barstow *et al.*, 1994) and mitochondrial enzyme activation (Hochachka and Matheson, 1992) are the sole determinants of the rate of oxidative phosphorylation. Whipp and Mahler (1980) found that during the onset from rest or light exercise, during phase II the $\dot{V}O_2$ kinetics were of a linear basis even if heart rate differed this suggested that O₂ utilisation must be the rate limiting factor (Yoshida *et al.*, 1995). By increasing O₂ delivery to the working muscle, by either breathing hyperoxic gas mixtures (Engelen *et al.*, 1996, MacDonald *et al.*, 1997) or by

increasing perfusion of blood to the working muscle (Grassi *et al.*, 1998a, Grassi *et al.*, 1998b, Grassi *et al.*, 2000) did not accelerate $\dot{V}O_2$ kinetics and a support for a phosphate-linked control of mitochondrial energetics (Rossiter *et al.*, 1999).

In summary, metabolic inertia and O_2 utilisation likely interact to determine the adaptation of muscle aerobic metabolism at exercise onset. This is important because the rate of increase in oxidative phosphorylation is limited by the adaptation of O_2 utilisation and/or O_2 utilisation mechanisms because it is the readjustment of oxidative phosphorylation that meets the new demand for ATP after a step increase in WR (Tschakovsky and Hughson, 1999).

2.4 The additional Slow Component during supra-threshold exercise intensity

The $\dot{V}O_2$ SC should not be confused with O_2 drift, which is, a phenomenon seen during prolonged duration moderate exercise (Kalis *et al.*, 1988, Coyle *et al.*, 1991b), or with the gradual rise in eccentric work (i.e. downhill running) (Klausen and Knuttgen, 1971). The continued increase in $\dot{V}O_2$ as time progresses both in the heavy exercise intensity domain (where $\dot{V}O_2$ will eventually stabilise at a higher than expected level), and in the severe exercise intensity domain (where it will not stabilise) is known as the $\dot{V}O_2$ slow component. The $\dot{V}O_2$ response becomes appreciably more complex, with both time- and amplitude-based non-linearities of response (Whipp, 1994).

For heavy intensity constant load exercise, the $\dot{V}O_2$ is characterised by an initial short delay of ~10-20s. Followed, by a rapid primary response whereby $\dot{V}O_2$ increases mono

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exponentially as a function of muscle oxygen uptake. Then a slowly developing component of $\dot{V}O_2$ kinetics emerges superimposed upon the rapid primary component of $\dot{V}O_2$ response at $\sim 80 - 120$ s after the onset of exercise (Barstow and Mole, 1991, Paterson and Whipp, 1991) and drives the $\dot{V}O_2$ to a delayed steady state that is above that predicted from the sub-GET $\dot{V}O_2$ -WR relationship (Hill *et al.*, 2003). There is uncertainty as to whether the primary component is slowed supra GET (Paterson and Whipp, 1991) or not (Barstow and Mole, 1991) or if the SC is the component slowing the response alone, with a separate delay and time constant (Whipp and Wasserman, 1972). The SC becomes apparent only if exercise duration is long enough to its emergence, e.g. > 3 min (Whipp and Wasserman, 1972). Therefore, the continued increase, beyond the 3rd minute, in $\dot{V}O_2$ as time progresses both in the heavy exercise intensity domain (where $\dot{V}O_2$ will eventually steady state although at a higher than expected level) and in the severe exercise intensity domain (where it will not steady state) is known as the $\dot{V}O_2$ slow component (Casaburi *et al.*, 1987, Barstow, 1994). Typically, the SC is expressed as the difference between the 6th min (or end-exercise) and 3rd min of exercise (Whipp and Wasserman, 1972). This simple approach has been criticised for underestimating the magnitude of the SC (Bearden and Moffatt, 2001b). The SC appears to develop most rapidly early in the exercise bout, i.e. 3-10 min (Casaburi *et al.*, 1987, Roston *et al.*, 1987, Poole *et al.*, 1988). The magnitude of this SC increases with WR for intensities supra GET.

To date the characteristics of the SC have eluded formal characterisation (Whipp and Wasserman, 1986, Barstow and Mole, 1991, Paterson and Whipp, 1991). Barstow and Mole (1991) found evidence for both exponential and linear SC behaviour, whereas

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Paterson and Whipp (1991) were unable to distinguish exponential and linear fits. What has been characterised is that the $\dot{V}O_2$ response is best described by a two component model, dealing with the SC as a separate component (Whipp and Wasserman, 1972).

The physiological mechanism(s) underlying the $\dot{V}O_2$ SC have yet to be clearly established (Scheuermann *et al.*, 2001). There are a number of factors postulated to contribute to the SC of $\dot{V}O_2$ observed during heavy intensity exercise. These include the effects of lactate (Casaburi *et al.*, 1989b, Barstow, 1994); epinephrine (Gaesser *et al.*, 1994, Womack *et al.*, 1995); cardiac and ventilatory work (Hagberg *et al.*, 1978, Womack *et al.*, 1995); temperature (Hagberg *et al.*, 1978, Poole *et al.*, 1991); potassium (Yoshida *et al.*, 1995); less efficient P-O coupling (Willis and Jackman, 1994); reduced chemical-mechanical coupling efficiency (Willis and Jackman, 1994) and recruitment of less efficient fast-twitch motor units (Coyle *et al.*, 1992, Horowitz *et al.*, 1994).

The primary origin of the $\dot{V}O_2$ SC appears to be the working muscles (Mole *et al.*, 1985, Poole *et al.*, 1991, Poole, 1994). Poole *et al.* (1991) demonstrated, by simultaneously measuring both pulmonary and muscular (e.g. leg) $\dot{V}O_2$ during cycle ergometry, that ~ 86 % of the increment in pulmonary $\dot{V}O_2$ beyond the 3rd min of exercise could be accounted for by the increase in muscle $\dot{V}O_2$. This indicates that the majority of the $\dot{V}O_2$ SC can be attributed to factors within the working muscles.

2.4.1 The relationship between blood lactate and slow component of $\dot{V}O_2$ kinetics

A compelling feature of the heavy intensity exercise domain is the tight coherence quantitatively and qualitatively of the temporal profiles of L_B and $\dot{V}O_2$. A close relationship has been demonstrated between the magnitude of the SC of $\dot{V}O_2$ kinetics and the increase in L_B accumulation (Casaburi *et al.*, 1987, Roston *et al.*, 1987, Whipp, 1987, Poole *et al.*, 1988, Whipp and Ward, 1990, Paterson and Whipp, 1991).

The increase in the SC of $\dot{V}O_2$ kinetics may be caused by metabolic acidosis; by increasing the oxygen supply (i.e. haemoglobin concentration), increasing the transportation to the working muscle and the promotion of aerobic metabolism (Stringer *et al.*, 1994). This concept has been doubted as a feasible explanation due to some of the underlying physiological implications. Another possible explanation has been suggested, that accumulation of intramuscular Hydrogen ions (H^+) may be responsible for the SC of $\dot{V}O_2$ kinetics by shifting the equilibrium of the creatine kinase reaction and generating free creatine concentration (Mahler, 1985, Capelli *et al.*, 1993). Furthermore, during the process of ATP hydrolysis free energy is reduced contributing to the increase in SC.

Another perhaps more plausible hypothesis is that it is not the lactate itself but the overall accompanying acidosis, mediated by the Bohr effect, that mediates the SC of $\dot{V}O_2$ (Wasserman *et al.*, 1991, Stringer *et al.*, 1994). Stringer *et al.* (1994) further suggested that increased O_2 delivery that has been induced by the onset of lactic acidosis can account for 62% of the SC of $\dot{V}O_2$. However, there is an argument that this

hypothesis does not sufficiently explain why during heavy intensity exercise the $\dot{V}O_2$ values obtained exceeds the predicted values from the $\dot{V}O_2$ -WR relationship (Whipp, 1994, Gaesser and Poole, 1996).

Despite the fact that the presence of the SC is always accompanied by an increased L_B concentration it stills remains contentious to what degree, if any, this increase modulates the SC (Zoladz and Korzeniewski, 2001).

2.4.2 The relationship between fibre type recruitment and slow component of $\dot{V}O_2$ kinetics

The human body skeletal muscular system exhibits two types of muscle fibres, exhibiting many different structural, histochemical and behavioural characteristics. The two muscle types are referred to as slow (type I) or fast (type II) twitch; this is due to the speed at which maximum tension can be achieved. It takes fast twitch fibres (FT) about 1/7 of the time slow twitch takes to achieve peak tension, this is due to higher concentration of myosin ATPase in FT. The FT fibres are further subdivided due to their affinity for aerobic capacity; i.e. type IIa and type IIx (Xu and Rhodes, 1999). The different characteristics of the fibre types are contraction speed, fatigability, ATPase, mitochondrial and glycolytic concentrations (Salmons and Vrbova, 1969).

The most popular conclusion is that $\dot{V}O_2$ SC arises from the exercising muscles during constant WR's. The appearance of the SC is mainly due to the recruitment of fast type II fibres, which have an 18% lower phosphate to oxygen ratio than type I fibres, this is

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thought to be due to a greater reliance on the α -glycerophosphate shuttle and not the malate-aspartate shuttle. Therefore, more oxygen is required to produce an equal level of ATP turnover and maintain the ability to sustain a given WR. Prolonged heavy intensity exercise causes the exercising limbs to generate ~86% of the pulmonary SC development (Poole *et al.*, 1991). Vollestad (1985) demonstrated that the recruitment of type IIb fibres increases in proportion to the exercise intensity. Barstow *et al.* (1996) characterised $\dot{V}O_2$ kinetics, during heavy incremental or constant exercise, as being a function of the % involvement of type I muscle fibres in the working muscles, i.e. the higher the % involvement the greater the initial rise in $\dot{V}O_2$. Pringle *et al.* (2003) found that the underlying muscle fibre distribution influenced the phase II rate of $\dot{V}O_2$, e.g. when there is a higher proportion of type I fibres present the $\dot{V}O_2$ on-kinetic response is faster (during heavy exercise) and more efficient. By depleting muscle fibre glycogen pool, there is a gain in the fast component and a reduction in the SC, which supports the motor unit recruitment pattern argument (Carter *et al.*, 2004).

Subjects with a high % of the low efficiency (type II) fibres are shown to have a high phosphate cost of force production, which in turn generates a greater $\dot{V}O_2$ SC (Rossiter *et al.*, 2001). A progression from one fibre type to the next is what incurs an additional increase in $\dot{V}O_2$, due to type II fibres being less efficient (Coyle *et al.*, 1992). The reasons for this were argued to be associated with early recruitment of type II fibres, more metabolic by-product accumulation and muscle membrane excitability which all lead to eventual neuromuscular fatigue. Therefore, an alternative explanation of the emergence of the SC has been demonstrated to be the fatigued muscle becoming less efficient due to the fatigue process itself (Poole *et al.*, 1991).

2.5 The effect of physical training status have on the SC of $\dot{V}O_2$ response

A reduction of the SC with training is highly desirable as this adaptation may allow longer periods of physical activity and increase work tolerance before fatigue.

Endurance training leads to cardiorespiratory adaptations such as; $\dot{V}O_{2max}$, economy of movement (Jones, 1998) and L_B responses to exercise (Davis *et al.*, 1979), accelerate the $\dot{V}O_2$ on-response at onset exercise (Hagberg *et al.*, 1980), to decrease the $\dot{V}O_2$ SC at a given WR (Casaburi *et al.*, 1987, Womack *et al.*, 1995). The decrease in SC amplitude is thought mainly to be due to increasing type I fibre distribution and increasing capillary and mitochondrial density (Holloszy and Coyle, 1984). The $\dot{V}O_2$ on-kinetics in a highly-trained athlete have been shown to be much faster than in a poorly trained individual (Whipp and Wasserman, 1972). The faster $\dot{V}O_2$ kinetics at the onset of heavy intensity exercise is important because it results in a faster attainment of steady state $\dot{V}O_2$ and reduces the O_2 deficit and limits L_B accumulation (Hochachka and Matheson, 1992).

An endurance training program was shown to remove the SC for the same absolute WR; this was due to the fact that the athletes had improved $v\dot{V}O_{2max}$ and, therefore, the same absolute velocity was now a lower % of $v\dot{V}O_{2max}$ (Billat *et al.*, 1999a), and had therefore become more economical. For subjects of varying aerobic power, the point of LT and its equivalent $\dot{V}O_2$ value may vary by as much as 35-80% of $\dot{V}O_{2peak}$. The SC of $\dot{V}O_2$ is attenuated rapidly in response to endurance training, ~50% decrease (magnitude ~220 ml.min⁻¹) after only two weeks training, with no further reduction after that; this suggests that any adaptation in the SC of $\dot{V}O_2$ occurs very early in a training program

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(Womack *et al.*, 1995). Where subjects had relatively high $\dot{V}O_{2\text{peak}}$, it was found that six weeks of endurance training caused an attenuation of the SC in running by ~35% or magnitude of $96 \text{ ml}\cdot\text{min}^{-1}$ (Carter *et al.*, 2000a). Carter *et al.* (2000) went on to explain this finding as an improvement in exercise tolerance; subjects were producing the same magnitude of SC but at greater WR than before, this was explained by the associated reduced recruitment of the less efficient type II fibres for the same absolute running speed post training.

If the balance of O_2 demand and availability plays a central role in hypoxic conditions, it can be assumed that the $\dot{V}O_2$ -WR relationship slope would be higher after training. Therefore, in normoxia endurance training would decrease the O_2 requirement at heavy intensity, which would induce, a decrease in the $\dot{V}O_2$ SC. Endurance training was found to induce a lowering of the slope of $\dot{V}O_2$ -WR relationship above the LT, which was said to be due to the peripheral adaptations such as alteration in muscle fibre type recruitment (Prieur *et al.*, 2005).

The importance of the above knowledge is that it determines how to train to limit $\dot{V}O_2$ SC and at the same time improving economy of movement, which should lead to improved performance. Athletes are most economical at WRs at which they habitually train. Since economy of movement is only of practical importance at the intended race pace, training should be at that pace to gain optimal benefits (Jones and Carter, 2000). Therefore, the measurement of economy must be at race pace to gain a true indication of $\dot{V}O_2$ requirement and to determine the effectiveness of the training intervention.

2.6 Factors affecting SC and $\dot{V}O_2$ kinetics

2.6.1 Mode of exercise

It is surprising that very few studies have examined the $\dot{V}O_2$ kinetics in any other mode of exercise than cycling, due to the interest in the $\dot{V}O_2$ SC. The SC is present in a range of exercise modalities; e.g. cycling (Hagberg *et al.*, 1980, Henson *et al.*, 1989, Casaburi *et al.*, 1992) and running (Nagle *et al.*, 1970, Costill *et al.*, 1971) and arm cranking (Cerretelli *et al.*, 1977, Casaburi *et al.*, 1992). The amplitude of the SC has consistently been reported to be exercise mode dependent (Demarle *et al.*, 2008) (discussed further in section 2.3.2.1). Although, it is worth noting that in comparison to cycling exercise of equivalent intensity, the amplitude of the SC found in running was somewhat smaller. Depending on the mode of exercise performed, when exercising at an absolute intensity, there is a significantly different effect of the $\dot{V}O_2$ kinetic response to heavy intensity exercise and the magnitude of the SC (Billat *et al.*, 1998b).

Pulmonary oxygen uptake has been described, during a step WR, for a variety of modes of exercise including arm cranking (Casaburi *et al.*, 1992, Koga *et al.*, 1996); leg extension (MacDonald *et al.*, 1998, Koga *et al.*, 2005); swimming (Demarle *et al.*, 2001); running (Jones and McConnell, 1999, Carter *et al.*, 2000b, Carter *et al.*, 2002); and cycling (Linnarsson, 1974, Barstow and Mole, 1991, Ozyener *et al.*, 2001). Differences in observed $\dot{V}O_2$ kinetics appear to be in some way caused by differences in muscle contraction recruitment between these exercises (Perrey *et al.*, 2001).

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Pedal frequency may also influence the magnitude of the SC as elite riders tend to opt for very high pedal frequencies in order to minimise type II motor unit contribution (Paterson and Moreno, 1990, Barstow *et al.*, 1996). However, when the internal work O_2 cost was taken into account, the magnitude of the SC was unchanged, either absolutely or as a proportion of the overall $\dot{V}O_2$ response for any pedal frequency between 45 - 90 $\text{rev}\cdot\text{min}^{-1}$ (Barstow *et al.*, 1996). This study set a constant 80 $\text{rev}\cdot\text{min}^{-1}$ for all tests and encouraged the subjects not to excessively grip or rock and roll torso, based on Barstow *et al.* (1996) findings.

In comparison to leg exercise, arm exercise demonstrates a slower time constant of the primary component of $\dot{V}O_2$ kinetics (Cerretelli *et al.*, 1977, Casaburi *et al.*, 1992, Koga *et al.*, 1996). It was proposed that, in general, upper body muscles are less trained and are of smaller muscle mass. Another difference between the arm and leg exercise is the significantly higher fast component gain in arm ($\sim 12.0 \text{ ml}\cdot\text{min}^{-1}\cdot\text{W}^{-1}$) compared to leg ($\sim 9.2 \text{ ml}\cdot\text{min}^{-1}\cdot\text{W}^{-1}$) exercise (Koppo *et al.*, 2002). In absolute terms, the amplitude of the $\dot{V}O_2$ SC is greater during cycling compared to arm cranking but similar in relative terms. The differences were noted by the later emergence of the SC and a longer fast component time constant in arm cranking (Koppo *et al.*, 2002). Poole and Richardson (1997) suggest that the recruitment of auxiliary muscles, i.e. hands, arms, shoulders and back, generates additional metabolic requirements which, therefore, play a role in SC development and magnitude. The additional $\dot{V}O_2$ response (SC), above GET, can be $>25\%$ of the final $\dot{V}O_2$ requirement (Koppo *et al.*, 2002).

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When compared to cycle ergometry during moderate and heavy intensity exercise, knee extension work, exhibited a significantly higher gain of the primary component of pulmonary $\dot{V}O_2$, but no fundamental difference in the time constant; a greater SC contribution; and a greater MRT (Koga *et al.*, 2005).

Rowing involves more upper and lower body exercise than running. Rowing has an optimal muscle recruitment alternation strategy; where continuous rowing starts with all involved muscles, but then later switches between back and quadriceps. The amplitude of SC was found to be higher for rowing than for exercise using either arms or legs. The proportion of the SC caused by engaged auxiliary muscles is much higher than the one generated by the primarily engaged muscles (Demarle *et al.*, 2008). Progressive exercise oxygen consumption, HR and L_B were all similar between cycling and rowing (Barfield *et al.*, 2003).

There are many biomechanical differences between cycling and running that may account for the differences in the amplitude of the SC; one of which is the mechanical efficiency. Cycling (20 - 25%) is shown to be much less mechanically efficient than running (45 - 70%) (Whipp and Wasserman, 1969). The fact that cycling produces a more pronounced SC is thought to be explained by the muscle contraction regimen and process this plays in the phosphocreatine dephosphorylation (Billat *et al.*, 1999b). Jones and McConnell (1999) reported that $\dot{V}O_2$, at 50% Δ , the difference between $\dot{V}O_2$ requirement at GET and $\dot{V}O_{2max}$ is termed delta (Δ), increased significantly more in cycling ($\sim 290 \text{ ml}\cdot\text{min}^{-1}$) compared to running ($200 \text{ ml}\cdot\text{min}^{-1}$). Carter *et al.* (2000)

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showed that $\dot{V}O_2$ kinetics is, on the whole, similar between cycling and running, the main difference is the amplitude of the SC and primary component.

There are significant differences in the $\dot{V}O_2$ response between the two exercise modes. During moderate and heavy intensity exercise the $\dot{V}O_2$ response has been demonstrated to be very similar between cycling and running. However, the amplitude of the overall $\dot{V}O_2$ response is significantly greater in running than cycling. Also, cycling has been shown to demonstrate significantly higher SC amplitude than running. Jones and McConnell (1999) found that treadmill running does indeed exhibit a $\dot{V}O_2$ SC. The fact that the SC amplitude is smaller in running than cycling at an equivalent work intensity, is apparent in both absolute terms and as a proportion of the overall $\dot{V}O_2$ response; cycling (~15-17%) compared with running (~7-10%). This fact may have a different effect on the accuracy of the three different methods in the calculation of economy of movement between exercise modes. Carter (2000) showed that mode of exercise had a significant effect on the magnitude of the SC discernible. Due to the magnitude of SC and its effect on the $\dot{V}O_2$ -WR relationship regression for predictions higher in the WR regression relationship, cycling ($334 \pm 68.9 \text{ ml}\cdot\text{min}^{-1}$) has been found to generate a larger SC than running ($204.8 \pm 31.9 \text{ ml}\cdot\text{min}^{-1}$). Therefore, any study investigating the impact of the SC needs to use cycling because of the greater SC and, therefore, its effect (Jones and Doust, 1996). Cycling also allows a greater range of WR intensities from within the moderate intensity domain, without changing the biomechanics to walking.

2.6.2 The effect prior exercise has on the amplitude of the SC and therefore the $\dot{V}O_2$ response

Many studies have investigated using a priming exercise intervention to identify any limitations to the rate which muscle and pulmonary $\dot{V}O_2$ increase (Barstow *et al.*, 1990b), when heavy intensity exercise is performed (Burnley *et al.*, 2000, Burnley *et al.*, 2002). Performance of prior moderate intensity exercise does not alter $\dot{V}O_2$ or L_B and appears not to enhance performance in heavy intensity exercise (Gerbino *et al.*, 1996, Burnley *et al.*, 2000). Also, prior heavy intensity exercise has been shown not to have an effect on moderate intensity exercise performance (Gerbino *et al.*, 1996). The effects of prior exercise priming can still be observed 30 - 45 min later but has returned to an original profile after 60 minutes (Burnley *et al.*, 2006).

The effect of prior exercise significantly changes the metabolic and gas exchange responses to subsequent exercise. The initial performance of heavy intensity exercise, but not moderate intensity exercise, quickened overall $\dot{V}O_2$ kinetics during subsequent heavy intensity exercise (Gerbino *et al.*, 1996), resulting in a reduction of the amplitude of the SC, but the time constant did not change (Bearden and Moffatt, 2001a, Koppo and Bouckaert, 2001, Scheuermann *et al.*, 2001). Many investigations have focused on the potential of prior exercise to enhance subsequent performance (Jones *et al.*, 2003b, Raymer *et al.*, 2007), due to the possibility of it reducing exercise O_2 requirement. The change in metabolic and gas exchange responses to subsequent exercise, is thought to be for many reasons; ATP turnover is performed at a higher % by aerobic contribution, increased blood flow and oxygen extraction by the muscle, a sparing of phosphocreatine

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and reduce lactic acid production (Jones *et al.*, 2003a). As both the primary and SC amplitudes of $\dot{V}O_2$ response to heavy exercise are shown to be related to muscle fibre type recruitment, it is suggested that performance of a priming heavy intensity exercise changes the muscle metabolic factors which in turn changes the muscle fibre recruitment order (Burnley *et al.*, 2002).

The performance of heavy intensity exercise preceded by heavy intensity exercise results in a reduction in amplitude of SC and a net speeding of the overall $\dot{V}O_2$ on-kinetics which is seen as a reduction in MRT (MacDonald *et al.*, 1997). Using a mathematical model that could discriminate between the primary and SC $\dot{V}O_2$ response illustrated no evidence that the phase II $\dot{V}O_2$ response could be increased by heavy intensity exercise priming (Burnley *et al.*, 2000). The apparent acceleration of overall response does not come from the acceleration of the primary response but from the reduction in the amplitude of the SC (Burnley *et al.*, 2000, Bearden and Moffatt, 2001b).

Subject position, i.e. supine or upright has been shown to affect the benefits of priming before heavy exercise. For upright cycling, the amplitude of the SC is significantly reduced, but there was no significant change in the Phase II time constant (Burnley *et al.*, 2000, Bearden and Moffatt, 2001a, Koppo and Bouckaert, 2001, Burnley *et al.*, 2002, Perrey *et al.*, 2003). However, in the supine position priming incurred a significant time constant reduction in Phase II and had no effect on the amplitude of the SC. The lower muscle perfusion pressure and muscle vasodilation in supine exercise may have created an O_2 limitation such that O_2 delivery had been occluded.

There is evidence that increased O₂ delivery occurs in the working muscles, in secondary exercise bout; this is indicated by elevated baseline $\dot{V}O_2$, HR, total haemoglobin, oxyhemoglobin saturation and reduced O₂ pulse (Burnley *et al.*, 2002). The mechanism of the effect of prior exercise priming has also been suggested to be O₂ transportation (Hughson and Morrissey, 1982). Recent advancements in technology have allowed the use of magnetic resonance spectrometry, which has demonstrated a significant (9%) sparing of intramuscular phosphocreatine during heavy intensity exercise when it has been preceded with heavy intensity exercise (Rossiter *et al.*, 2001), however, preceding with moderate intensity exercise has no significant affect.

2.7 The importance of the $\dot{V}O_2$ -WR relationship and the debate over linearity or non-linearity across the full range of WR's

The $\dot{V}O_2$ -WR relationship depicted during incremental or constant load exercise tests have been the physiological variable most frequently used to describe exercise tolerance in humans (Zoladz *et al.*, 1998a). The $\dot{V}O_2$ response is stated to increase linearly with WR and, therefore, $\dot{V}O_2$ -WR relationship is considered to be of dynamic linear characteristics (Whipp and Wasserman, 1972, Whipp and Mahler, 1980, Whipp, 1987, Henson *et al.*, 1989). The characteristics of the $\dot{V}O_2$ -WR relationship, during moderate exercise, can be described as having an invariant time constant and having proportional amplitude for a given increase in WR (Barstow and Mole, 1991, Barstow *et al.*, 1993). A linear $\dot{V}O_2$ -WR relationship is often reported for all WRs until $\dot{V}O_{2max}$ (Medbo *et al.*, 1988) and stated by authoritative texts (Astrand and Rodahl, 2003, Wilmore and Costill, 2004).

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There are major underpinning assumptions involved in the use of this linear $\dot{V}O_2$ -WR relationship to predict exercise tolerance in humans. Firstly, that there is a linearity of the $\dot{V}O_2$ -WR relationship evaluated for the full range of submaximal WRs (Margaria *et al.*, 1963, Di Prampero, 1986). Secondly, that a steady state $\dot{V}O_2$ is achieved during sub- and supra-GET WRs in the first four min (Daniels *et al.*, 1977, Morgan *et al.*, 1989). This linear relationship has been used to estimate $\dot{V}O_{2max}$ (Green and Dawson, 1993, Marles *et al.*, 2006), calculation of O_2 deficit (Medbo *et al.*, 1988), velocity at $\dot{V}O_{2max}$ (Daniels *et al.*, 1977) and economy of movement (Foster and Lucia, 2007).

Marles (2006) used linear regression to calculate the slope and the intercept of the $\dot{V}O_2$ -WR relationship for each subject and used the data recorded sub VT to extrapolate up to the maximum power output achieved to attain their $\dot{V}O_{2max}$. The relationship was calculated from plots starting at 35W and increasing by 35W every two minutes with four plots used overall, with a linear regression calculated, e.g. $y = 9.8257x + 608.5$ and predicted absolute $\dot{V}O_{2max}$ of $3.016 \text{ L}\cdot\text{min}^{-1}$. This can be criticised on the bases that sufficient duration at each stage has not allowed for certain, a steady state $\dot{V}O_2$ to be attained, or the emergence of the SC and, therefore, it can be argued is it a true estimation of $\dot{V}O_{2max}$.

Medbo *et al.* (1988) stated that 10 x 10 min duration bouts with a range of 35 - 100 % $\dot{V}O_{2max}$ to construct a precise linear $\dot{V}O_2$ -WR relationship and concluded that the linear extrapolation of the O_2 requirement is justified even for the highest intensities. This conclusion was based on four arguments that supported the assumptions that O_2 demand is constant throughout and linear $\dot{V}O_2$ -WR relationship holds true to enable

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extrapolation. Firstly, for exercise below $\dot{V}O_{2max}$, anaerobic ATP formation is of little significance in energy provision (Margaria *et al.*, 1963); secondly, at higher speeds economy of movement probably does not improve (Cavanagh and Kram, 1985); thirdly, the reduced $\dot{V}O_{2max}$ in hypoxia did not affect the O_2 deficit accumulation (Dill and Adams, 1971); fourthly, a levelling off in the $\dot{V}O_2$ was seen in all subjects (Hagberg *et al.*, 1978). Di Prampero (1986) states that the linear relationship features stability in economy of movement independently of any increase in WR within the range of 50-80% $\dot{V}O_{2max}$.

Bangsbo (1990) criticised Medbo's work (1988) on numerous accounts; firstly, the difficulty in justifying the use of a linear $\dot{V}O_2$ -WR relationship when measurements below GET are independent and those above GET are dependent on sampling time; secondly, lack of explanation of criteria for excluding those values that deviated from the linear regression; thirdly, not using elite trained runners. Therefore, the main contention was based upon the methodology employed in the investigation and not necessarily the underlying physiology. Hansen (1988) explained that the fast increments of 35 W used by Medbo *et al.* (1988) would have lowered the slope of the $\dot{V}O_2$ -WR relationship. Henson (1989) suggested that if their study had also neglected to include the sub-GET data and any data that expressly deviated from a linear outcome, then they too would have found a linear $\dot{V}O_2$ -WR relationship albeit with a steeper slope.

Investigation of the effect pedalling frequency has on $\dot{V}O_2$ kinetics and, therefore, on the establishment of the linear $\dot{V}O_2$ -WR relationship (Zoladz *et al.*, 1998b, Pringle *et al.*, 2003). Zoladz (1998b) found a gradual insignificant increase in $\dot{V}O_2$ when the

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pedalling frequency was increased from 60 to 100 rpm but a significant increase in $\dot{V}O_2$ when the pedalling frequency further augmented to 120 rpm. Pedalling frequency was also shown to have an effect on $\dot{V}O_2$ SC (Pringle *et al.*, 2003), they found when pedalling frequency increased from 35 to 115 rpm the amplitude of the $\dot{V}O_2$ SC significantly increased, this was probably due to the change in motor unit recruitment patterns. This adds weight to the importance of using a fixed pedalling frequency throughout the exercise test, in the range of 60-100 rpm, when determining the use of a linear $\dot{V}O_2$ -WR relationship (Noordhof *et al.*, 2010).

Being able to express $\dot{V}O_2$ related to a particular WR provides a useful way of comparing individuals and/or building an aerobic profile of an individual, which gives a measure of economy. Green and Dawson (1993) doubted the validity of using the $\dot{V}O_2$ -WR relationship for the prediction of economy. So a comparison of the linear $\dot{V}O_2$ -WR relationship based on exercise intensities sub GET were made with those based on exercise intensities supra GET, finding that supra GET yielded a 14% greater slope (for cyclists) than sub GET slope. Therefore, concluding that the $\dot{V}O_2$ -WR relationship was non-linear along the entire range and the degree of non-linearity increased with increasing subject aerobic power. This information lead them to believe that there may exist two linear slopes one sub and one supra GET.

There is wide assumption that a linear $\dot{V}O_2$ -WR relationship exists despite substantial contrary evidence (Whipp and Wasserman, 1972, Henson *et al.*, 1989, Poole *et al.*, 1994, Zoladz *et al.*, 1995, Zoladz *et al.*, 1998a). The reason for the reluctance to accept the presence of the SC is due to the fact that it undermines some of the fundamental

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concepts in exercise physiology, e.g. steady state, O_2 deficit and economy of movement (Smith *et al.*, 2006). It is difficult to understand why a constant and linear relationship should be expected between $\dot{V}O_2$ and WR during incremental exercise tests where WR performed supra GET because a SC in $\dot{V}O_2$ kinetics emerges (Hansen *et al.*, 1988, Zoladz *et al.*, 1995, Zoladz and Korzeniewski, 2001). The SC superimposed on the primary response elevates the $\dot{V}O_2$ kinetics above that expected from the linear relationship estimated steady state requirement (Whipp and Wasserman, 1972, Casaburi *et al.*, 1987, Whipp, 1987, Whipp, 1994, Zoladz *et al.*, 1995, Wilkerson *et al.*, 2004).

However, the primary and SC have been demonstrated to be independent of each other, and the amplitude of the primary response remains linear throughout the entire range of submaximal WRs. The divergence away from linearity is solely due to the emergence of the SC, which adds a $\dot{V}O_2$ requirement which steepens the slope after GET (Barstow and Mole, 1991). There are a number of reasons why the non-linearity of the $\dot{V}O_2$ -WR relationship has not been recognised and the most important are related to the type of protocol used; these often give very few data points at heavy intensities, so that it is not easy to identify or test for non-linearity and any isolated data points which deviate from linearity may be dismissed either as experimental noise or the consequence of disproportionate increase in ventilatory, cardiac or postural costs (Zoladz *et al.*, 1995).

The $\dot{V}O_2$ SC is particularly interesting to exercise physiologists because it indicates that the efficiency with which the body uses oxygen to produce energy is progressively lost while exercise continues at exactly the same speed. When the ramp incrementation rate is slow, a delayed onset SC becomes evident as an additional or excess $\dot{V}O_2$ creating an

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upward concavity in the $\dot{V}O_2$ -WR relationship, generating $\dot{V}O_2$ values greater than those predicted from the extrapolation of sub-GET data plots (Whipp and Mahler, 1980, Roston *et al.*, 1987, Whipp, 1987, Hansen *et al.*, 1988). The duration of each exercise intensity interval is important because short intervals (e.g. <2 min) at each WR preclude the development and/or detection of the $\dot{V}O_2$ SC (Poole and Richardson, 1997). This additional $\dot{V}O_2$ takes the overall $\dot{V}O_2$ requirement for given work rate (i.e. $\dot{V}O_2/W$) substantially above the 9-11 ml.min⁻¹.WR illustrated in moderate intensity exercise. The first step to understanding $\dot{V}O_2$ kinetics during heavy intensity exercise would be to recognise that the $\dot{V}O_2$ -WR relationship is non-linear (Hansen *et al.*, 1988). Zoladz *et al.* (1995) highlighted that a non-linear relationship between $\dot{V}O_2$ and WR, in incremental tests, had been documented previously (Whipp *et al.*, 1986, Hansen *et al.*, 1988), but the significance and underlying mechanisms of these observations has not been widely recognised or systematically investigated.

Failure to consider the SC facet of the $\dot{V}O_2$ response may confound the interpretation of metabolic studies (Henson *et al.*, 1989). The finding that the most precise estimation of total $\dot{V}O_2$ requirement over the entire submaximal range is to actually measure sub and supra GET WR to determine $\dot{V}O_2$ (Aisbett and LeRossignol, 2003). There is some debate as to the form of this non linearity. Firstly, suggestions that there are two linear slopes one sub GET and a steeper one supra GET (Hansen *et al.*, 1988, Barstow and Mole, 1991, Zoladz *et al.*, 1998c). Others have suggested the $\dot{V}O_2$ -WR relationship due to the SC will depict an upward concave (Whipp and Wasserman, 1972, Whipp *et al.*, 1982, Whipp, 1987) and actually described as curvilinear (Lacour *et al.*, 1991, Bangsbo, 1996, Zoladz *et al.*, 1998a). The curvilinear relationship suggests a less steep slope

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below GET and a steeper slope at WR's above GET, and lactic acid is thought to play a dominant role in this break from linearity due to its occurrence around LT (Henson *et al.*, 1989).

The energy requirement during supra-GET exercise is underestimated by the use of the extrapolation of the $\dot{V}O_2$ -WR relationship from sub-GET measured data plots due to this superimposed SC (Bangsbo, 1996, Bosquet *et al.*, 2008). Exercise in the supra GET domain has this superimposed additional $\dot{V}O_2$ requirement that causes an underestimation by the linear regression and also indicates a reduction in economy, which can be detrimental to exercise that lasts longer than 4 min (Gonzales and Scheuermann, 2008). Acknowledgement of the SC presence challenges our understanding of muscle energetics and exposes serious flaws in the calculation of O_2 deficit and economy (Poole and Richardson, 1997, Smith *et al.*, 2006). In the case of endurance athletes who perform at the edge of their limits of exercise tolerance, an increase in $\dot{V}O_2$ requirement may cause early fatigue (Zoladz and Korzeniewski, 2001).

The existence of $\dot{V}O_2$ SC during any bout of exercise has major implications for the description and assessment of exercise and for the computation of O_2 deficit and economy (Jones and Burnley, 2009). It is reasonable to expect training adaptations, which would reduce, the amplitude of the SC and, therefore, reduce the underestimation by extrapolation from sub-GET WR (Prieur *et al.*, 2005). The identification and measurement of the effectiveness of factors that can alter economy is the key to elite sport (Roston *et al.*, 1987). Endurance training moves the GET to a higher % of $\dot{V}O_{2max}$ increasing the range of WR that the $\dot{V}O_2$ -WR relationship is linear (Poole *et al.*, 1994).

Knowledge of an accurately predicted or measured economy of movement is needed to enable training interventions to be followed to enhance sports performance and/or to measure the success of a training intervention on sport performance (Jones and Burnley, 2009). The change from moderate to heavy intensity exercise is thought to change the $\dot{V}O_2$ -WR relationship due to the hierarchal recruitment of different muscle fibre types with lower mechanical efficiency (Zoladz *et al.*, 1995). Therefore endurance training promotes adaptation to type I muscle fibres which are determined to be the most economical and non-fatigable.

2.8 The different methods of calculating economy of movement

The search for a standard approach to quantifying economy of movement is still an important aim. If there was such a thing, this would allow for comparisons between participants to be made in a direct and accurate manner. However, there is no such universally agreed standard approach to calculate economy. The British Association of Sport and Exercise (BASES) recommends that four exercise speeds are carried out for four min stages at speeds equivalent to 50-90 % $\dot{V}O_{2max}$ and state this is common practice when $\dot{V}O_{2max}$ is known. There are fundamental problems with this approach. The main issue is that setting WR's based on a percentage of $\dot{V}O_{2max}$ alone, ignores any exercise intensity differences between individuals due to differences in GET and $\dot{V}O_{2max}$ $\dot{V}O_2$ values. This means that if GET is a high percentage of an individuals' $\dot{V}O_{2max}$ then only the final WR of 90 % $\dot{V}O_{2max}$ would be in the heavy intensity domain. Whereas, an athlete with a GET that is a low percentage of an individuals' $\dot{V}O_{2max}$ then it is possible that all WR's would be in the heavy intensity domain. As exercise

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intensity has an effect on the $\dot{V}O_2$ kinetic response, and importantly as to whether the response is linear or not then WR intensity must be made uniform for comparisons to be valid. Where % $\dot{V}O_{2max}$ has been used to determine a fixed WR to measure economy then the issue is what WR appropriately replicates the intensity that each athlete train at or even compete at. Therefore, the selected WR's are often unrealistic, especially for any comparison because not all athletes compete at the same WR intensity. Also, making comparisons between athletes at an absolute WR potentially ignores any differences that might occur because of differences in relative intensity or GET. A variance of as much as 50 % has been reported between individuals in the absolute oxygen requirement from a Fixed WR based on % $\dot{V}O_{2max}$ (Coyle *et al.*, 1988). However, many studies have still used % $\dot{V}O_{2max}$ to identify the exercise intensity, 75% $\dot{V}O_{2peak}$ (Sherman and Jackson, 1998); 85% $\dot{V}O_{2max}$ (Franch *et al.*, 1998) and 50-90 % $\dot{V}O_{2peak}$ (Coyle, 2005).

Therefore, there are many conceptual issues with the use of % $\dot{V}O_{2max}$ to determine exercise intensity. The widely used way of quantifying exercise intensity is to use the difference between $\dot{V}O_2$ at GET and $\dot{V}O_{2max}$ (Koga *et al.*, 1997, Bearden and Moffatt, 2000). This difference is usually referred to as Δ (Burnley *et al.*, 2000, Carter *et al.*, 2000a, Jones *et al.*, 2006). For example, an individual with power output of 300W at $\dot{V}O_{2max}$ and 100W at GET; 50% Δ would be at an associated power output of 200W. This enables the exercise intensity to be better determined on an individual basis and also, enables comparison between the individuals.

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The data, identification and markers used to determine the threshold point is not universal either and can lead to differences in the determination of the threshold point on the same data set, leading to confusion and misinterpretation.

The determination of LT using lactate has been shown to have as much variation as 13% (79-92% $\dot{V}O_{2max}$) on the same data (Bassett and Howley, 2000). Coyle *et al.*, (1988) looked at 14 trained cyclists, homogeneous for $\dot{V}O_{2max}$, to examine the relationship between the LT and time to fatigue at 88% $\dot{V}O_{2max}$ intensity. The subject group that had high-LT (81.5% $\dot{V}O_{2max}$) were able to distribute the same WR, over a larger muscle mass than low-LT (65.8% $\dot{V}O_{2max}$), therefore, proportioning less load on the muscle fibres recruited to do the work. The results showed vast differences in performance (60.8 vs. 29.1 min) and lactate concentrations post-exercise (7.4 vs. 14.7 mmol.L⁻¹) respectively, demonstrating an ability of the high-LT group to cycle faster and longer. The fact that most research on economy utilises $\dot{V}O_2$ raw data to determine VT or GET, which is possible because the respiratory response has been shown to closely follow the profile response of lactate (Beaver *et al.*, 1986). The issue here is that VT has been identified predominately on visual inspection of the data plots and verified by second and third examinations. This can lead to considerable variation in VT point identified as it can come down to individual interpretation of inflection points in the data. The use of GET is an improvement because the threshold is finally determined by plotting $\dot{V}CO_2$ against $\dot{V}O_2$. The problem here is that protocol and terminology have become confused here, and the wrong term is used for the protocol actually used to determine the threshold plot.

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Despite the fact that $\dot{V}O_2$ -WR relationship obtained from incremental or constant load exercise tests are the most often applied criterion of human exercise tolerance, it seems surprising how little attention has been paid to the additional, non-linear increase, described as either two linear regression lines with GET as the inflection point or a curvilinear response, in $\dot{V}O_2$ occurring during supra-GET intensities. As competitive athletes often display a homogeneous fitness profile, it is suggested that economy of movement would be the best indicator of performance. The additional SC $\dot{V}O_2$ response to the primary response adds to the so called standard approach for calculating economy of movement, which leads to underestimation of the overall $\dot{V}O_2$ requirement.

Key exercise physiology textbooks have been reluctant to acknowledge the very existence of this $\dot{V}O_2$ SC (Astrand and Rodahl, 2003, Wilmore and Costill, 2004). In part, this is understandable because the SC challenges some of the fundamental concepts in exercise physiology including the notion of steady state $\dot{V}O_2$, O_2 deficit, economy of movement and the control of muscle energetics. The determinants of exercise tolerance and the limitations to sports performance can therefore be better understood through an appreciation of the physiological significance of the fast and slow components of the dynamic $\dot{V}O_2$ response to exercise (Burnley and Jones, 2007). Any reduction in economy of movement is detrimental to sports performance, for any sport involving muscular work with a duration of greater than 30s and therefore it is important any factors which alter the O_2 requirement are identified (Gonzales and Scheuermann, 2008). The main consequence of the flaw in the assumption that the relationship between $\dot{V}O_2$ and WR is linear is the difficulty to accurately estimate O_2 requirement at supra GET intensities. This explains why an increased $\dot{V}O_2$ for work at

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intensities supra GET has important implications for exercise performance in endurance events and the limited exercise tolerance of patients with cardiorespiratory disease (Zoladz and Korzeniewski, 2001). One of the important implications is that if $\dot{V}O_2$ is increasing then the economy of movement decreases as a function of time (Poole *et al.*, 1991). Many protocols have been utilised to stop the emergence of the SC and to ensure that the linear $\dot{V}O_2$ -WR relationship is attained. These protocols have limited the stage duration to inhibit the emergence of SC; have used limited number of data plots to base the regression on; fast incremental stages (Hansen *et al.*, 1988); and, most alarmingly have removed any data plots that deviate from the linear $\dot{V}O_2$ -WR relationship (Medbo *et al.*, 1988), without justification other than does not fit the linear relationship (Bangsbo *et al.*, 1990). Hansen *et al.* (1988) stated that if they had omitted any data plots that deviated from the linear, they too would have confirmed a linear relationship as would anybody else following the same criteria. The manipulation of the duration of stages meets all the concepts of $\dot{V}O_2$ kinetics, i.e. sufficient time for steady state to be achieved and for the fast component to develop but without considerable contribution from the SC, as the SC is of delayed onset and is thought to start occur after 2.5 - 4 min after the onset of heavy intensity exercise (Bearden and Moffatt, 2000). This will enable the $\dot{V}O_2$ -WR relationship to be of linear nature but will incur an underestimation of the true oxygen requirement of performing at a specific heavy intensity exercise because in reality during training or a competitive race the SC, even if delayed, adds an additional requirement to the true oxygen requirement. If the duration of each stage of the incremental test is sufficiently long enough (i.e. >3min) then a $\dot{V}O_2$ SC is incurred, which produces a concave upwards response of the $\dot{V}O_2$ -WR relationship for WR above GET. When highly trained athletes are $\dot{V}O_2$ tested, it is recommended that the duration

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of the exercise be long enough to appreciate the full $\dot{V}O_2$ response of the steady state and that the WR test is run at should be as close as possible to race pace (Bernard *et al.*, 1998). This, in turn, manifests a reduced economy of movement for supra-GET exercise (Whipp, 1994). The acceptance of an apparent linearity in the $\dot{V}O_2$ response to WR's above GET provides important implications both for understanding and practice of exercise physiology (Jones *et al.*, 1999). The anaerobic energy requirement during heavy intensity exercise is not therefore taken into account when duration is insufficient to illicit a SC additional requirement. It is well known that L_B is elevated during heavy intensity exercise and reflects lactate production in working muscles and, therefore, represents an anaerobic contribution to $\dot{V}O_2$ requirement as much as 10% and cannot be excluded from the true overall $\dot{V}O_2$ requirement as this will enforce an underestimation (Bangsbo *et al.*, 1990). This fact will be detrimental to true comparisons between athletes.

An additional problem of comparing studies is that they have utilised different procedures to estimate the relationship between $\dot{V}O_2$ -WR. A particular study used an iterative procedure that excluded certain data plots at heavy intensity until convergence to a linear relationship occurred, without any defined justification behind the exclusions (Medbo *et al.*, 1988). Any data can be made to fit linearity using this kind of procedure, especially if no fundamental reasoning is given for the exclusion of data plots other than to fit the linear $\dot{V}O_2$ -WR relationship.

Other differences in protocol or participants that would affect the calculation of economy and the ability to make comparisons between athletes have been the training

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level of the participants involved, i.e. comparisons between elite and recreational athletes where other known variables such as $\dot{V}O_{2\max}$ maybe having a greater effect on the calculation of economy due to heterogeneity (Weston *et al.*, 2000); using participants from differing disciplines, i.e. comparing middle-distance athletes with long-distance which it is known that competition and training occur at different exercise intensities and therefore would affect the $\dot{V}O_2$ response; and finally comparisons made between sexes, i.e. using a protocol of a known running speed e.g. $16 \text{ km}\cdot\text{h}^{-1}$ even though research has shown that males have a higher mean $\dot{V}O_{2\max}$ and economy is therefore different due to different intensity WR incorporated by females. There is not enough research done on female athletes to make generalised comparisons (Astorino, 2008).

A final variable in protocol utilised that effects the validity of the measurement of economy is whether continuous or discontinuous exercise bouts are utilised (Scott, 1999). Research into the effect of prior heavy exercise has highlighted changes in the $\dot{V}O_2$ response to heavy intensity exercise. Importantly one of these changes is to reduce the $\dot{V}O_2$ SC and consequently the final net end-stage $\dot{V}O_2$ which would dampen the underestimation of the economy of movement value (Burnley *et al.*, 2000). However, as long-distance performance is of continuous nature then measurement of economy of movement should replicate this fact (Burnley and Jones, 2007).

Foster and Lucia (2007) state that the standard approach to measuring economy of movement which has emerged over the last 30 years, involves WR's at progressively increasing power output or speeds in stages of 4 - 10 minute duration (e.g. long enough

to ensure steady state is achieved). The intensity of these stages should be below the GET, to avoid the emergence of SC which will distort the $\dot{V}O_2$ and could prevent the steady state being achieved. Investigation into the practicality and accuracy of this method to measure the true $\dot{V}O_2$ requirement throughout a full range of WR, including moderate and heavy intensity exercise, is required before this method can be termed the standard approach.

2.9 Summary

There are three key determinants of endurance performance which are $\dot{V}O_{2max}$, sustainable percentage of $\dot{V}O_{2max}$ and economy. Of these physiological factors, $\dot{V}O_{2max}$ has traditionally been considered the most important for determining performance level. However, this is only true when dealing with a heterogeneous group of athletes that there is a strong correlation with performance. When dealing with a homogeneous group, such as an elite group, the correlation with performance is poor. Another variable must, therefore, be more important in these homogeneous groups. The best indicator of performance levels within these homogeneous groups has been shown to be economy of movement.

There are three methods of calculating economy of movement; measuring the $\dot{V}O_2$ response at a fixed WR; using a series of incremental WR stages that cover the full range of steady state WR's and by using a regression extrapolating to a given WR; and, the Foster and Lucia (2007) method of using a series of sub-GET only WR's and by using a regression extrapolating to a given WR. There are limitations to all of these

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methods that make it difficult to determine the most appropriate for meaningful comparisons.

Foster and Lucia (2007) also state that, at supra-threshold intensities, the delayed additional phase SC will dictate that steady state conditions are unlikely to be achieved. The above statements and the fact that economy of movement can only be accurately measured at speeds or power outputs that elicit steady state $\dot{V}O_2$ is important when determining the $\dot{V}O_2$ requirement at a given WR. However, steady state is only delayed during heavy intensity exercise therefore allowing measurement of economy of movement to be undertaken (Zoladz *et al.*, 1998a).

The $\dot{V}O_2$ kinetic responses to various WR's are used to determine economy. The fact that $\dot{V}O_2$ kinetics alter dependent on the intensity domain exercise is performed in complicates this calculation. The fixed WR method utilises % $\dot{V}O_{2max}$ which can be difficult because participants could be working at differing relative intensities of their individual $\dot{V}O_{2max}$ (Morgan *et al.*, 1989). When using the full range of WR's, those that are above GET have an additional requirement, i.e. SC, of $\dot{V}O_2$ that drives the steady state value of $\dot{V}O_2$ above that predicted from the $\dot{V}O_2$ -WR relationship. The $\dot{V}O_2$ -WR relationship has been shown to be linear throughout full range of WR's (Medbo *et al.*, 1988), curvilinear (Zoladz *et al.*, 1998a) or to have two clear distinct linear relationships (Whipp and Wasserman, 1972). The final method of sub-GET only WR's to eliminate contamination by this SC assumes linearity in the full range of WR's. Foster and Lucia (2007) state that the standard approach to measuring economy has emerged to be exercising at a progressively increasing WR in stages of 4-10 minutes duration (e.g.

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long enough for steady state attainment). The WRs have been kept sub GET to ensure the SC does not occur and drive $\dot{V}O_2$ above the expected level. The emergence of the SC would signify a change in economy of movement, which in turn has implications on exercise tolerance as it is suggested that it would underestimate the true economy.

When athletes are tested for comparative or to build personal aerobic profile, the duration of the exercise should be sufficient to elicit steady state and include supra GET WR's to appreciate the true $\dot{V}O_2$ response. The fact that training and performance are carried out at heavy exercise intensities the measurement of economy should be calculated at that race intensity and to be able to identify effectiveness of training adaptations. Nobody as yet has investigated whether the two predictive methods accurately predict the $\dot{V}O_2$ requirement or economy at 75% Δ by comparing to a fixed WR measurement as the criterion. The reasoning for the importance of knowing this is to determine whether there should be a standard predictive method, as stated by Foster and Lucia (2007) or whether predictive methods are not accurate enough because they underestimate the values.

3.0 Methods

3.1 Pilot study

The purpose of the pilot study was to determine the broadest range of WR's that could be used for the main study. The importance, therefore, was to determine the lowest possible WR that demonstrates a discernible $\dot{V}O_2$ response. The lowest power output that a clear $\dot{V}O_2$ response was discernible was shown to be presented at 50 W (see Appendix A). Therefore, 50 W was set as the lowest WR used in the main study.

3.2 Participants

The number of participants was determined by prior power analysis, assuming the SC magnitude of $330 \text{ ml}\cdot\text{min}^{-1}$ reported for cycling by Carter *et al.* (2000) as the expected mean difference. This power analysis showed that eight participants would be sufficient to detect this effect. A more conservative number of 12 participants were selected to ensure an effect.

Twelve physically active males volunteered as participants for the study. The participants were recruited from the students and staff of the University of Gloucestershire. All participants take part in physical activity at least 2-3 times per week and their mean \pm SD age, height and body mass were: 29 ± 9 years, 1.81 ± 0.07 m and 81.4 ± 10 kg respectively (see Appendix B for individual results). All participants were fully informed of the procedures, possible risks of the tests and their right to

withdraw at any point. Written informed consent, and a completed health history questionnaire were required from each participant for them to take part in the study (see Appendix C & D). All procedures employed were approved by the University of Gloucestershire Research Ethics Committee.

3.3 Study Design

3.3.1 General Design Information

The participants were tested on four separate days. The initial test was a maximal ramp test to exhaustion or failure to maintain cadence and at least 48 hr recovery period between this test and any subsequent test carried out was enforced. The final three tests were counterbalanced using a balanced Latin Square Design to control for potential order and carryover effects. Each design was carried out by two participants.

The final three tests included an incremental_{sub}, incremental_{full} and a fixed WR. The incremental_{sub} consisted of five WR's stages of six min in duration all set below GET. The incremental_{full} consisted of five WR's stages of six min in duration across a broad range of WR's. If the final stage of the full incremental test had to be terminated before completion then this test was repeated first before moving onto any subsequent tests, so as to ensure that there was no compromise to the counterbalanced design. The fixed WR was to be ten minutes in duration at 75% Δ . The 75% Δ was chosen by the present study as this has been suggested to be a comfortable WR (Morgan and Craib, 1992), at which a steady state would be attained and, approximates, to the most frequently maintained

intensity in endurance races (Sherman and Jackson, 1998). The recovery period between the subsequent three tests was set to at least 24 hrs. All tests were performed at the same time of day, to control for circadian variation (Valdez *et al.*, 2010).

3.3.2 Equipment set-up and calibration

The participants were asked to stay seated for five minutes prior to exercise to ensure that the starting baseline was true resting values. Heart rate (HR) was measured throughout all tests using short-range telemetry (RS800cx, Polar, Kempele, Finland). While participants were seated the chest-mounted transmitter on an elastic strap was attached, and the wrist mounted receiver placed on their arm. Heart rate was recorded at 5 s intervals for the duration of each test.

All tests were carried out using an electromagnetically braked cycle ergometer (Excalibur Sport, Lode, Groningen, NL). The cycle ergometer had an adjustable saddle (both horizontally and vertically) and drop handlebars. The horizontal and vertical adjustments of the handlebars and saddle were measured using a tape measure and recorded to ensure that each participant had the same position during all tests.

Participants were instructed to maintain a cadence of 80 rev.min⁻¹ throughout all tests. If the cadence fell by more than 5 rev.min⁻¹ then verbal encouragement was given for efforts to be made to return the cadence to the required range. If, after three encouragements, the cadence could not be returned to required level then the test was terminated. This marked the end of the maximal ramp test to exhaustion. However, if the test was terminated during the final stage of the full incremental test, then the test

was repeated with a downward adjustment made in power output of the final stage. This downward adjustment of power output was 5% Δ (i.e. 85% Δ would be adjusted to 80% Δ).

Respiratory data were measured on a BxB basis using a mass spectrometer system (EX671, Ferraris Respiratory Europe Ltd., Hertford). Prior to each exercise test, the on-line analyser was calibrated using a bottled gas of known concentrations; 5.02% CO₂, 4.99% Ar, 14.99% O₂ and 75% N₂ (Linde Gases, UK). The turbine cartridge (Interface Associates, California, US) was connected to a flow transducer and calibrated immediately prior to each test. A 3 L precision syringe (Pulmonary Data Services Instrumentation, Louisville, US) was used to calibrate the flow signal as per manufacturer's instructions. During all tests, the participants were cooled with a floor fan (FE-50 Cyclone, Cranlea & Co., Birmingham) throughout all exercise tests.

3.4 Study protocols

3.4.1 Maximal ramp test

The maximal ramp test to exhaustion was to determine the $\dot{V}O_{2\text{peak}}$, peak power (W_{peak}), GET for each participant. The first two minutes of the test were set at 0 W to allow respiratory data to stabilise. At the end of this two minute unloaded period, the power output immediately rose to WR manipulated to coincide with level of fitness of the participant to terminate the test approximately 12 min. Then continued to increase by a ramp of 20 W.min⁻¹ until volitional exhaustion or inability to maintain the

predetermined cadence was achieved. At the termination of the test, the power output was reduced to 80 W to provide a five minute active recovery period.

3.5 Data analysis

The following raw data from the maximal ramp test to exhaustion of time, $\dot{V}E$, $\dot{V}O_2$, $\dot{V}CO_2$, mixed expired O_2 ($M_{exp}O_2$) and CO_2 ($M_{exp}CO_2$) acquired from the online analyser were exported to an Excel for Windows (Microsoft Office 2010) spread sheet. All subsequent data analysis was carried out in Excel.

The raw data for time were transformed by interpolation into data points that could be used to calculate $\dot{V}O_{2peak}$ and other averaging calculations. The ventilatory equivalents (e.g. $\dot{V}E / \dot{V}O_2$ and $\dot{V}E / \dot{V}CO_2$) were calculated and graphically plotted to identify the respiratory compensation point (RCP) (Whipp *et al.*, 1986). Respiratory compensation point was identified according to the criteria of a more rapid increase in $\dot{V}E$ than and $\dot{V}CO_2$ (i.e. increase in $\dot{V}E/CO_2$) which causes a decrease in $M_{exp}CO_2$. The data from the first two minutes and beyond RCP were removed. Allowing for a transit delay time of 20 s for the $\dot{V}O_2$ response from muscle to mouth (Jones and Poole, 2005), the $\dot{V}O_{2peak}$ and W_{peak} were calculated by taking the highest 10 s moving average, this averaging helped to reduce noise in the data. The GET was determined from the respiratory data (averaged for every complete 10 s sequential period during the ramp test), primarily using the ventilatory slope (V-slope) method (Beaver *et al.*, 1986), but with secondary plots of ventilatory equivalents and mixed exp gas concentrations used to verify this calculation (Whipp *et al.*, 1986). The resultant GET and W_{peak} were then used to

determine the WRs for the subsequent three tests (see section 4 and Appendix E for individual results).

3.6 The predictive regression protocols and the fixed WR

The incremental_{sub} method consisted of five WR stages of six minute duration. The initial stage was set at 50W and the following stages were calculated into four equal steps in W between 50 W and 95% of the power at GET. The incremental_{full} method consisted of five WR stages of six minute duration. The initial stage was set at 50 W; the following stages were calculated into four equal steps in WR between 50 W and 85% Δ (see Appendix E for individual results). For these two predictive methods the 4-6 minute was the collection period for each stage. The fixed WR method against which the predictive techniques would be compared consisted of cycling for 10 min at a WR of 75% Δ of power output at $\dot{V}O_{2peak}$. This fixed WR method had two collection periods; one at 4-6 min and one at 8-10 minutes.

The collection period of 4-6 min of each stage, to reduce noise in the $\dot{V}O_2$ (L.min⁻¹) BxB data, had any values that were three or more Standard Error of the Estimate (SEE's) removed. Then the mean and slope of the $\dot{V}O_2$ response for the final two minutes of each stage (including the 4-6 min of fixed WR method) were calculated. The five $\dot{V}O_2$ (L.min⁻¹) means, for sub-GET and full incremental methods, were regressed and the predicted $\dot{V}O_2$ (L.min⁻¹) at 75% Δ were calculated. The resultant $\dot{V}O_2$ provided a prediction of economy of movement at 75% Δ W_{peak} (L.min⁻¹) and along with the resultant $\dot{V}O_2$ from the fixed 75% Δ WR were recorded for each participant.

3.7 Statistical Analysis

All statistical tests were carried out using IBM SPSS statistics for Windows (Version 19.0). The mean slope, for each collection period of the incremental (sub and full) and fixed WR, were compared to zero using a one sample t-test to confirm the existence of a steady state.

The $\dot{V}O_2$ required to exercise at 75% Δ were calculated, using a linear regression based on the utilised mean $\dot{V}O_2$ measured at each of the five stages for the two predictive methods. The fixed WR measured the true value of $\dot{V}O_2$ required, at the collection period 8-10 min due to the 4-6 min period being significantly greater than zero, therefore, not in steady state, to exercise at 75% Δ .

These calculated and measured values of economy of movement at 75% Δ were then entered into a within subjects ANOVA to identify differences in the oxygen uptake ($L \cdot \text{min}^{-1}$) from the three different methods. A significant effect between the predicted values compared to the measured value were investigated post hoc using Bonferroni corrected paired t-tests. Also, a significant effect between the predicted values themselves was investigated. The group data are mean \pm SD unless otherwise stated. The alpha was set equal to 0.05 for all analyses before data collection.

4.0 Results

The calculated and measured variables from the maximal ramp test are illustrated in Table 4.1. The mean responses to the maximal ramp test are demonstrated in Figure 4.1 (see Appendix E for individual results).

Table 4.1: The physiological variables (mean \pm SD) recorded during the volitional ramp test, or calculated from the ramp test data at predetermined points.

	Power (W)	165 \pm 53
	HR (b.min⁻¹)	133 \pm 11
Gas Exchange Threshold	$\dot{V}O_2$ (L.min⁻¹)	1.93 \pm 0.56
	Power (W) at 95% of GET	157 \pm 50
<hr/>		
	Power (W)	332 \pm 53
Peak	HR (b.min⁻¹)	181 \pm 10
	$\dot{V}O_2$ (L.min⁻¹)	3.66 \pm 0.54
<hr/>		
	Power (W) at 75% Δ	237 \pm 37
Calculated WR as % Δ	Power (W) at 85% Δ	271 \pm 43
<hr/>		

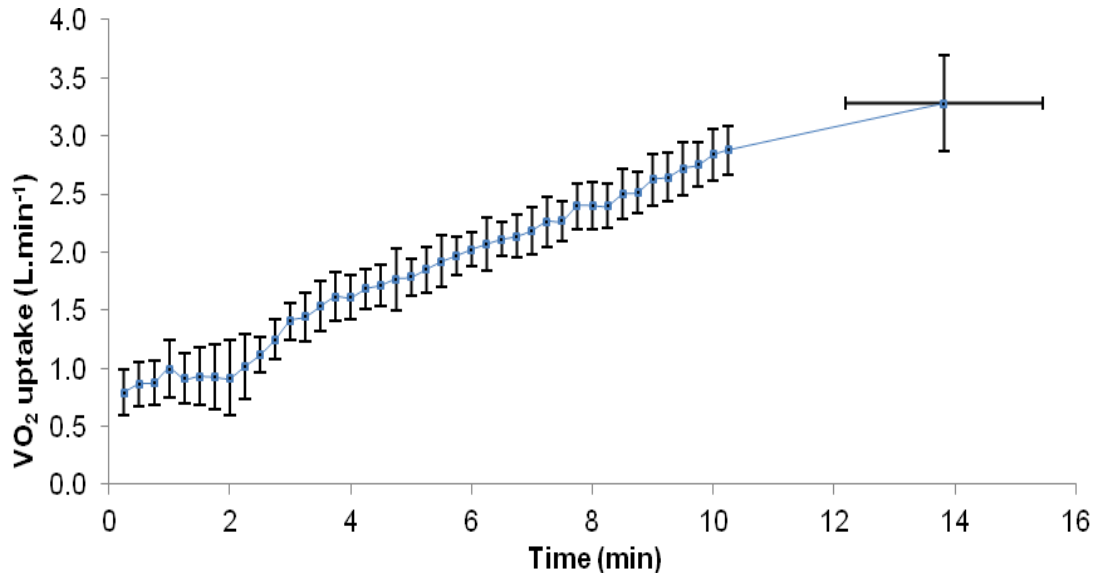


Figure 4.1: The mean response to the maximal ramp test to volition; data points are 15s sequential averages and the error bars represent 1 SD.

Figure 4.2 demonstrates a typical V-slope plot of $\dot{V}CO_2$ versus $\dot{V}O_2$, with the GET determined by the $\dot{V}CO_2$ starting to increase faster than the $\dot{V}O_2$ so that the slope becomes steeper.

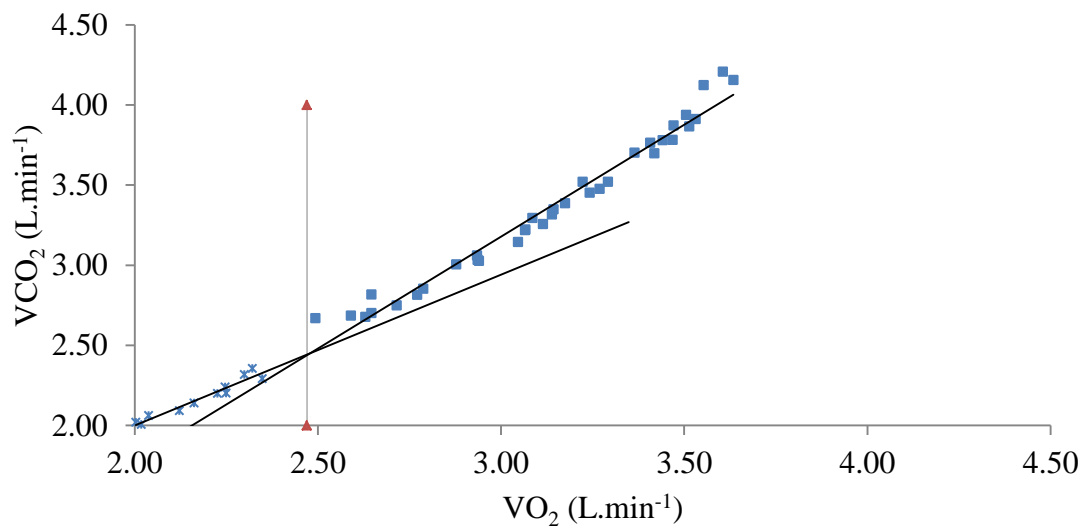
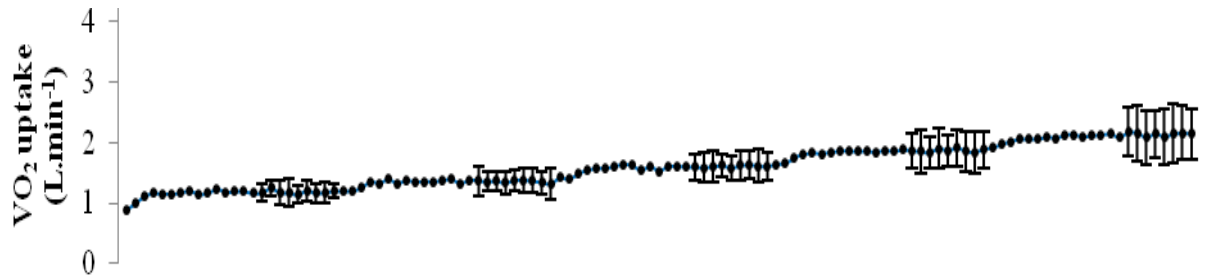
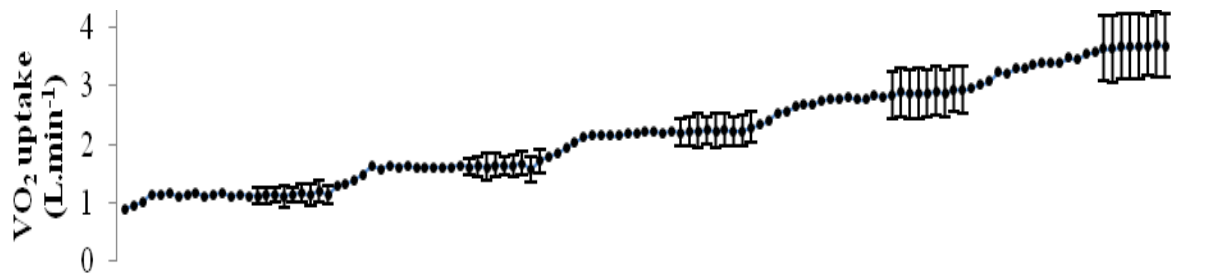


Figure 4.2: A typical plot for the determination of GET

a)



b)



c)

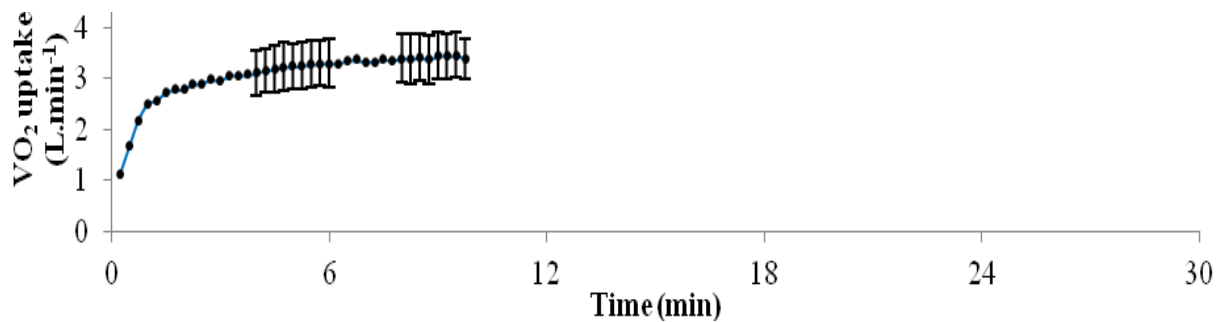


Figure 4.3: The mean $\dot{V}O_2$ response to the three methods of calculating economy of movement where; a) The $\dot{V}O_2$ uptake ($L \cdot \text{min}^{-1}$) response during the predictive sub GET 30 minute incremental test. b) The response of $\dot{V}O_2$ ($L \cdot \text{min}^{-1}$) uptake during a predictive full incremental 30 minute test. c) The response of $\dot{V}O_2$ ($L \cdot \text{min}^{-1}$) uptake during the fixed WR ten minute test at $75\% \Delta \dot{V}O_{2\text{peak}}$. Each plot represents 15s moving averages, the final two minutes of each stage and 4-6 and 8-10 min stage of fixed WR test with error bars illustrating the SD.

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Table 4.2 summarises the physiological variables at each stage of the incremental tests and the fixed WRs two stages. The 4-6 min collection period of the measured 75% Δ method demonstrated a significant difference to zero (see Table 4.2), which confirms that a steady state had not been attained at this point in the test.

Table 4.2: The physiological variables determined from the two incremental and fixed WR methods of calculating economy of movement.

Test	Stage	Power (W)	$\dot{V}O_2$ (L.min ⁻¹)	Heart Rate (b.min ⁻¹)	Slope (L/min ⁻²)	p value (1 sample t-test)
Incremental_{Sub}	1	50 ± 0	1.19 ± 0.16	100 ± 11	-0.011 ± 0.056	0.515
	2	77 ± 12	1.36 ± 0.17	109 ± 11	-0.014 ± 0.080	0.565
	3	104 ± 25	1.61 ± 0.23	117 ± 12	0.011 ± 0.048	0.460
	4	130 ± 37	1.87 ± 0.31	126 ± 14	0.003 ± 0.030	0.729
	5	157 ± 50	2.14 ± 0.43	135 ± 14	0.009 ± 0.048	0.529
Incremental_{Full}	1	50 ± 0	1.13 ± 0.13	98 ± 8	0.007 ± 0.059	0.695
	2	106 ± 11	1.62 ± 0.17	114 ± 8	-0.005 ± 0.048	0.748
	3	161 ± 22	2.24 ± 0.26	137 ± 8	0.015 ± 0.049	0.309
	4	216 ± 33	2.91 ± 0.40	157 ± 8	0.028 ± 0.048	0.071
	5	271 ± 43	3.70 ± 0.55	176 ± 7	0.035 ± 0.060	0.071
Fixed WR	4 - 6 min	237 ± 37	3.24 ± 0.45	165 ± 11	0.091 ± 0.044	p<0.001*
	8-10 min	237 ± 37	3.43 ± 0.45	172 ± 11	0.031 ± 0.061	0.107

Indicates a significant difference from zero.

The fixed WR method to measure economy of movement at 75% Δ expressed a $\dot{V}O_2$ requirement of $3.426 \pm 0.453 \text{ L}\cdot\text{min}^{-1}$. The two estimated protocols demonstrated energy requirement underestimating this level; incremental_{sub} linear regression $2.899 \pm 0.404 \text{ L}\cdot\text{min}^{-1}$ and the incremental_{full} linear regression $3.213 \pm 0.473 \text{ L}\cdot\text{min}^{-1}$ (see Appendix F for individual results). Therefore, both protocols demonstrated an underestimation of the true $\dot{V}O_2$ requirement; the incremental_{full} protocol by $0.214 \pm 0.212 \text{ L}\cdot\text{min}^{-1}$ and incremental_{sub} by $0.527 \pm 0.301 \text{ L}\cdot\text{min}^{-1}$ of exercising at 75% Δ . This underestimation of the economy of movement during cycling at 75% Δ is demonstrated in Figure 4.4.

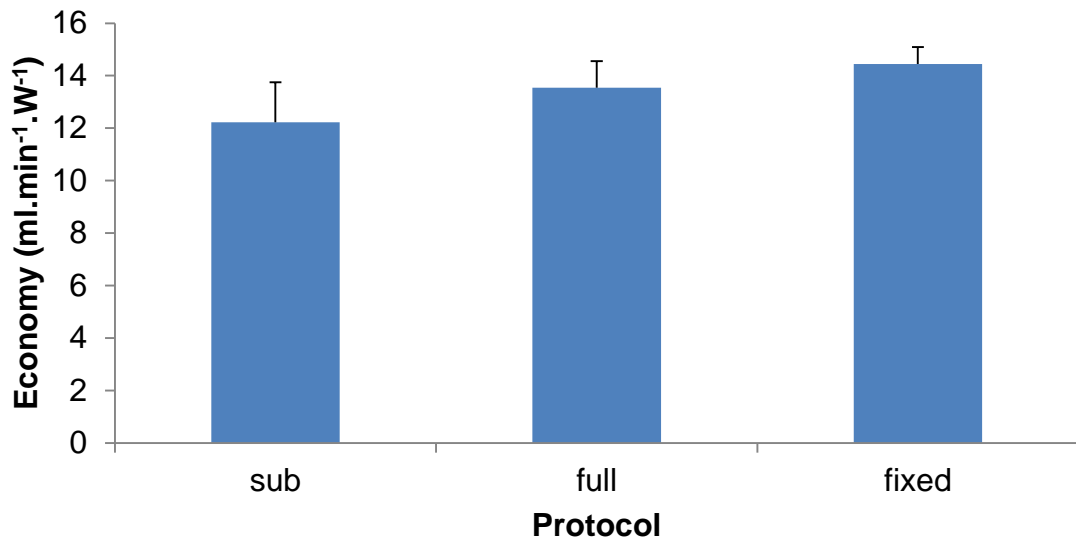


Figure 4.4: The comparison of the economy of movement calculation from the two predictive methods versus the fixed WR.

A main effect was found that the mean $\dot{V}O_2$ requirement used to determine economy of movement predicted from the regression methods differed significantly from the measured fixed WR $\dot{V}O_2$ requirement; the predicted incremental_{sub} ($p < 0.001$) and predicted incremental_{full} ($p = 0.012$). The predicted incremental_{sub} demonstrated a significantly greater underestimation than the predicted incremental_{full} ($p = 0.037$) (see Appendix G).

5.1 Key Findings

The principal finding of the present study was that the predictive incremental_{sub} method significantly underestimated the calculation of economy of movement when compared to the criterion fixed WR measured economy of movement at intensity of 75% Δ . The fact that this method underestimates the $\dot{V}O_2$ requirement at 75% Δ , demonstrates that the Foster and Lucia (2007) statement that the incremental_{sub} WR's method should be considered the standard approach should not be considered as such. The predictive incremental_{full} method, also, significantly underestimated the calculation of economy of movement when compared to the criterion fixed WR measured economy of movement at intensity of 75% Δ . However, the incremental_{sub} method underestimates the economy of movement at intensity of 75% Δ by significantly more than the incremental_{full} method.

Foster and Lucia (2007) also stated that steady state was unattainable after GET and therefore WRs supra-GET should not be included in any regression. The present study, however, did find that steady state $\dot{V}O_2$ was attained in all stages of the submaximal tests (see Figure 4.2 & Table 4.2). However, the t-test did highlight in the criterion fixed WR test that steady state was significantly not attained at the 4-6 minute stage but had done so by the eight to ten minute stage.

5.2 The calculation of economy of movement

The present study key finding that incremental_{sub} method underestimates the measured $\dot{V}O_2$ requirement refutes the Foster and Lucia (2007) statement that sub-GET only WRs should be used in the regression, using the linear $\dot{V}O_2$ -WR relationship, to predict economy of movement. The present study findings are in contradiction to the still widely held belief, derived from authoritative texts, that the $\dot{V}O_2$ -WR relationship is linear up to $\dot{V}O_{2max}$ (Wilmore and Costill, 2004; Astrand and Rodahl, 2003; Brooks and Fahey, 1984). Medbo (1988) also has stated that the $\dot{V}O_2$ -WR relationship is linear up to $\dot{V}O_{2max}$. Nevertheless the present study findings agree with those reported by Bangsbo (1993) and Bosquet (2008) who reported that extrapolating the sub-GET only WR by regression based on the linear $\dot{V}O_2$ -WR relationship underestimated the $\dot{V}O_2$ requirement of WRs in the heavy intensity domain. The present study findings that $\dot{V}O_2$ requirement has deviated from the predicted requirement from the extrapolated sub-GET only linear $\dot{V}O_2$ -WR relationship, is also in agreement with results reported by several other authors (Zoladz, Duda and Majerczak, 1998; Zoladz, Rademaker and Sargeant, 1995; Hagberg, Mullin and Nagle, 1978; Whipp and Wasserman, 1972). Henson (1989) demonstrated that $\dot{V}O_2$ for all WRs supra GET are elevated above that predicted from the extrapolated sub-GET only linear $\dot{V}O_2$ -WR relationship.

The observation that $\dot{V}O_2$ does not increase proportionately with WR is not new (Zoladz, Duda and Majerczak, 1998; Zoladz, Rademaker and Sargeant, 1995; Casaburi *et al.*, 1987; Hagberg, Mullin and Nagle, 1978). The present study agrees with the past recommendations that the conceptual basis of quantifying total oxygen requirement (i.e.

economy) while exercising at a given heavy intensity WR needs to consider that aerobic and anaerobic metabolism contributes to the overall energy requirement (Morgan, Martin and Krahenbuhl, 1989). This understanding consequently demonstrates that quantification aerobic requirement alone during heavy intensity exercise will underestimate the measured $\dot{V}O_2$ requirement at that WR (Hansen *et al.*, 1988; Bransford and Howley, 1977). The author of the present study agrees with Zoladz (1995) that the non-linearity of the $\dot{V}O_2$ -WR relationship should have been recognised more often. There are a number of reasons why past studies have found linearity. The most important are related to the methodology employed. These include the fast increments that do not allow time for the manifestation of the SC (Fletcher, Esau and Macintosh, 2009), the use of very few data points at heavy intensities (Franch *et al.*, 1998), and the removal of any data points that deviate from linearity on the basis that they are either noise or the consequence of a disproportionate increase in cardiac, postural or ventilatory costs (Medbo *et al.*, 1988).

The present study recommends that further research needs to be carried out on the accuracy of a curvilinear regression and a supra-GET only WR regression. This recommendation is based upon based study findings that the $\dot{V}O_2$ response was non-linear (Sherman and Jackson, 1998; Hansen *et al.*, 1988), or curvilinear in response (Zoladz, Duda and Majerczak, 1998; Bangsbo, 1996; Lacour *et al.*, 1990; Whipp and Wasserman, 1986). Other researchers have reported non-linear models significantly improved the accuracy of predicting the economy of movement (Londeree, 1986; Daniels *et al.*, 1977).

The present study agrees with Zoladz (1998) that the presence of the SC during incremental exercise in the heavy intensity domain needs to be taken into account for practical significance when studying or measuring economy of movement. Whipp & Ward (1993) state that the presence of the SC undermines the assumption of models that use base their prediction of economy on the linear function of WR during heavy intensity exercise. The present study, therefore, agrees with the Bosquet (2008) study that the presence of the SC is a major flaw in these assumptions and clearly makes accurate prediction of economy of movement difficult. The author agrees with Jones (2006) that the ideal method would be to measure the economy of movement directly at the athletes' race pace but disagrees with Jones (2006) recommendation that sub-GET only method to avoid the complexity created by the existence of the SC. The present study recommends that further research is required before any predictive method can be practically called the standard approach due to the underestimations present in those classed as such at present.

5.3 Potential mechanisms that might explain this response

The use of sub-GET only WR regression was found, in the present study, to significantly underestimated the $\dot{V}O_2$ response. Three factors that have been shown to alter the $\dot{V}O_2$ kinetics for heavy intensity exercise are prior bout of heavy intensity exercise, exercise duration, aerobic training and mode of exercise. The protocol utilised in the present study for the predictive regression tests may itself be shaping the SC and therefore the $\dot{V}O_2$ kinetic response. The continuous protocol of five stages of six minute WR's may be having a compound effect on the steady state response as each stage

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raises the baseline $\dot{V}O_2$ for the start of the next stage. Prior exercise induces a myriad of changes in skeletal muscle physiology; including increases in blood flow, oxygenation, oxidative enzyme activity, O_2 extraction and electromyographic activity.

Perrey (2003) concluded that the priming effect of moderate exercise enabled a better adaptation of the oxidative metabolic processes at the onset of heavy exercise. This may be reducing the $\dot{V}O_2$ response by priming the heavy intensity exercise and lowering the $\dot{V}O_2$ requirement. Prior heavy intensity exercise has been shown to result in significantly faster $\dot{V}O_2$ kinetics in subsequent heavy intensity bouts caused by a reduction in the amplitude of the SC and an increased primary $\dot{V}O_2$ response. The mechanisms can be expressed simply as being related to the delivery and distribution of O_2 to the working muscles (Hughson, Cochrane and Butler, 1993; Linnarsson, 1974) or to utilisation of O_2 determined by the kinetics of the intramuscular oxidative processes (Grassi *et al.*, 1996; Cerretelli *et al.*, 1977). Prior exercise is said to promote increased muscular efficiency in aerobically fit athletes (Gonzales and Scheuermann, 2008) by making more O_2 available and therefore accelerating $\dot{V}O_2$ kinetics (MacDonald, Pedersen and Hughson, 1997). Gerbino *et al.* (1996) postulated that the effects can be attributed to an enhanced muscle O_2 delivery consequent to a greater muscle vasodilation and rightward shift of the oxyhemoglobin dissociation curve resulting from the residual acidemia and elevated muscle temperature.

The present study utilized 4-6 min stages exercise duration to try to minimise the effect of exercise duration as a confounding factor. Past studies have manipulated exercise duration, by using < 3 min exercise to calculate economy (Jones, 2000). This has been

used to eliminate any SC emergence and measure just primary response. Medbo (1988) stated that 10 min of exercise was required to obtain a true oxygen uptake response and a steady state to be ensured. The idea of the incremental test protocols was to minimise the physical discomfort experienced by participant and gain an accurate valid measure of the physiological variable investigating. Also, there is the knowledge that oxygen uptake keeps increasing, at a slower rate, until end of exercise; constant-load or long duration incremental tests. This phenomenon is known as the slow upward drift of the oxygen uptake response (Camus *et al.*, 1988). This needs to be minimized as much as possible, therefore, keeping the duration down to the minimum needed to ensure steady state is obtained.

The present study used an experimental design where continuous exercise occurred; this elevated the baseline values at the onset of each stage. Reporting that $\dot{V}O_2$ baseline increased from 0.896 ± 0.079 to 1.913 ± 0.276 L.min⁻¹ (stage 5) during the incremental_{sub} test and from 0.854 ± 0.140 to (stage 5) 3.037 ± 0.449 L.min⁻¹ during the incremental_{full} test. The $\dot{V}O_2$ response at the onset of subsequent exercise bouts (i.e. steps) has been demonstrated to have higher baseline values (Wilkerson *et al.*, 2004; Koppo and Bouckaert, 2001). Also, demonstrating that $\dot{V}O_2$ at the onset of the second exercise is higher, when prior exercise was performed, reporting an increased $\dot{V}O_2$ baseline of 1.235 ± 0.148 vs. 0.981 ± 0.085 ml.min⁻¹, $p < 0.001$ (Marles *et al.*, 2006). Highlighting that baseline $\dot{V}O_2$ prior to second bout of heavy intensity exercise is elevated compared to the baseline value at onset from rest. The perception that the response time is accelerated may also be an artefact of the elevated baseline $\dot{V}O_2$ in the subsequent heavy intensity exercise (Koppo and Bouckaert, 2001). The influence of

elevations in baseline $\dot{V}O_2$ from step progression from bout to bout has a subsequent effect, therefore, on the expression of the primary amplitude (Sahlin *et al.*, 2005; Wilkerson *et al.*, 2004; Burnley *et al.*, 2000). Wilkerson (2007) found that pulmonary $\dot{V}O_2$ kinetics in the transition from moderate to heavy intensity WR was profoundly altered (i.e. baseline $\dot{V}O_2 \sim 1.66 \text{ L}\cdot\text{min}^{-1}$) compared to light to heavy exercise (i.e. baseline $\dot{V}O_2 \sim 0.80 \text{ L}\cdot\text{min}^{-1}$). The present study used continuous stages to calculate economy from the $\dot{V}O_2$ -WR relationship. The outcome of this could be that the experimental design is in fact the artefact that is causing the underestimation of the economy of movement. This elevated baseline $\dot{V}O_2$ kinetics was the reason why the SC was not modelled in this study, as there was no way of identifying what were changes in primary gain response and what was SC amplitude response.

As the present study used an experimental design where continuous exercise was utilized, each stage may actually be priming the body ready for the next stage of exercise and altered the $\dot{V}O_2$ response thereafter. In so doing reducing the SC effect and therefore reducing the deviation away from the $\dot{V}O_2$ -WR relationship predicted values. This means that although this present study found a significant underestimation in the incremental_{full} method, it may in reality have been greater and/or actually modelled the curvilinear response more closely. This may have altered the $\dot{V}O_2$ requirement at end exercise by steepening the primary slope and reducing the effect of the SC. The reduced effect of SC actually has reduced the underestimation of the criterion 75% Δ WR. Prior heavy intensity exercise affects the $\dot{V}O_2$ kinetics by increasing the absolute amplitude of the $\dot{V}O_2$ and a reduction in the amplitude of the SC. Gerbino (1996) demonstrated that a prior heavy intensity exercise bout resulted in faster overall $\dot{V}O_2$ kinetics during a

second bout of heavy intensity exercise. Subsequent investigations established that this acceleration of overall $\dot{V}O_2$ kinetics was chiefly consequent to a reduced $\dot{V}O_2$ SC amplitude (Koppo and Bouckaert, 2001; Burnley *et al.*, 2000) and an increase in the net amplitude of the primary Phase (Perrey *et al.*, 2003).

The present study has found that during cycling the economy of movement is substantially underestimated when utilising an incremental_{sub} regression to predict $\dot{V}O_2$ at heavy intensity WR; which is in agreement with the majority of research on cycling that has found similar underestimations (Coyle, 2005; Zoladz, Duda and Majerczak, 1998; Zoladz, Rademaker and Sargeant, 1995; Coyle *et al.*, 1992). The past research that has suggested an existence of a linear $\dot{V}O_2$ -WR relationship, apart from having protocols that limit the emergence of the SC, have been carried out on running based tests. Explanations for these differing findings between the modes of exercise have been argued when comparisons between running and cycling have been. These comparisons have shown cycling and running are relatively similar in the overall $\dot{V}O_2$ kinetics, with the exception of the primary and SC amplitudes having differing responses. Therefore, the finding in this study that, the economy of movement is substantially underestimated when utilising an incremental_{sub} or incremental_{full} regression to predict $\dot{V}O_2$ at heavy intensity WR during cycling exercise may not be the case when running, i.e. the incremental_{full} may not actually significantly differ from the measured value. If this was the case then full regressions may be accurately used to predict economy of movement.

The final factor that has been shown to affect $\dot{V}O_2$ kinetics in the heavy intensity exercise domain is aerobic or endurance training (Womack *et al.*, 1995; Hagberg *et al.*,

1980). Oxygen uptake kinetics have been shown to alter following a period of endurance training (Casaburi *et al.*, 1987). According to Womack *et al.* (1995) the majority of this effect is due to a reduction in the SC.

5.4 Implications for measurement of economy of movement

No previous studies have made a meaningful comparison between the predictive methods of $\text{incremental}_{\text{sub}}$ and $\text{incremental}_{\text{full}}$ and the measured fixed WR to determine the accuracy of their prediction. The present study was, therefore, the first to empirically demonstrate evidence that these methods significantly underestimate the measured $\dot{V}O_2$ requirement. This finding refutes the claim by Foster and Lucia (2007) that the sub-GET only WRs should be used as the standard approach, as the present study finding of an underestimation demonstrates that this method is not representative of working $\dot{V}O_2$ at the important race pace. An issue with comparing athletes based on economy of movement measurements from regression models are that test speeds are rarely fast enough to reflect race intensities (Daniels and Daniels, 1992). The present study used a 75% Δ exercise intensity which has been shown to be representative of race intensities across the range of endurance events (Astorino, 2006). The present study agrees with Bangsbo (1993) and Zoladz (1995) that predictions using $\text{incremental}_{\text{sub}}$ or $\text{incremental}_{\text{full}}$ data plots will underestimate the actual O_2 requirement at these heavy intensity WR's. The measurement of economy of movement needs to accurately assess the O_2 requirement to allow comparisons between athletes (Fletcher, Esau and Macintosh, 2009), and to demonstrate the effectiveness of a training intervention, as a lower metabolic rate for the race pace WR represents a lower fraction of $\dot{V}O_{2\text{max}}$

(Davison, Van Someren and Jones, 2009). This would have important implications for the routine assessment of aerobic or endurance fitness in athletes. Therefore, the current recommendation would be to actually measure economy of movement at a fixed race pace with a constant 10 min run or ride.

The present study demonstrated that the collection period of 4-6 mins in duration was sufficient to allow for the SC to emerge and the $\dot{V}O_2$ response to steady state. Unlike other studies that have not found a SC due to their lack of sensitivity to detect it. For example, studies have employed shorter stage durations (<3min), thus, not allowing for the SC and therefore actual $\dot{V}O_2$ requirement to manifest (Aisbett and LeRossignol, 2003) or have incorporated a fast incremental stages (Bentley, Newell and Bishop, 2007). However, in agreement with Medbo (1988) the present study suggests that 10 stage durations would be more appropriate for future protocols. This was due to the finding in the present study of the 4th and 5th stage of the incremental_{full} being close to acceptance of being significantly different to zero.

5.5 Limitations of study

The principal aim of the present study was to determine the accuracy of two predictive incremental regression methods to determine economy of movement at a fixed WR of 75% Δ . In order to achieve this, the initial threshold in $\dot{V}O_2$ kinetics had to be identified in order to demarcate the moderate and heavy intensity exercise domains and to accurately calculate the relative WR of 75% Δ . However, there are many issues and limitations around the identification of this point.

The present study decided that the availability of a far greater number of respiratory data for the calculation of GET or VT compared to LT would improve accuracy. The majority of research (Miura *et al.*, 2009; Langsetmo *et al.*, 1997; Wasserman, Beaver and Whipp, 1994; Beaver, Wasserman and Whipp, 1986) on $\dot{V}O_2$ kinetics has used respiratory methods to estimate LT. The fact that the study was based on $\dot{V}O_2$ kinetic responses lent itself better to using GET than LT. The present study decided that the limitations involved with the identification of LT using L_B measurements have led to vast controversy over the definition, and the techniques used for detection and the resultant measurements vary widely. These limitations include the lack of a precise criterion for the definition of LT, numerous sample sites, detection of L_B accumulation. Majority of studies have failed to consider possible differences in lactate levels among venous, mixed venous, arterial and capillary blood (Bosquet, Léger and Legros, 2002). All of these factors, can lead to as much as 13% variation (79 – 92 % $\dot{V}O_{2max}$) in the identification of LT on the same data and therefore, make any comparisons between studies difficult (Bassett and Howley, 2000).

The present study decided to use a fixed relative WR of 75% Δ as the exercise intensity to measure economy of movement. The principal aim was to identify differences in the calculations of economy of movement at a relevant intensity for all endurance athletes so that future accurate comparisons could be made between athletes and over time by an athlete. Past research has shown that intra-person variability needed to be considered when normalising exercise intensity for constant work-rate exercise, since exercise at 50% of $\dot{V}O_{2max}$ may be above the GET in one participant but below it in another,

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resulting in marked differences in the metabolic and gas exchange responses to exercise (Shimizu *et al.*, 1991). To control for this, the present study, utilised the % Δ method to ensure that participants are exercising within the desired exercise intensity domain (Ozyener *et al.*, 2001). The 75% Δ was chosen by the present study as this has been suggested that it is a comfortable WR (Morgan and Craib, 1992) and approximates to the most frequently maintained intensity in endurance races (Sherman and Jackson, 1998).

The present study set the cadence of each test to 80 rev.min⁻¹ which allowed for standardisation and comparisons to be made. Given the marked differences in both efficiency and $\dot{V}O_2$ requirement of a given work-rate, it is conceivable that cadence differences would influence the power-duration relationship (Pringle, Doust, Carter, Tolfrey and Jones, 2003; Gaesser and Brooks, 1975). Therefore, given the body of research available on the effects of pedal cadence typically suggests that cadences within a range of ~60-100 rpm have little effect on overall $\dot{V}O_2$ kinetics (Hill *et al.*, 2003), the present study decided that the middle cadence of this range would be appropriate for all athletes with minimal effect on the calculation of economy.

The final limitation was the participant population utilised in the study. This participant population ranged considerably in age (29 ± 9 yrs) and their training status. The variability in the level of training status, was highlighted by the considerable range in the power output (W) achieved at GET and $\dot{V}O_{2 \max}$. These points suggest that the participant population was of a heterogeneous nature. If a homogeneous sample population, i.e. trained cyclists, had been studied the SC response would be smaller in

amplitude (the SC is still existent in elite cyclists (Lucía, Hoyos and Chicharro, 2000)) but the variability between participants smaller, speculating that the results would be similar. However, future study on a homogeneous population of elite cyclists should be carried out to confirm or disprove this.

5.6 Recommendations for future research

The present study used five continuous six min stages to calculate the linear regressions on. No study to date has directly investigated the effect of continuous incremental exercise on the calculation of economy of movement. However, research into continuous and the effect of priming exercise have shown that there is a compounding effect on the overall amplitude and the reduction in the amplitude of the SC (Marles *et al.*, 2006; Burnley *et al.*, 2000; Scott, 1999). Marles *et al.* (2006) found that continuous incremental exercise accelerates the $\dot{V}O_2$ kinetics in response to an increase in WR. The finding in the present study of an underestimation by $\text{incremental}_{\text{sub}}$ and $\text{incremental}_{\text{full}}$ during continuous exercise may in effect not be measuring the full extent of the underestimation. Future research is needed to clarify whether discontinuous stages could affect the determination of economy of movement.

The present study used cycling as the mode of exercise to determine the accuracy of predictive linear regression methods to calculate economy of movement. Carter *et al.* (2000) demonstrated that $\dot{V}O_2$ kinetics were similar for running and cycling, with the exception of the primary (higher for running) and SC amplitudes (lower for running). A SC, however, has been shown to be elicited during incremental heavy intensity exercise

it is of a lower magnitude (Carter *et al.*, 2000). To evaluate the effect these differences in the $\dot{V}O_2$ kinetic response of mode of exercise, there is a need for research to carry out the present study on running.

The present study interestingly found that during the criterion method of 10 min exercise at 75% Δ at the 4-6 minute stage a steady state had not been attained but had been by the 8-10 min stage which agrees with Medbo (1988) that ten min of constant WR exercise is required to obtain steady state. This finding disagreed with Foster and Lucia (2007) that steady state was unattainable at heavy intensity exercise. However, during the last two stages of the incremental_{full} regression method although not reported as significantly non-steady state the p value was close to being accepted, i.e. 0.071. Whipp and Wasserman (1972) state that the duration of the exercise which the data were analyzed dictates whether steady state will be attained or not. Medbo (1988) stated that 10 min stage durations were needed to ensure steady state. Hagberg (1980) went as far as to report that to assess if steady state can be achieved within 10 minutes of exercise measurements must be made beyond the 10 minute mark. For future research the present study finding of 4-6 min duration heavy intensity being close to acceptance as non-steady state for the final two stages of the full regression method and is actually shown to be non-steady state for the fixed WR, suggests that the stage duration should actually be increased to 8-10 min as per Medbo *et al.* (1988) to allow for a full true response. Future investigations should actually study different durations of the stages to find which is shortest that a clear steady state attainment occurs at 75 and 85% Δ . However, from a practical viewpoint, if this practice was to be used as an applied physiological assessment routinely, it would be very time consuming.

The present study recruited physically active participants. Previous studies that have measured economy of movement have mainly recruited elite athletes (Coyle, 2005; Jones, 1998) but have not investigated the accuracy of determining economy with using the sub-GET only WR regression. Therefore, further research is required into what effect training status has on the level of underestimation of using a linear regression (sub-GET only or full range).

The present study has provided empirical evidence that $\text{incremental}_{\text{sub}}$ and $\text{incremental}_{\text{full}}$ methods of predicting economy both significantly underestimate the measured $\dot{V}O_2$ at the fixed WR. Further additional investigation by the present study found that the curvilinear response suggested by Zoladz (1995 & 1998) also underestimated the measured $\dot{V}O_2$ at the fixed WR. The present study, although based upon only three data plots investigated a supra-GET only regression. This protocol also underestimated the measured value, however, was the method that underestimated by the least value. Future research should therefore investigate fully the accuracy of using these two methods to predict economy of movement.

5.7 Conclusions

The key finding of the present study was that using $\text{incremental}_{\text{sub}}$ WRs to extrapolate along a linear regression significantly underestimated the measured $\dot{V}O_2$ from the fixed WR for economy of movement. Therefore, this is the first study to empirically demonstrate that this method is not representative of the working $\dot{V}O_2$ kinetics and as

such has no practical use and should not be used to predict economy of movement. The present study also demonstrated that the incremental_{full} method significantly underestimated the measured $\dot{V}O_2$ from the fixed WR for economy of movement. However, the incremental_{full} was shown to significantly underestimate the economy of movement by much less than the incremental_{sub} method. These underestimations refute the Foster and Lucia (2007) statement that the incremental_{sub} can be the standard approach or even a meaningful prediction of economy.

The level of underestimations of economy observed in the present study might have been affected by the continuous nature of the incremental protocol utilised, the duration of exercise stages, the level of aerobic training and/or the mode of exercise utilised. These four factors have been shown to have the potential to alter the $\dot{V}O_2$ kinetics for heavy intensity exercises. As the present study used an experimental design where continuous exercise was utilized, each stage may actually be priming the body ready for the next stage of exercise, creating an elevated the baseline value and altering the $\dot{V}O_2$ response thereafter. In so doing reducing the SC effect and therefore reducing the deviation away from the $\dot{V}O_2$ -WR relationship predicted values (Bailey *et al.*, 2009; Pringle, Doust, Carter, Tolfrey, Campbell, *et al.*, 2003; Burnley *et al.*, 2002). The present study utilised cycling as the mode of exercise due to the magnitude of SC being the greatest in this exercise and therefore any research investigating the effect of this component needs to utilise cycling. However, consideration must be given to the fact that running differs in the amplitude of the primary and SC of the overall $\dot{V}O_2$ kinetics and therefore warrants investigation into whether this mode of exercise would have a different effect on the accuracy of the incrementalsub only WRs on the prediction of

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economy. The present study incorporated participants of physically active nature and as elite athletes have been shown to exercise at far higher intensities before deviation from the $\dot{V}O_2$ -WR relationship occurs this may reduce the level of underestimation. Future research needs to investigate the elite level athletes to determine if the level of underestimation that occurs. Elite level athletes have been shown to still elicit a SC and therefore a deviation from the $\dot{V}O_2$ -WR relationship based on sub-GET only WRs.

The present study determined that steady state was achievable at WRs as high as 85% Δ which is important as steady state during heavy intensity exercise has in the past been reported as was either unattainable (Foster and Lucia, 2007), or delayed beyond 6-8 (Whipp and Ozyener, 1998) or more than 20 mins (Medbo *et al.*, 1988). The attainment of steady state ensured that for the purposes of the present study that the WRs performed were within the heavy intensity domain. However, interestingly, the present study found that the 4-6 min stage of the constant fixed WR that the $\dot{V}O_2$ was not in steady state but had achieved this by the 8-10 min point. This is in agreement with Medbo (1988) who stated that during constant WR exercise at least 10 min was required for steady state to be achieved. This could be due to the fact that during the regression tests the body is primed by the preceding bout which speeds the $\dot{V}O_2$ response and a raises of the baseline $\dot{V}O_2$, whereas during the constant intensity criterion test which has a transition from rest takes longer to steady state due to the slow addition of the SC.

The findings of the present study agrees with the statement (Hansen *et al.*, 1988) that the first step to understanding the $\dot{V}O_2$ kinetics and the modelling of, during heavy intensity exercise, would be to recognise that a SC will be present and therefore cause

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the $\dot{V}O_2$ requirement to deviate from the linear $\dot{V}O_2$ -WR relationship. The SC will be present due to the fact that the runner's ability to use the oxygen most economically at race pace that contributes substantially to endurance performance. Therefore, dictating that an additional criterion test should be administered to calculate economy of movement and exercise tolerance. This test should select a WR close to the race intensity in the case of endurance athletes who compete at a stable pace (Bernard *et al.*, 1998). However, the present study acknowledges that future research needs to investigate fully the accuracy of the curvilinear and incremental_{supra} methods to study first before confirming this.

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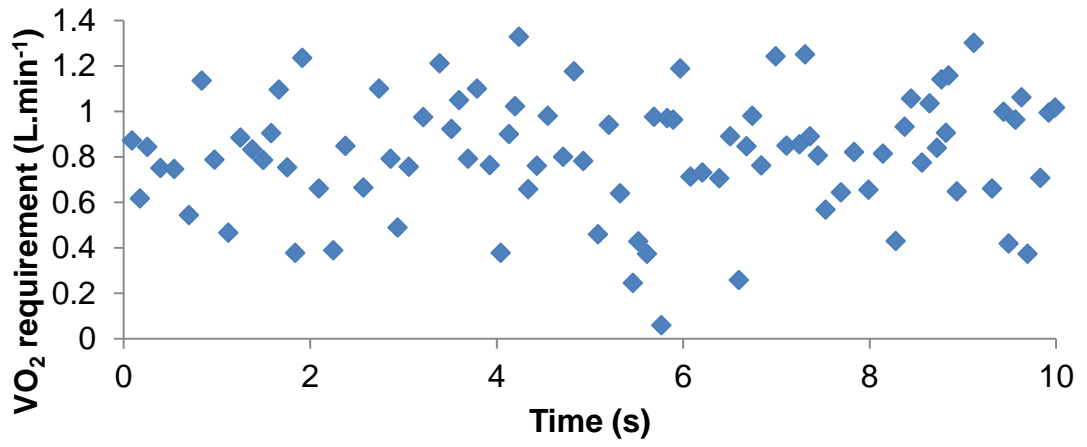
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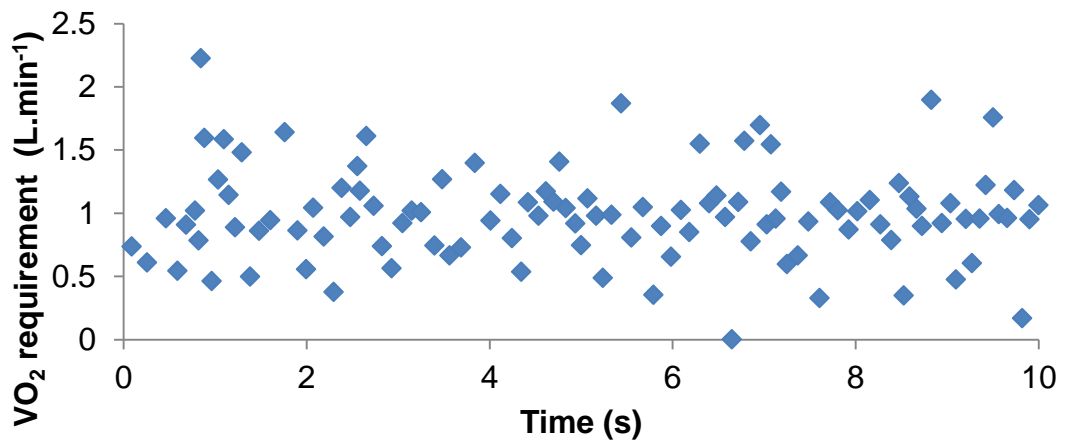
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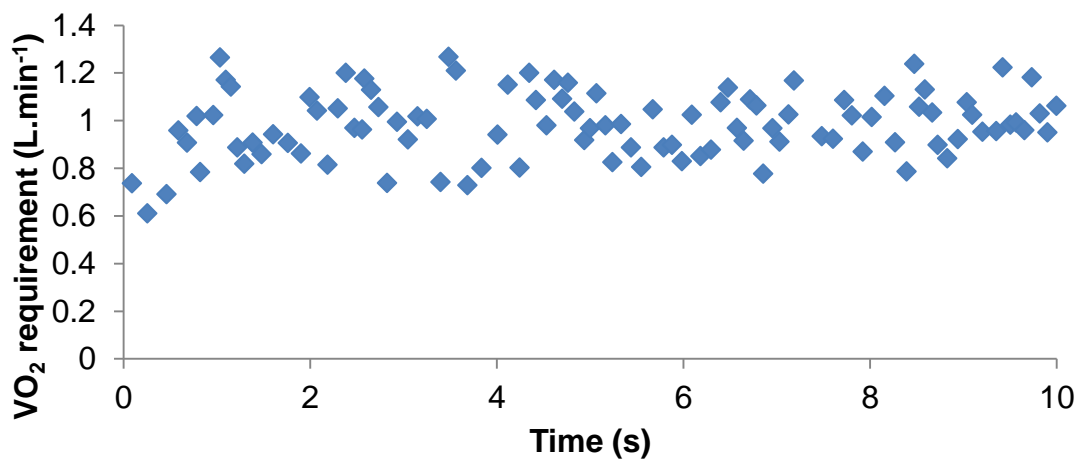
VO₂ requirement at 20W WR



VO₂ requirement at 40 W WR



VO₂ requirement at 50W WR



APPENDIX B

Table -1: The individual age, body mass and height of the participant and the calculation of mean \pm SD.

	Age (yrs.)	Body Mass (kg)	Height (m)
	23	84.4	1.82
	46	94.2	1.94
	32	98.5	1.85
	25	82.8	1.87
	30	76.1	1.74
	43	87.4	1.78
	32	74.2	1.76
	20	61.7	1.77
	23	83.4	1.85
	23	65.1	1.74
	20	86.6	1.82
	35	81.8	1.72
Mean	29	81.4	1.81
SD	9	10.7	0.07



SPORT & EXERCISE LABORATORIES

Informed Consent Form

Description of study:

The participants were asked to attend on four separate occasions, with at least 48 hours between the maximal test and the next test to allow for complete recovery and from then on at least 24 hours between the other tests. The initial test will be a maximal ramp test, to determine the VO_{2peak} and other important values. The two of the last three tests will consist of 5 x 6 min stages of sub-GET or sub-supra GET power outputs and the third will be 10 mins at 75% of VO_{2peak} .

I have had full details of the tests I am about to complete explained to me. I understand the risks and benefits involved, and that I am free to withdraw from the tests at any point. I confirm that I have completed a health questionnaire, and I am in a fit condition to undertake the required exercise.

Name:

Signed:

Date:

Tester:

Signed: Date:

*to be completed only if the participant is under 18 years of age

SPORT & EXERCISE LABORATORIES**Health Questionnaire****About this questionnaire:**

The purpose of this questionnaire is to gather information about your health and lifestyle. We will use this information to decide whether you are eligible to take part in the testing for which you have volunteered. It is important that you answer the questions truthfully. The information you give will be treated in confidence. Your completed form will be stored securely for 5 years and then destroyed.

Section 1, which has been completed by the tester, provides basic information about the testing for which you have volunteered. Sections 2 to 7 are for you to complete: please circle the appropriate response or write your answer in the space provided. Please also complete section 8. Sections 9 and 10 will be completed by the tester, after you have completed sections 2 to 8.

Section 1: The testing (completed by tester)

To complete the testing for which you have volunteered you will be required to undertake:

Moderate exercise (i.e., exercise that makes you breathe more heavily than you do at rest but not so heavily that you are unable to maintain a conversation)



Vigorous exercise (i.e., exercise that makes you breath so heavily that you are unable to maintain a conversation)



The testing involves:

Walking	<input type="checkbox"/>	Generating or absorbing high forces through your arms	<input type="checkbox"/>
Running	<input type="checkbox"/>	Generating or absorbing high forces through your shoulders	<input type="checkbox"/>
Cycling	<input checked="" type="checkbox"/>	Generating or absorbing high forces through your trunk	<input checked="" type="checkbox"/>
Rowing	<input type="checkbox"/>	Generating or absorbing high forces through your hips	<input checked="" type="checkbox"/>
Swimming	<input type="checkbox"/>	Generating or absorbing high forces through your legs	<input checked="" type="checkbox"/>
Jumping	<input type="checkbox"/>		

Section 2: General information

Name: Sex: M F Age:

Height (approx.): Weight (approx.):

Section 3: Initial considerations

1. Do any of the following apply to you? No Yes
- a) I have HIV, Hepatitis A, Hepatitis B or Hepatitis C
 - b) I am pregnant
 - c) I have a muscle or joint problem that could be aggravated by the testing described in section 1
 - d) I am feeling unwell today
 - e) I have had a fever in the last 7 days

(If you have answered “Yes” to question 1, go straight to section 8)

Section 4: Habitual physical activity

- | | | |
|--|----|-----|
| 2a. Do you typically perform moderate exercise (as defined in section 1) for 20 minutes or longer at least twice a week? | No | Yes |
| 2b. Have you performed this type of exercise within the last 10 days? | No | Yes |
| 3a. Do you typically perform vigorous exercise (as defined in section 1) at least once a week? | No | Yes |
| 3b. Have you performed this type of exercise within the last 10 days? | No | Yes |

Section 5: Known medical conditions

- | | | |
|---|----|-----|
| 4. Do any of the following apply to you? | No | Yes |
| <ul style="list-style-type: none"> a) I have had insulin-dependent diabetes for more than 15 years b) I have insulin-dependent diabetes and am over 30 years old c) I have non-insulin-dependent diabetes and am over 35 years old | | |
| 5. Have you ever had a stroke? | No | Yes |
| 6. Has your doctor ever said you have heart trouble? | No | Yes |
| 7. Do both of the following apply to you? | No | Yes |
| <ul style="list-style-type: none"> a) I take asthma medication b) I have experienced shortness of breath or difficulty with breathing in the last 4 weeks? | | |

8. Do you have any of the following: cancer, COPD, cystic fibrosis, other lung disease, liver disease, kidney disease, mental illness, osteoporosis, severe arthritis, a thyroid problem? No Yes

(If you have answered “Yes” to any questions in section 5, go straight to section 8.)

Section 6: Signs and symptoms

9. Do you often have pains in your heart, chest, or the surrounding areas? No Yes
10. Do you experience shortness of breath, either at rest or with mild exertion? No Yes
11. Do you often feel faint or have spells of severe dizziness? No Yes
12. Have you, in the last 12 months, experienced difficulty with Breathing when lying down or been awakened at night by shortness of breath? No Yes
13. Do you experience swelling or a build up of fluid in or around your ankles? No Yes
14. Do you often get the feeling that your heart is racing or skipping beats, either at rest or during exercise? No Yes
15. Do you regularly get pains in your calves and lower legs during exercise that are not due to soreness or stiffness? No Yes
16. Has your doctor ever told you that you have a heart murmur? No Yes
17. Do you experience unusual fatigue or shortness of breath during everyday activities? No Yes

(If you have answered “Yes” to any questions in section 6, go straight to section 8.)

Section 7: Risk factors

- | | | |
|--|----|-----|
| 18. Does either of the following apply to you? | No | Yes |
| a) I smoke cigarettes on a daily basis | | |
| b) I stopped smoking cigarettes on a daily basis less than 6 months ago | | |
| 19. Has your doctor ever told you that you have high blood pressure? | No | Yes |
| 20. Has your doctor ever told you that you have high cholesterol? | No | Yes |
| 21. Has your father or any of your brothers had a heart attack, heart surgery, or a stroke before the age of 55? | No | Yes |
| 22. Has your mother or any of your sisters had a heart attack, heart surgery, or a stroke before the age of 65? | No | Yes |
| 23. Do any of the following apply to you? | No | Yes |
| a) I have had insulin-dependent diabetes for less than 15 years | | |
| b) I have insulin-dependent diabetes and am 30 or younger | | |
| c) I have non-insulin-dependent diabetes and am 35 or younger | | |

Section 8: Signatures

Participant: Date:

Guardian*: Date:

(*Required only if the participant is under 18 years of age.)

Section 9: Additional risk factors (to be completed by the tester if relevant)

24. Is the participant’s body mass index $>30 \text{ kg/m}^2$? No Yes

25. Has the participant answered no to questions 2a **and** 3a? No Yes

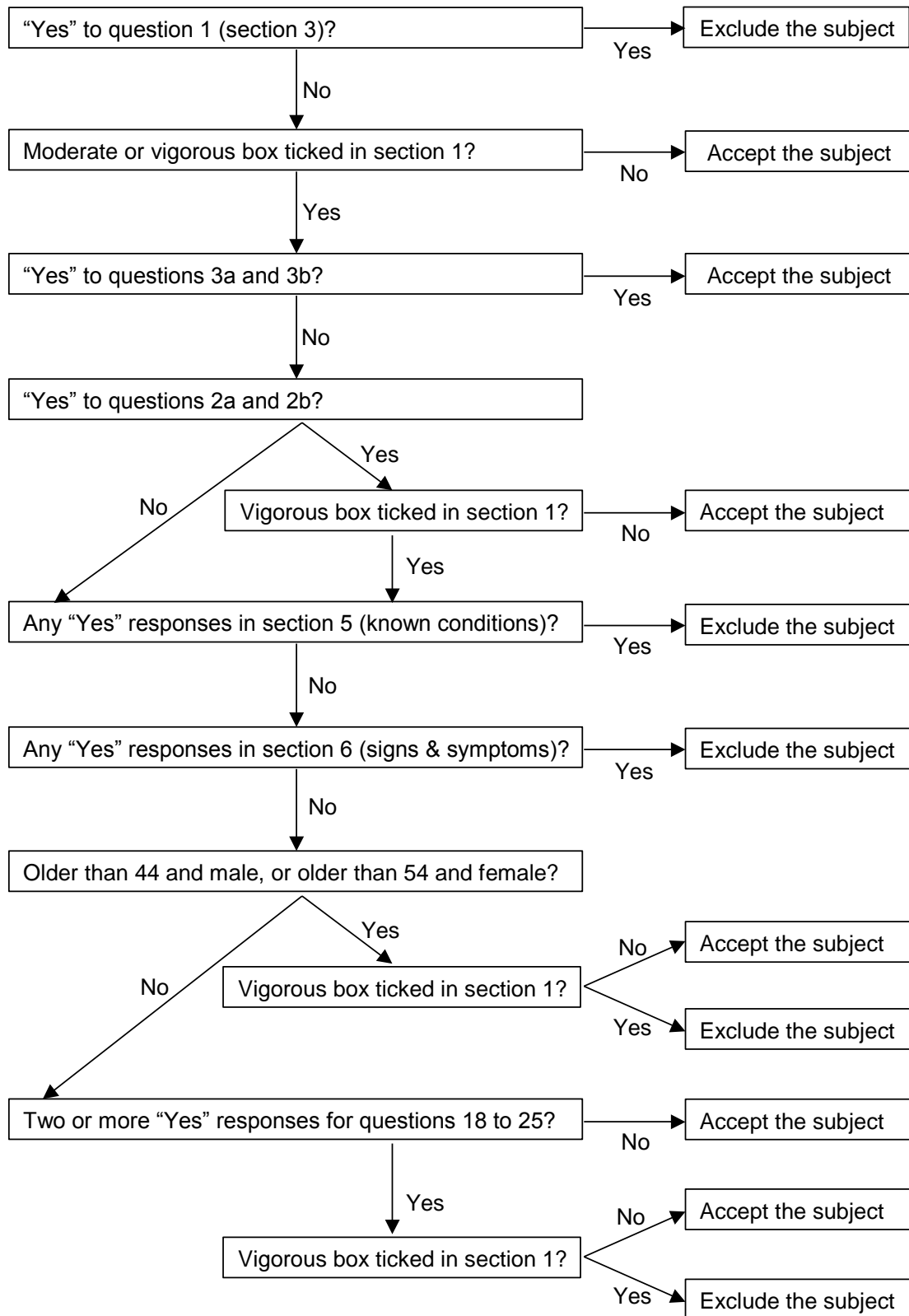
Section 10: Eligibility (to be completed by the tester)

26. Is the participant eligible for the testing? No Yes

Name (of tester):

Signature: Date:

Processing the completed questionnaire – a flow diagram



Preparing and processing pre-test health questionnaires

Introduction

These notes should be read in conjunction with the standard Health Questionnaire of the sport & exercise laboratories. They are intended to assist staff and students with a) preparing a health questionnaire for distribution to a potential participant and b) processing the completed questionnaire. The questionnaire is designed to gather the information needed to decide whether an individual is or is not eligible for a particular set of testing. This information is highly confidential and should be handled accordingly. During the course of a project or sequence of testing, it is the tester's responsibility to ensure that all completed health questionnaires are kept under lock and key and that the information they contain remains confidential. On completion of the project or sequence of testing, these questionnaires should be submitted to a technician, who will store them for 5 years for insurance purposes.

Preparing the questionnaire

First you need to summarise the cardiorespiratory demands of the testing by indicating whether it involves moderate or vigorous exercise. You should tick the moderate box for sub-lactate threshold exercise and the vigorous box for supra-threshold exercise or when testing is likely to invoke a marked cardiorespiratory response. For example, it would be appropriate to tick the vigorous box if the testing involves cold-water immersion, sustained isometric muscle actions or sustained exercise in an unusually hot or humid environment. If cardiorespiratory demands of the testing are minimal, you should not tick either box. However, if you are unsure you should err on the side of caution. Similarly, if you are unsure whether the exercise involved in a particular set of testing will be sub- or supra- threshold, tick the vigorous box. Next you need to summarise the musculo-skeletal demands of the testing by naming the activity and giving an indication of the forces involved in the testing so that the participant can make a judgement about whether any physical problem they have is likely to be aggravated. If you are unsure, err on the side of caution.

Processing the completed questionnaire

The process all laboratory users are expected to follow to reach a decision about whether a particular participant is eligible for testing is outlined below. This process is closely aligned with Olds and Norton's (1999) interpretation of the American College of Sport Medicine's Guidelines for Exercise Testing and Prescription (ACSM, 1995, 2000). It is underpinned by two key principles: first that the risk of a cardiac or other

potentially fatal event occurring in response to exercise is low in individuals who are accustomed to meeting the cardiorespiratory demands of the exercise; second that the risk of such an event occurring in an unaccustomed individual depends on their age, whether they have particular medical conditions or show signs or symptoms of cardiovascular or pulmonary disease, and how many risk factors for cardiovascular disease they have. The process itself comprises a series of sequential steps.

1) Automatic exclusions

Question 1 covers blood-borne diseases, pregnancy, muscle or joint problems, recent fever or feeling unwell on the day. If the participant answers 'Yes' to any of the criteria they are automatically excluded.

2) Cardiorespiratory demands

Section 4 of the standard questionnaire summarises how often they typically exercise and when they last performed moderate or vigorous exercise. An individual should be deemed to be accustomed to a particular intensity of exercise if they typically experience it at least twice a week for moderate or once a week for vigorous exercise and have done so within the last 10 days. Individuals who show themselves to be accustomed to moderate exercise need to be screened further if the testing involves vigorous exercise but accept them if it involves moderate exercise. All participants are eligible for testing where the cardiorespiratory demands are minimal (for which neither the moderate nor the vigorous box would be ticked in section 1).

3) Known medical conditions

If there are any "yes" responses in section 5 exclude the participant, otherwise go to step 4.

4) Signs and symptoms of cardiovascular or pulmonary disease

If there are any "yes" responses in section 6 exclude the participant, otherwise go to step 5.

5) Age and sex

If the participant is older than 44 and male, or older than 54 and female, and the testing involves moderate exercise only, accept the participant or if the exercise is vigorous exclude the participant.

If they are younger than 45 and male, or younger than 55 and female, proceed to step 6.

6) Risk factors for cardiovascular disease

The tester should have completed section 9. To calculate the individual's body mass index (BMI), divide their body mass in kg by their height in cm squared. A BMI of $>30 \text{ kg/m}^2$ constitutes one risk factor. To classify the participant as sedentary or otherwise, use the information from section 4: a "no" response to question 2a **and** 3a constitutes one risk factor.

In section 7 and 9. if there is one or less "yes" response, accept the participant.

If there are two or more "yes" responses and the testing involves moderate exercise only, accept the participant or if it involves vigorous exercise, exclude the participant.

7) Signatures

Accepting or excluding a participant involves answering "yes" or "no" in section 10. Then print your name and sign and date the form. You then need to explain your decision to the participant.

It is sufficient for all participants (except those who report one or more signs or symptoms of cardiovascular or pulmonary disease), to provide a brief oral explanation of why they have been excluded. For those with two or more signs or symptoms, Appendix 8 contains a standard letter warning that the signs and symptoms listed on the questionnaire are not definitive indicators of disease and inviting the excluded participant to discuss with their GP the sensations or events they have reported.

Appendix 7 is a flow diagram showing how to process the completed questionnaire. The principle is that the processing stops when a decision to accept or exclude the participant can be made. Often this point will be reached after two or three steps. Performing all seven steps would only be necessary for testing involving moderate or severe exercise for which the potential participant is young and sedentary, with no known medical conditions or signs and symptoms.

Routine testing vs. specific projects involving special populations

Participants who would normally be excluded from a particular type of testing may be eligible provided the testing is conducted under medical supervision (e.g. in a cardiac rehabilitation programme). Projects involving high-risk populations, or vigorous exercise in moderate risk populations, involve medically qualified personnel and are most likely to be conducted in a hospital environment.

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APPENDIX E

Table 4.1: The W, HR and VO₂ at GET and peak values and the calculated power and VO₂ from these points in the ramp test.

Power (W) at GET	HR at GET (b.min ⁻¹)	VO ₂ at GET (L.min ⁻¹)	Power at				Power at VO ₂ peak (W)	Power at 75% VO ₂ peak (W)	Power at 85% VO ₂ peak (W)
			95% GET (W)	Power _{max} (W)	HR at W _{peak}	VO ₂ peak (L.min ⁻¹)			
249	128	2.67	237	418	169	4.45	408	308	348
220	151	2.46	208	385	180	3.83	363	263	303
177	140	2.14	167	346	203	3.77	335	244	280
97	136	1.27	92	274	180	3.35	265	198	225
132	120	1.71	124	303	174	3.34	296	212	246
127	123	1.16	123	287	164	3.52	268	215	236
102	127	1.37	96	289	186	3.29	278	203	233
134	134	1.78	125	316	184	3.52	310	224	261
124	121	1.26	118	250	189	2.62	240	184	207
192	134	2.33	181	381	175	4.33	369	279	319
235	153	2.44	222	366	184	3.43	337	248	284
196	130	2.52	185	373	178	4.46	368	269	308
Mean	165	133	157	332	181	3.66	320	237	271
SD	53	11	50	53	10	0.54	52	37	43

APPENDIX F

Name	Sub	Sub/Supra (Linear)	Supra (Linear)	Sub/Supra (Curvilinear)	Meas (8-10 min)
Matt Black	2.60551	3.16718	3.18326	3.15751	3.32217
Don Vinson	2.72235	3.00043	3.02574	2.98784	3.44372
Steve Draper	3.31719	3.57970	3.61011	3.57604	3.96620
Colin Baker	2.81070	3.24718	3.26326	3.24299	3.50383
Ben Moreland	3.33709	4.17923	4.21378	4.18761	4.07846
Simon Padley	2.60393	3.33779	3.36666	3.33167	3.61630
Matthew Westerman	2.31781	2.35348	2.36681	2.37969	2.74908
Lee Furneaux	3.17735	2.89974	2.90772	2.89175	3.09962
Peter Habershon	3.64431	3.63451	3.66406	3.63317	4.12130
Luke Coles	2.71227	3.41195	3.44804	3.43087	3.19643
Mark Jeffreys	3.06697	3.01364	3.02740	3.00591	3.14530
Gary McLean	2.47420	2.72550	2.73794	2.72338	2.87016
	2.899	3.213	3.235	3.212	3.426
	0.404	0.473	0.481	0.472	0.453

Name	sub/meas	supra/meas L	Supra (Linear)	supra/measured C	sub/meas(4/6)
Matt Black	0.717	0.155	0.139	0.165	0.635
Don Vinson	0.721	0.443	0.418	0.456	0.403
Steve Draper	0.649	0.386	0.356	0.390	0.425
Colin Baker	0.693	0.257	0.241	0.261	0.647
Ben Moreland	0.741	-0.101	-0.135	-0.109	0.569
Simon Padley	1.012	0.279	0.250	0.285	1.059
Matthew Westerman	0.431	0.396	0.382	0.369	0.141
Lee Furneaux	-0.078	0.200	0.192	0.208	-0.278
Peter Habershon	0.477	0.487	0.457	0.488	-0.014
Luke Coles	0.484	-0.216	-0.252	-0.234	0.427
Mark Jeffreys	0.078	0.132	0.118	0.139	-0.192
Gary McLean	0.396	0.145	0.132	0.147	0.282
	0.527	0.214	0.191	0.214	0.342
	0.301	0.212	0.214	0.216	0.382

Descriptive Statistics

	Mean	Std. Deviation	N
Sub	2.8999442	.40358319	12
Full	3.2027883	.48397693	12
Measured	3.4260475	.45322340	12

Mauchly's Test of Sphericity^b

Within Subjects Effect	Mauchly's W	Approx. Chi-Square	df	Sig.	Epsilon ^a		
					Greenhouse-Geisser	Huynh-Feldt	Lower-bound
protocol	.724	3.236	2	.198	.783	.891	.500

Tests the null hypothesis that the error covariance matrix of the orthonormalized transformed dependent variables is proportional to an identity matrix.

a. May be used to adjust the degrees of freedom for the averaged tests of significance. Corrected tests are displayed in the Tests of Within-Subjects Effects table.

b. Design: Intercept

Within Subjects Design: protocol

Pairwise Comparisons

Measure: MEASURE_1

(I) protocol	(J) protocol	Mean Difference (I-J)	Std. Error	Sig. ^a	95% Confidence Interval for Difference ^a	
					Lower Bound	Upper Bound
1	2	-.303*	.102	.037	-.589	-.016
	3	-.526*	.087	.000	-.771	-.282
2	1	.303*	.102	.037	.016	.589
	3	-.223*	.061	.012	-.397	-.050
3	1	.526*	.087	.000	.282	.771
	2	.223*	.061	.012	.050	.397

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Bonferroni.