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THE EFFECT OF BODY MASS CHANGE ON CYCLING EFFICIENCY

BY

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ABSTRACT

Cycling efficiency is a measure of the ability to convert stored energy into power, and is considered a key determinant of cycling performance. Cycling efficiency has recently been manipulated with various techniques, but most prominently with high intensity training in habitual cyclists and using calorie restriction in sedentary obese participants. It was therefore the primary aim of this thesis to explore the efficacy of utilising a short- and medium-term calorie restriction intervention, to manipulate efficiency with participants accustomed to cycling. A secondary aim was to investigate the validity of measuring efficiency in a field-based environment. Male club level cyclists were recruited for the investigations, which comprised of a moderate -500 $kcal \cdot day^{-1}$ deficit, utilising portion control and measuring efficiency at both absolute and relative steady-state intensities. Seventeen participants completed the short-term, two-week intervention which utilised a randomised cross-over design. Although a significant reduction in body mass was attained, RMR, gross and net efficiency across all intensities and TT power remained stable. Field and laboratory comparisons indicated that prior to statistical correction absolute efficiency was significantly lower in the field, but after accounting for differences in power, cadence and environmental conditions, no differences were present. Twenty-nine participants conducted the medium-term study and were assigned either to calorie restriction or to no dietary intervention. Following a reduction in mass in the calorie restriction group and an increase in the group given no dietary intervention, a significant interaction between mass and efficiency was found across gross and net efficiency workloads. A six week follow-up period indicated that the process of calorie restriction and not absolute body mass reduction was the main mechanism for altering efficiency. This thesis suggests that efficiency can be manipulated both positively and negatively with calorie manipulation, and that these changes are linked to both laboratory and field based performance.

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SUMMARY OF INVESTIGATIONS

Cycling efficiency research has increased in popularity over the past decade and is currently regarded to be a key determinant of performance. Despite a strong rational for the link with performance, improvements in efficiency are rarely empirically confirmed with performance testing. Utilising research and theories from a health and weight loss perspective, in combination with the frequent practice of trained and elite cyclists to reduce mass prior to competition to improve power-to-weight ratio, body mass change as a result of calorie restriction was considered a valid and under researched intervention strategy. Therefore the primary aim of this thesis was to explore the short- and medium-term effects of body mass change on steady-state efficiency and time-trial performance. A secondary aim was to explore the efficacy of measuring efficiency in a field environment.

Study 1 - Variability of body composition assessment, blood parameters, energy expenditure and time-trial performance.

Within and between-day variability of the key variables were assessed prior to experimentation for the purpose of sample size calculation, to assess reliability and streamline protocols. Both within-day and between-day variation indicated that the Durnin and Womersley (1974) 4-site skinfold method had the lowest body fat % variability (CV: 1.12 %) and was the closest in absolute prediction of fat mass to an air-displacement plethysmography device (CV: 3.82 %). Between-day variability determined that RMR measurement could be streamlined to 20 min for subsequent experimental chapters, whilst body mass perturbations provided an insight into the level of mass stability amongst participants (CV: 0.54-0.82 %), equating to a weekly change in body mass of 0.38-0.57 kg for a 70 kg participant. The variability of efficiency was assessed across three workloads; 150 W, 50 % and 60 % W_{max}. All three workloads showed a lower variability when calculated as gross efficiency (CV: 2.89-6.17 %) opposed to net efficiency (CV: 4.30-8.83 %) and in turn the higher sensitivity to change. TT laboratory performance variability (CV: 2.28-3.89 %) was considered similar, although slightly higher to previous studies using trained participants (CV: 1.9-2.19 %, Smith et al., 2001). This indicated that club level cyclists recruited for the reliability study were satisfactorily accustomed to TT performances. In regard to blood analysis, this assessment was also the first to demonstrate the natural weekly variability in a non-hospitalised population using a new portable device (i-STAT).

Study 2 - The effect of short-term calorie restriction on cycling efficiency and performance.

Little is known about the short-term effect of calorie restriction in a non-obese exercising population, where it is likely that a reduction in total kilocalorie intake will reduce carbohydrate availability, having a negative effect on both efficiency and performance. Therefore, the aim of this study was to explore the effect of a short-term (two week), moderate calorie restriction (-500 $kcal \cdot day^{-1}$) on gross, net efficiency and TT performance. Sixteen male cyclists (age 42 ± 9 yrs, body fat 22.3 ± 5 %) were recruited from local cycling clubs, completed a $\dot{V}O_{2max}$ test and three efficiency and TT performance trials (16.1 km). The intervention consisted of a randomised crossover design where a significant reduction in body mass (-1.24 kg) and fat mass (-0.81 kg) was observed during the intervention period ($P < 0.05$, in all cases), with no significant reduction in lean mass ($P > 0.05$). There was also no significant difference in RMR, TT power or TT power expressed relative to body mass ($P > .05$). There was however a significant increase in TT economy (3 %) ($P < 0.01$), but no significant changes in either gross or net efficiency across intensities following short-term calorie restriction. This data suggests that efficiency measurement is a reasonably robust measure to changes in body mass and composition and that TT exercise capacity is not compromised in club cyclists following a moderate calorie deficit for a two-week period.

Study 3 - A field and laboratory comparison of gross efficiency and performance.

Cycling efficiency and economy are frequently measured in a laboratory environment and assumed representative of outdoor cycling, despite limited empirical research in the field. Therefore, it was the aim of this study to develop protocols to measure efficiency in a field environment and to further explore the link between efficiency and performance. Twenty-eight male club level cyclists completed a $\dot{V}O_{2max}$ test in the laboratory prior to a randomised efficiency and TT performance measurement in both the field and laboratory (one week apart). Laboratory testing was performed on a stationary ergometer and field testing on the participants' road bicycle fitted with a power wheel device. The results initially indicated that cyclists were less efficient in the field; however, after adjusting for differences in power, cadence and environmental factors, efficiency values were considered similar ($P > .05$). Field and laboratory TT power had a high positive relationship ($r = 0.8$, $P < .001$). This finding provided evidence to support the notion that laboratory gross efficiency measurement is representative of field efficiency. But, these novel findings also highlighted the importance of controlling for variables (e.g. air speed < 3.0 $m \cdot s^{-1}$) and accounting for confounding variables in the analysis.

Study 4 - The effect of medium-term body mass change on cycling efficiency and Performance.

Changes in body mass have been previously described in studies reporting improvements in efficiency yet, it has not been investigated if greater body mass changes than seen in Study 2, could directly influence efficiency in a habitualised population. Twenty-nine male cyclists were either randomised to a six week body mass reduction group or given no dietary intervention. The study consisted of a pre, post and follow-up phase separated by six weeks. A $\dot{V}O_2max$ test followed by an efficiency and TT performance trial were conducted during each phase of testing. Participants were divided on the basis of mass change, with the mass reduction group significantly reducing mass by -2.3 kg, fat mass by -1.0 kg and lean mass by -1.3 kg ($P < .01$). The participants that were given no dietary instruction gained a similar but opposing magnitude of body mass by 1.9 kg and fat mass by 1.2 kg ($P < .05$), with relative stability in fat-free mass 0.7 kg ($P > .05$). Significant interactions between group effects were present in gross efficiency measured at 150 W and 60 % W_{max}, and net efficiency at 60 % W_{max}. This was suggestive that body mass and by extension energy imbalance has the potential to have both a negative and positive influence on cycling efficiency with a greater negative effect on efficiency with mass gain. Performance power was also not significantly affected by the medium-term intervention but did show a similar pattern to TT economy and steady-state efficiency, providing further evidence that efficiency and performance are indeed linked.

Overall, the investigations demonstrated that efficiency could be manipulated in a trained population, with relatively small changes in body mass. Due to a return of efficiency following mass stability, the results indicated that the process of energy imbalance and not necessarily the absolute change in mass is the main cause for the changes in efficiency. The results also indicated that efficiency may only be temporarily altered with energy imbalance and that resting metabolism remains stable in an exercising population in the early stages of mass change.

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LIST OF SYMBOLS AND ABBREVIATIONS

ADP	Adenosine diphosphate
AMPK	AMP-activated protein kinase
ATP	Adenosine triphosphate
BMR	Basal metabolic rate
BUN	Blood Urea Nitrogen
CAD	Cadence
CE	Cycling economy
CHO	Carbohydrate
CI	Confidence interval
Cl^-	Chloride
CV	Coefficient of variation
Δ	Delta; change
DE	Delta efficiency
EAT	Exercise activity thermogenesis
EE	Energy Expenditure
F_1O_2	Fraction of inspired oxygen
FAT	Lipid
FEV_1	Forced expiratory volume
FFM	Fat-free mass
GE	Gross efficiency
GEE	Generalised estimating equation
GI	Glycaemic index
Glu	Glucose
H+	Hydrogen ion
HB	Haemoglobin
Hct	Haematocrit
HR	Heart rate
HR_E	Exercising heart rate
HR_{max}	Maximal heart rate
HR_R	Resting heart rate
HUM	Humidity
ISAK	International Society for the Advancement of Kinanthropometry
K^+	Potassium
kcal	Kilocalorie
kg	kilogram
kJ	Kilojoule
LCD	Low calorie diet
LCFA	Long chain fatty acids
LN	Natural log
N	Number
Na^+	Sodium
NE	Net efficiency

NEAT	Non-exercise activity thermogenesis
NO_3^-	Inorganic dietary nitrate
IGF-1	Insulin-like Growth Factor
NREE	Non-resting energy expenditure
O_2	Oxygen
PCA	Portable clinical analyser
PCO_2	Partial pressure of carbon dioxide
pH	Blood acidity
P_i	Inorganic phosphate
PRO	Protein
REE	Resting energy expenditure
RER	Respiratory exchange ratio
RMR	Resting metabolic rate
rpm	Revolutions per minute
RQ	Respiratory quotient
SD	Standard deviation
SEM	Standard error of the mean
SF	Skinfold
SRM	Schoberer Rad Messtechnik
TCO_2	Total carbon dioxide
TDEE	Total daily energy expenditure
TE	Typical error
TEF	Thermic effect of food
TEM	Total error of the measurement
TGV	Thoracic gas volume
TMP	Temperature
TT	Time-trial
VAM	Variable average mean
VLCD	Very low calorie diet
VC	Vital capacity
$\dot{V}CO_2$	Carbon dioxide output
$\dot{V}_E$	Minute ventilation
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal oxygen uptake
W	Watts
WE	Work efficiency
W_{max}	Maximum minute power
W_{mean}	Mean watts

CHAPTER 1 – INTRODUCTION

1.1 Preface

Exercise efficiency is a major factor associated with successful outcomes in sport and exercise performance (Joyner and Coyle, 2008). Theoretically to maximise performance of an individual, a high ratio of useful work compared to the total energy expended is key to successful outcomes; this is particularly relevant where competition winning margins are small, and the 'cost' of inefficiencies could account for the resulting differences in performance between individuals (Jeukendrup et al. (2000). Efficiency (or economy) is commonly cited as a differentiating factor between elite athletes in this context, and thus research in this field investigating methods to enhance efficiency and economy is advancing (Jobson et al., 2012, Bonacci, Chapman, Blanch and Vicenzino, 2009).

Despite a clear theoretical link to sport and exercise performance, the increase in research surrounding efficiency and economy has a number of distinct limitations. Early published work did not necessarily use adequate numbers of participants, and a number of studies failed to use appropriate techniques in the collection of data to allow robust conclusions to be supported (Moseley and Jeukendrup, 2001). This led to research into different activities drawing different conclusions. For example, during running where there are very large inter-individual differences in economy, even research with small sample sizes and simplistic research design could identify differences which has led to substantial advances in research in this mode of exercise (Pereira & Freedson, 1997). This was not the case for cycling exercise however, where inter-individual differences appear to be substantially smaller compared to running, and thus conclusions indicated from many early papers that efficiency in cycling was not different between trained and untrained individuals, and thus training could not change this parameter (Moseley, Achten, Martin and Jeukendrup, 2004; Nickleberry and Brooks 1996). However, the consequences of the early conclusions that efficiency does not differentiate between trained and untrained cyclists resulted in the lower volume of literature and understanding of energy expenditure in the field of cycling compared to the research on runners.

A review of the literature in **Chapter 2** clearly identifies studies that have demonstrated differences between participant groups, or changes in efficiency with a specific intervention, however a substantial number of these studies have failed to include any performance marker in their experiments (Jobson, Hopker, Korff and Passfield, 2012). This is important to allow sport and exercise scientists to move away from a theoretical basis (of a particular intervention) to an evidence based approach derived from applied research. A further critical point regarding the performance parameter is the published data from a number of sources indicating a negative relationship between exercise efficiency/economy and maximal oxygen uptake. Because maximal oxygen uptake is the most cited performance indicator amongst all of the endurance literature (Sloth, Sloth, Overgaard & Dalgas, 2013; Jobson et al., 2012), any reduction in this parameter may not be beneficial to performance, and thus investigation in this field must consider performance assessments to clarify changes for the purposes of the application of any intervention. Beyond the lack of consistent performance data, there are other aspects of studies that have investigated exercise economy and efficiency that appear not to have been fully considered. In the estimation of energy expenditure, the utilisation of oxygen and excretion of carbon dioxide are measured. These respiratory gases are indicative of substrate use during exercise and thus can be altered by nutritional intervention.

It is therefore essential that there is tight control of pre-test nutritional intake; this again is not detailed in much of the previous literature when cross comparing groups of athletes, repeated measurement during competition and non-competition phases of training, and pre- post-interventions (Cole, Coleman, Hopker and Wiles, 2014; Hopker, Coleman & Passfield, 2009a). Associated with nutrition is energy balance and in the short, medium and long term has been shown to influence the substrate use estimations from the literature (and thus alter the energy expenditure of an individual). Primarily data derived from inactive participants, in the area of health intervention has demonstrated changes in resting metabolism with changes in exercise and with alterations in body mass/body composition (Poole and Hensen 1988). More recently however, the changes in energy expenditure have been more apparent during exercise rather than at rest (Goldsmith et al., 2010; Amati, Dubé, Shay and Goodpaster, 2008; Rosenbaum et al., 2003) Indeed, in this field corrections for size differences between participant groups are often factored into analysis due to the impact upon primary outcome variables (such as energy expenditure). This is also be a very important concept to consider when assessing the sports performer; there can be substantial changes in body mass/body composition over relatively short periods of time due to the relatively high energy expenditures compared to inactive participants. To date, health-related research has demonstrated fluctuations in energy expenditure at rest and to deliver mechanical work into ergometry systems following reductions and gains in body mass (Poole and Henson, 1988). This fundamental consideration has not been considered in any of the papers evident in the sports performance literature using laboratory based ergometry. The running literature has focussed on minimising body mass in this field, however this has primarily focussed upon minimising mechanical work, but the measurement of mechanical work during running is currently technologically challenging based on wide variations and changes in biomechanics (Boyer, Freedman-Silvernail, Hamill, 2014). If energy expenditure were altered during changes in body mass/composition, then for fixed mechanical workloads there theoretically would be changes in efficiency/economy measures; this has not been considered in the sport science literature, and is not reported in the papers published in this field to date (Hopker, Coleman and Passfield, 2009a). More contemporary work, has begun to address some of these limitations and authors are now citing equipment developments, training practices, nutritional interventions and altitude exposure as potential interventions that could enhance efficiency and economy in sports including both running and cycling (Balsalobre-Fernández, Santos-Concejero and Grivas, 2016; Barnes and Kilding, 2015; Williams, Raj, Stucas, Fell, Dickenson and Gregory, 2009).

The small inter-individual differences present in cycling provide arguably the most consistent and controlled mode of exercise to accurately assess the effectiveness of an intervention. This is particularly relevant for an intervention hypothesised to alter energy expenditure. Cycling therefore makes it possible to detect small and relevant changes in economy/efficiency, which has the potential to directly affect performance. This thesis will initially discuss energy expenditure from a basic and fundamental standpoint of 'energy', to provide a unique perspective highlighting the assumptions and limitations associated with energy measurement, which are frequently overlooked. Exploring energy from this level will lead to a more comprehensive understand of the implications of changes in whole organism efficiency, and the limitations with determining exactly where improvements or reductions occur along the energy transfer chain.

CHAPTER 2 – REVIEW OF LITERATURE

2.1 Energy

Energy is defined as the capacity for doing work and in biological systems is measured in kilocalories (kcal) or kilojoules (Kj), where one kcal is the amount of heat required to raise the temperature of 1 kilogram (kg) of water by 1 ºC (National Research Council, 1989). Work has been defined by Wiser (2000, pp. 7) as 'the product of a force acting upon a body, times the distance the body moves in response to that force'. The laws of thermodynamics are used to understand the conversion of potential energy into usable energy to achieve work. The first law of thermodynamics adapted from the law of conservation of energy and described by Sadava, Heller, Orians, Purves and Hillis (2013), detailed that in an isolated system the total amount of energy is constant, where energy can be transformed but not created nor destroyed. This law explains how energy is always conserved but may appear as if it is absent due to the transference of energy. The second law of thermodynamics explains that when energy is converted, although the total energy does not change the amount of energy to do work is always less than the original amount of energy (Sadava et al., 2013). This law brings about the notion of usable and unusable energy that is attributed to molecular disorder. Due to the phenomenon where energy is required to bring order, the conversion of energy be it chemical or a physical process can never be 100 % efficient. Biological systems are rarely closed or isolated; therefore, the total amount of energy stored can be calculated by subtracting the amount of energy that crosses the system boundary (Serway and Jewett, 2015). In humans, the system boundary would be the epidermis also known as the cuticle or skin. Understanding the conversion of energy is imperative to determine how best to try to improve usable energy and reduce unusable energy while cycling. Energy conversion can be described with five main types; chemical, potential, kinetic, mechanical and heat energy (Wiser, 2000). Frictional forces and fluid resistance will be discussed later in this thesis (**Chapter 3**) as they have a greater bearing on efficiency and performance.

2.1.1 Chemical energy

Food intake is mainly comprised of three individual molecules (carbon, hydrogen and oxygen) which in combination create the macronutrients; carbohydrates (CHO), lipids (FAT) and proteins (PRO), with the addition of Nitrogen to form PRO. (Turner, Cooney, Kraegen and Bruce 2014). During the process of digestion and absorption, the macronutrient bonds are broken with the aid of enzymes, to transfer energy by phosphorylating adenosine diphosphate (ADP) with an inorganic phosphate (P_i) to adenosine triphosphate (ATP). Transferring the energy to ATP ensures the conservation of the energy in a universal format that can be used throughout the body as potential kinetic energy, and as such is commonly referred to as the energy currency. Energy can then be released from ATP with the addition of H_2O (hydrolysis) and in the presence of ATPase enzymes. This fundamental conversion transfers chemical energy into potential kinetic energy (Winter and Fowler 2009). Even at this most basic level of synthesising and degrading ATP, the exact efficiency of energy conversion within a biological system is unknown. The energy available from an ATP nucleotide has been determined with in vitro studies (externally controlled environment) studies, which ascertained that 7.3 $kcal \cdot mol^{-1}$ of energy is available from the hydrolysis process. However it is suggested that in vivo (within a biological system) this value can be as much as 10 $kcal \cdot mol^{-1}$, due to the presence of free energy released from on-going phosphorylation (Akinterinwa and Cirino, 2009). This issue is further compounded by several different mechanisms to achieve ADP phosphorylation and ATP hydrolysis, with the efficiency of the process dependent on; the type of macronutrient, the availability of O_2, the ratio of ATP:ADP:P_i and quantity of H+ (hydrogen ions) within the inter-membrane space per unit of O_2 consumed (Salin, Auer, Rey, Selman and Metcalfe, 2015). Additionally, the energy conversion efficiency of macronutrients is also dependent on the coefficient of digestibility where the proportion of energy that can be processed is reduced by a greater amount of dietary fibre (Hendriks, van Baal and Bosch, 2012). Dietary fibre can reduce the absorption of kcal's by as much as 4 % in the average omnivore diet (2500 $kcal \cdot day^{-1}$, macronutrient ratio [CHO:FAT:PRO] 60:20:20) and 6 % for the same equivalent quantity of kcal's and ratios for vegetarians (Hendriks, van Baal and Bosch, 2012). Bomb calorimetry, which is the method to determine the absolute calorific content of food does not take into account factors such as reduced oxidation and absorption in relation to fibre content. Consequently, the calorific value of macronutrients is reported as the total energy value from bomb calorimetry, minus the unusable energy from incomplete digestion, absorption and the energy excreted as urine and faeces (James, 1995). In the process to determine the ratio between usable and unusable energy, there is a certain degree of standardisation within the calculations to determine the efficiency of energy conversion. Therefore, it is also possible that there are individualistic factors, which can influence the efficiency of macronutrient energy conversion within the gastrointestinal tract. Certain conditions such as celiac disease reduce the efficiency of energy absorption and therefore conversion (Rolfes, Pinna and Whitney, 2015); with environmental factors such as calorie restriction also reported to improve energy conversion (Abete, Navas-Carretero, Marti and Martinez, 2012). The average calorific value for the macronutrients are as follows; CHO = 3.8 kcal·g^{-1}, PRO = 4.0 kcal·g^{-1} and FAT = 9 kcal·g^{-1} (Collins, Hunking and Stear, 2011) with the exact calorific values dependent on the specific source of the macronutrient. In addition to the source and fibre content of the macronutrient affecting the calorific value, protein calorific values are also dependent on the nitrogen content which on average causes ~20 % reduction in the amount of usable energy determined from bomb calorimetry (Jumpertz, Venti, Le, Michaels, Parrington, Krakoff, Votruba, 2013). Consequently, using the average calorific values for the macronutrients creates inaccuracies regarding the total amount of kcals consumed, versus the amount of usable kcals due to individualistic and environmental conditions.

2.1.2 Chemical energy storage

In the event that there is a surplus of usable energy, dietary macronutrients can be stored in an inert form as a multi-branched polysaccharide glycogen, or as fatty acid triglycerides in cytosolic lipid droplets more commonly known as adipose tissue (Iqbal and Hussain, 2009; Turner et al. 2014). Due to the additional processes of converting potential chemical energy so that it can be stored, there is a further reduction in usable energy. The synthesis and degradation of glycogen in the liver is primarily used to stabilise blood sugar levels, while the glycogen in the muscles is used to provide a readily available energy supply for kinetic and mechanical movement (Berg, Tymoczko and Stryer, 2002). The magnitude and rate of glycogen synthesis is particularly affected by CHO intake and the current level of stored glycogen verses the maximal storage capacity in the muscles and liver (Maughan and Burke, 2002). The level of degradation is affected by periods of prolonged calorie restriction and exercise that can cause a substantial shift in the amount of glycogen stored. A single ATP molecule is required to form a complete glycogen polysaccharide and the degradation is largely a passive process, which results in an overall high storage efficiency of ~ 97 % (Berg, Tymoczko and Stryer, 2002). All three macronutrients can be stored as fatty acid triglycerides, with the liver being the main organ for fatty acid synthesis (Vanderkooi, 2014). The predominant dietary fat is triacylglycerol with the conversion to adipose tissue reported to be ~ 89 % in animal studies due to the direct storage pathway (Donato and Hegsted, 1985). Due to CHO and PRO requiring fatty acid synthesis prior to adipose tissue up-take, the conversion to adipose tissue is lower with the reported efficiency ~ 34 % for CHO and ~ 36 % for PRO (Donato and Hegsted, 1985), although it is difficult to determine the exact energy conversion efficiency.

2.1.3 Kinetic energy

Kinetic energy in this thesis will be referred to as the movement of a specific body part as a direct result of chemical energy enabling muscular contraction (Nigg, Stefanyshyn and Denoth, 2000). In a cycling context the circular movement of the legs predominantly in the sagittal plane, is the dominant kinetic energy used to produce force at the pedals and cranks, with additional movement at the pelvis, torso, arms and head being considered in the majority unhelpful for efficient force production. Effective cycling technique can be further determined by the direction of the force applied during a pedal cycle, known as effective force production (Bini, Hume, Croft and Kilding, 2013). Unlike the majority of kinetic motion, the pedalling movement in the legs during seated cycling can largely be controlled with consistent bicycle set-up, making cycling a highly reproducible exercise for the study of changes in energy expenditure (Ericson, Nisell and Nemeth, 1988). The magnitude of kinetic energy while cycling is largely dependent on leg force and cadence, with cadence providing a measure of the rate of leg turnover per minute ($rev \cdot min^{-1}$) and a measure of the change in kinetic energy due to leg mass stability.

2.1.4 Mechanical energy

Mechanical energy is a form of kinetic energy which involves the movement of a machine and or its respective parts (Wiser, 2000); in this thesis, mechanical energy will therefore be used to refer to the movement of external objects such as bicycle wheels, handlebars, cranks and pedals. Power output provides a measure of the mechanical energy that is applied by the cyclist to the pedals and is reported in Watts ($W \cdot min^{-1}$). When measured at the cranks, power is calculated by the torque force multiplied by the angular velocity of the crank arm. The mechanical energy applied to the crank is then transferred to the wheels via a chain to the hub of the rear wheel. This transference of energy to the wheels results in the cyclist and bicycle being propelled forward. Mechanical energy is also used to steer and correct imbalance while riding, although considered a necessary use of kinetic and mechanical energy, this movement does not aid cycling speed and will be considered non-useful energy.

2.1.5 Mechanical Potential energy

Mechanical energy is also affected by the sum of kinetic and potential energy acting on an object due to its motion or position (Whiting and Zernicke, 2008). Mechanical potential energy is equivalent to mass (kg) multiplied by gravitational acceleration (9.8 m.s^2) and by the change in height of the centre of mass (m); within a road cycling context this can be explained when a cyclist is riding up and over a hill. If a cyclist was to maintain the same power output but the gradient of the road changed from being level to an incline, the cyclist would have a reduction in mechanical energy reducing horizontal speed, but would gain potential energy (body mass multiplied by the change in altitude) (Swain, 1994). Due to the mass component, reducing body mass would reduce the amount of potential energy achieved for the same height elevation, but then would also reduce the force required to achieve the same height (Kyle, 2003). This saving of energy to reach the top of the hill would be beneficial as the gain in potential energy from having a higher mass would be less than the energy saved with a lighter mass due to the second law of thermodynamics. Potential energy is also presented in respective to the crank arm position, with the greatest potential energy when the crank arm is at top dead centre (**Figure 2.1**).

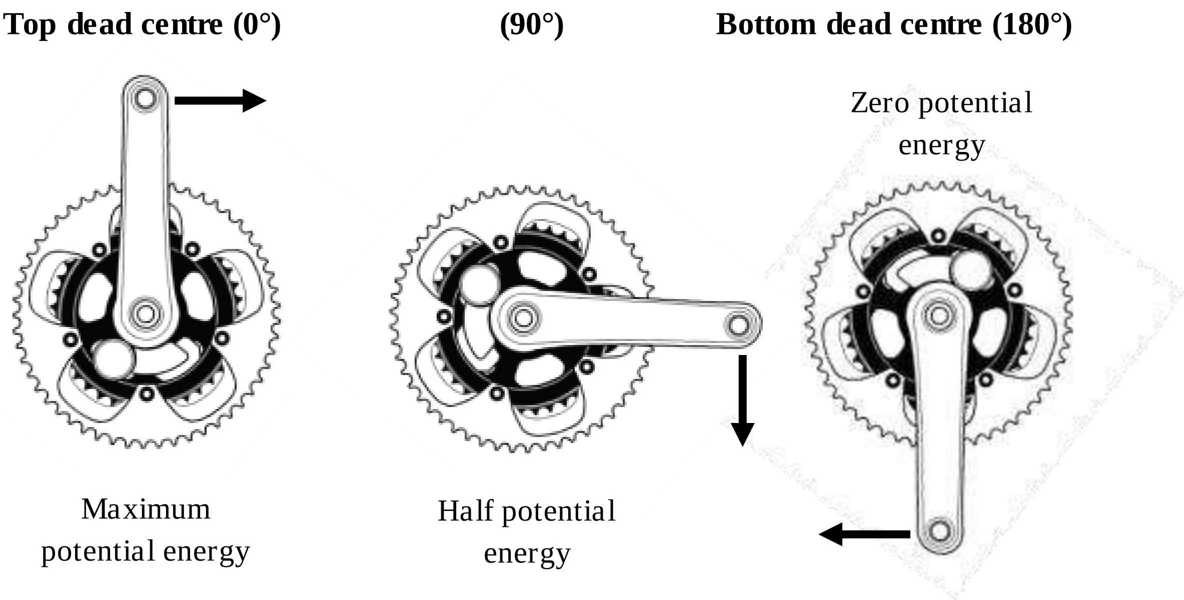


Figure 2.1 Change in crank potential energy from top dead centre to bottom dead centre.

2.1.6 Heat energy

Humans are an example of a homeotherm (animal that maintains a constant elevated body temperature) where heat energy makes up the largest amount of transferred energy. Core body temperature has a very narrow optimal range between 36.4 and 37.3 °C (Nicoll, 2002), with excess heat energy that is not required to maintain core body temperature, considered unusable energy (Heerwagen, 2003). The environmental temperature has a large influence on the amount of energy required to maintain core body temperature, with colder conditions substantially increasing the need for the amount of heat energy required to maintain core body temperature. Heat is transferred in three main ways; conduction, radiation and evaporation. Heat is predominantly transferred to the environment via the skin, with heat also transferred through the respiratory tract during breathing and the excretion of waste products. Although heat transference in the body is often assumed to be predominantly a dissipation of heat to the environment, radiation and conductive energy transference mechanics can also result in the body gaining heat energy if the environment is hotter than the body's periphery. The below equation explains and sums all of the potential factors that influence the total amount of heat exchange.

$$J_{Q \cdot total} = [K \cdot (T_a - T_S)] - [(580\, kcal \cdot L) \cdot J_{H_2O}]$$

Equation 1. Potential heat exchange factors. Where: $J_{Q \cdot total}$ = Total heat exchange, K = the combined constant of the thickness of the skin, subcutaneous body fat, thermal conductiveness and radiation, T_a = ambient temperature, T_S = skin temperature, J_{H_2O} = rate of evaporation (Schafer, 2003).

The skin and subcutaneous body fat have a key role in determining the insulating ability of the overall energy system boundary and the subsequent resistance to change of core body temperature relative to the environmental conditions. The body is able to regulate heat dissipation to the environment under a reflex physiological control system, which adjusts the flow of cutaneous blood to the periphery (Rowell, 1977). Consequently skin and fat thickness as well as skin temperature feature in all of the separate energy transference equations (Schafer, 2003). A thicker insulating layer is considered beneficial in a cold environment, but has a negative effect on the ability to dissipate heat in hotter environments or when exercising causes an increase in the amount of heat production. Convection is also a key factor that can increase the rate of evaporation and conductive heat dissipation by reducing the effective thickness of insulating layers (both biological and manmade). Convection is particularly influential while cycling due to the fast mean cycling speeds reported in professional races (> 40 $km \cdot h^{-1}$, Helou et al. 2010) that are often combined with varying wind conditions.

2.2 Energy expenditure

The process to determine the specific efficiency of each energy transfer within the human body from consumption of food to mechanical energy is extremely difficult, although theoretically possible to estimate. Therefore, sports scientists commonly utilise measures of whole organism energy expenditure. Total daily energy expenditure (TDEE) is the total amount of energy over a 24 hour period and is broadly divided into four main types; Basal metabolic rate (BMR), non-exercising activity thermogenesis (NEAT), thermic effect of food (TEF) and exercising activity thermogenesis (EAT). These can be simplified to resting energy expenditure (REE) and non-resting energy expenditure components (NREE) (Trexler, Smith-Ryan and Norton, 2014) (**Figure 2.2**).

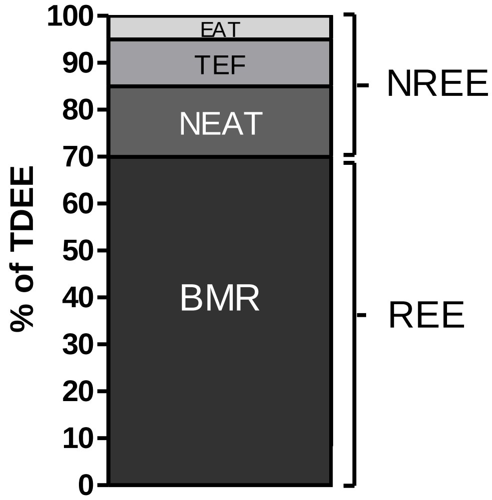


Figure 2.2 Components of total daily energy expenditure (TDEE) adapted from Trexler, Smith-Ryan and Norton (2014). Note: BMR, basal metabolic rate, NEAT, non-exercise activity thermogenesis, TEF, thermic effect of food, EAT, exercise activity thermogenesis, NREE, non-resting energy expenditure, REE, resting energy expenditure.

2.2.1 Calorimetry measurement

The Gold standard of the measurement of TDEE is doubly labelled water, however this method is expensive and difficult to standardise the NREE component in free living conditions. Consequently, direct and indirect calorimetry provide an alternative measure, which can better differentiate between the component parts of TDEE. In particular, the EAT component of NREE and REE comprise the majority of the energy expenditure research, with only small increases in the rate of REE having the greatest potential to increase TDEE, as it encompasses such a substantial proportion (Landsberg et al., 2009). Exercise activity thermogenesis on the other hand tends to be explored from both a health and a performance perspective, where either an increase in the rate of EAT would be beneficial for weight-loss or reducing the rate of EAT would be beneficial when energy availability is a limiting factor for performance.

2.2.2 Indirect Calorimetry

Indirect calorimetry is the most accessible, widely used and versatile estimation of energy expenditure due to the vast level of specialised equipment required for direct calorimetry (Kaiyala and Ramsay, 2011). The calculation of energy expenditure via indirect calorimetry is based on the principle that oxygen consumption ($\dot{V}O_2$) directly reflects ATP-turnover (Medbo, 2008; Cangley and Ansley, 2009). This principle is based on the assumption that there is a linear relationship between oxygen consumption (oxidation) and ATP resynthesis (phosphorylation). Although this is largely true, the exact ratio of $\dot{V}CO_2$ to $\dot{V}O_2$ to re-synthesise ATP is also dependent on the macronutrient oxidised and the respiratory pathway (Salin, Auer, Rey, Selman, and Metcalfe 2015). The Respiratory Quotient (RQ) value describes the ratio of $\dot{V}CO_2/\dot{V}O_2$ at the cellular level, whereas the Respiratory Exchange Ratio (RER) is the measured pulmonary ratio, measured with either direct or indirect calorimetry. The RER is only assumed equivalent of RQ when there is metabolic equilibrium during rest or exercise. Steady-state exercise is essential to allow time for both $\dot{V}O_2$ (2-3 minutes) and $\dot{V}CO_2$ (5 minutes) components to equilibrate (Whipp and Wasserman, 1972). The RQ value for CHO is 1.0, because an equal number of O_2 molecules are required in relation to the number of CO_2 molecules that are produced. Fat contains more carbon and hydrogen atoms than CHO and so requires more O_2 relative to the number of produced CO_2, typically resulting in an RQ value of 0.7. Protein oxidation has an RQ value of ~ 0.85 however, the degradation of PRO for energy is often assumed to be consistent and negligible with a neutral or positive energy balance (Rehrer, Hellemans, Rolleston, Rush and Miller, 2010). When an RER > 1.0 is recorded, the assumption of a negligible anaerobic contribution is violated, and as anaerobic energy expenditure cannot currently be satisfactorily calculated, energy expenditure calculations are restricted to sub-maximal intensities (Medbo, 2008; Cangley and Ansley, 2009). Within the calculation of energy expenditure, $\dot{V}O_2$ is more influential due to the limited range of RER having only a maximum 8 % influence on energy expenditure (Péronnet and Massicotte, 1991). Ventilation ($\dot{V}_E$) and oxygen extraction are the two constituent components of $\dot{V}O_2$, making-up the second tier of oxygen uptake, with ventilation able to be further divided into breathing frequency and tidal volume (third tier). Despite indirect calorimetry being able to provide the breakdown of the constituent elements of $\dot{V}O_2$, energy expenditure below the first tier of RER and $\dot{V}O_2$ are rarely reported (**Figure 2.3**).

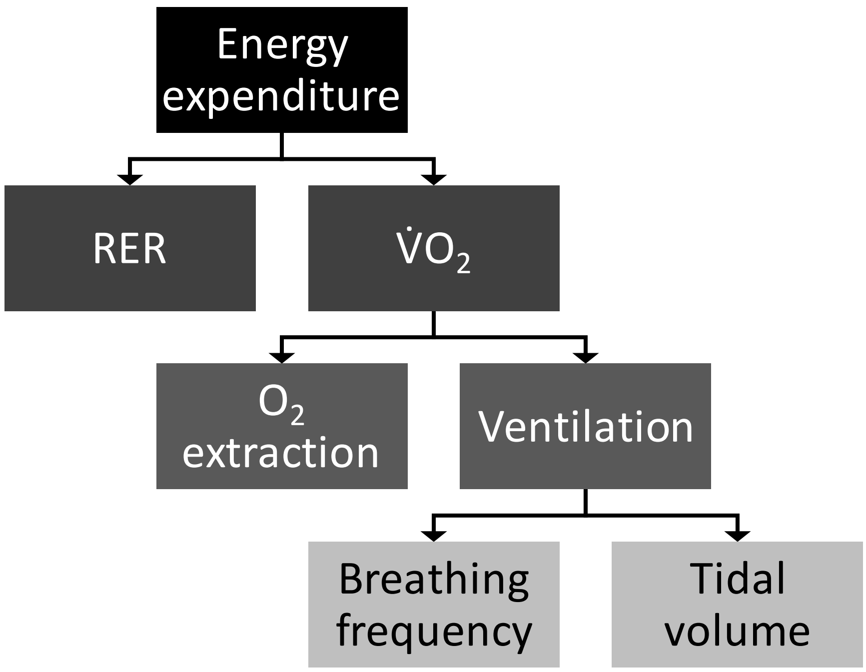


Figure 2.3 Breakdown of energy expenditure measurement via indirect calorimetry. Note: RER, respiratory exchange ratio, $\dot{V}O_2$, oxygen uptake.

2.2.3 Basal metabolic rate and resting metabolic rate

Basal metabolic rate is the rate that the body uses energy to sustain life at rest in a post-absorptive state in a thermoneutral environment and presented as $kcal \cdot min^{-1}$ (Berdanier, Berdanier and Zempleni, 2009). It can be separated into the energy required to maintain cellular structure and function (essential energy expenditure) and energy required to maintain core body temperature described as homeothermy (Landsberg, Young, Leonard, Linsenmeier and Turek, 2009). Homeothermy has been calculated to make-up ~ 2/3rds of BMR, making the transference of heat both to and from the environment a key consideration for BMR measurement (Girardier and Stock 1983). In order to ensure an accurate BMR the protocol requires a 12 hour fasting period to guarantee a post-absorptive state, with measurement conducted while lying in a motionless and supine position, ideally soon after awakening from sleep in the morning. Due to the strict controls of BMR, an overnight stay is commonly employed to ensure stringent adherence, however this requires designated facilities and substantial expense that is often impractical (Zurlo, Larson, Bogardus and Ravussin, 1990). Despite the legitimacy and reported < 1 % error with BMR measurement (Donahoo, Levine and Melanson, 2004), resting metabolic rate (RMR) is more frequently used, as it provides a more practical method for assessing energy expenditure, which requires a less stringent protocol with only a 2-4 hour fast. Although RMR has been described as up to 10 % higher than BMR (National Research Council, 1989), RMR is arguably a better representation of a real world scenario. Despite RMR, REE and BMR often used interchangeably, the term RMR is correctly used when describing the rate of resting energy in $kcal \cdot min^{-1}$, whereas REE is used to describe resting energy when extrapolated over a 24-hour period (Manore, Meyer, Hompson, 2009). Resting energy expenditure comprises the largest component of TDEE (~ 80 %) for the vast majority of the population (Nieman et al., 2006; Landsberg et al. 2009) and despite making-up a smaller proportion when high volumes of exercise are conducted, REE has the potential to have a substantial influence on TDEE. Numerous factors can influence RMR, with a summary of the key variables presented in (**Table 2.1**). Most notably, fat-free mass (FFM) has the largest influence on RMR according to an amalgamation of prediction equations composed by Sabounchi, Rahmandad and Ammerman (2013), with total mass being the next strongest predictor and fat-mass adding a small improvement to the prediction.

Table 2.1 The key factors that influence resting metabolic rate.

Factor	Effect on resting metabolic rate (RMR)
Body Size	
Body mass	↑RMR with ↑body mass (Hulbert and Else, 2004)
Fat-free mass (FFM)	↑RMR with ↑FFM (Hulbert and Else, 2004)
Fat mass	↑RMR due to ↑fat mass (weaker relationship) (Sabounchi, Rahmandad & Ammerman, 2013),
Age	↓RMR with ↑ age following full maturation, with ↓FFM the likely cause (Lazzer, et al., 2010)
Gender	Males have a higher RMR even after accounting for FFM (Sabounchi, Rahmandad & Ammerman 2013)
Genetics	Variation in RMR explained by familial relationship (Bogardus et al., 1986), regression analysis suggested genetics may account for the 15 % unexplained variation in TDEE (Weyer, Snitker, Rising, Bogardus, Ravussin, 1999).
Environmental	↑BMR with ↓ Temperature (Leonard et al., 2002)
Physical activity	
Cardiovascular fitness	↔BMR with ↑$\dot{V}O_{2max}$ following 9 weeks of aerobic training (Bingham et al., 1989)
Acute exercise	↑RMR (~3 %) 48 hours following high intensity exercise (Williamson & Kirwan, 1997)
Physiological factors	
Body temperature	10-13 % ↑RMR with each 1°C ↑ body temperature (Du Bois 1921, cited in Landsberg, Young, Leonard, Linsenmeier & Turek, 2009).
Severe dieting/ starvation	↓RMR when accounting for ↓fat mass and FFM (Dulloo & Jacquet 1998)
Short term VLCD + aerobic training	Aerobic training only marginally ↑RMR from a 13 % reduction (severe calorie restriction) to a 12 % reduction (Henson, Poole, Donahoe and Heber, 1987).
Feasting or overeating	↑RMR by ~11 % with an additional 1500 $kcal \cdot day^{-1}$ above energy balance (Apfelbaum, Bostsarron & Lacatis, 1971).
Illness and injury	↑RMR (Long, Schaffel, Geiger, Schiller & Blakemore, 1979)
Caffeine	100 mg ↑RMR by 3-4 % (Dulloo, Geissler, Horton, Collins & Miller, 1989).
Smoking; nicotine	Smokers have a ↑RMR by 60 $kcal \cdot day^{-1}$ compared to non-smokers adjusted for FFM (Blauw et al., 2015)

Adapted and updated from Manore, Meyer and Hompson (2009). Note: RMR, resting metabolic rate, BMR, basal metabolic rate, FFM, fat free mass, TDEE, total daily energy expenditure, VLCD, very low calorie deficit (< 800 kcal, Wadden, Byrne and Krauthamer-Ewing, 2006). Where studies have measured BMR, BMR has been prioritised over RMR.

2.2.4 Exercise Activity Thermogenesis (EAT)

Exercise activity thermogenesis is comprised exclusively of volitional sporting-like exercise energy expenditure (Levine, Vander Weg, Hill, Klesges, 2006). Despite EAT tending to make up the smallest contribution of TDEE, in elite athletes and dedicated amateur participants the proportion of EAT can be substantially higher. Exercise activity thermogenesis is therefore particularly relevant for competitive athletes and participants due to limited glycogen storage and available blood glucose for prolonged endurance performance (Devlin and Williams, 2005). EAT also provides an indication of the level of adaptation that may have occurred due to an increase in training volume and or intensity. Exercise intensity has a strong positive association with EAT and so is rarely reported in isolation without both a mode of exercise and steady-state intensity (Pritzlaff, 2000). Due to often limited movement allowed by metabolic cart based indirect calorimetry devices, the majority of research has focussed almost exclusively on treadmill walking/running and cycle ergometers. EAT is frequently measured with power values to describe the intensity and total work completed, to enable whole organism efficiency calculation that is also referred to as metabolic efficiency (Hintzy, Mourot, Perrey and Tordi, 2005).

2.3 Efficiency

Whole organism efficiency provides a measure of the ability to convert chemical energy into mechanical energy and is defined as the ratio of work done to energy expended (Gaesser and Brooks, 1975). The work done refers specifically to the power applied to the cranks verses total chemical energy expended and is therefore a measure of effective work (Faria, Parker and Faria, 2005). It is reasoned that whole-organism efficiency measurement is satisfactorily sensitive to detect a global change in efficiency, with smaller changes in energy conversion both positive and negative only detectable when the sum of the changes results in an overall change. As a result, measuring only a single efficiency value reduces the precision in terms of the location of changes in energy conversion efficiency, with the additional vulnerability that an equal cellular positive improvement could be cancelled out by an equal negative change at a different location along the energy transfer chain. Nonetheless, it is based on the notion that an overall change in efficiency is more relevant for performance than likely smaller cellular changes.

$$Efficiency = \left(\frac{Work\ done}{Energy\ expenditure}\right) \times 100$$

Equation 2. General efficiency (Gaesser and Brooks, 1975)

There are four main equations used to calculate cycling efficiency; Gross (GE) has no baseline correction, Net (NE) corrects for RMR, Delta (DE) corrects for the previous work rate energy, and Work (WE) corrects for the energy required to turn unloaded cranks (0 Watts) (Gaesser and Brooks 1975; Moseley and Jeukendrup, 2001; Hintzy et al., 2005). Efficiency can be presented as a ratio out of 1 or presented as a percentage, which is the most commonly reported form.

2.3.1 Gross efficiency

Gross efficiency is the most frequently reported calculation (Gaesser and Brooks, 1975), and is one of the more sensitive and reliable measures when all methods were reviewed by Hintzy, Mourot, Perrey and Tordi (2005). However, gross efficiency shows evidence of distorting the linear relationship between increasing work rate and energy expenditure (Cavanagh and Kram, 1985). This phenomenon is caused largely by RMR making-up a smaller relative proportion of total energy expenditure as work rate increases, and as a result becomes more exaggerated the higher the workload (Gaesser and Brooks, 1975; Pool 1988). Gross efficiency values were originally reported by Gaesser and Brooks (1975) to range between 7.5-20.4 %, however in competitive cyclists this range has been reported to be between 18-23 % (Coyle et al., 1992), with a gross efficiency mean value as high as 24.4 % reported in well trained triathletes (< 30 years of age) (Brisswalter, Wu, Sultana, Bernard and Abbiss, 2014). The purported reasons for the discrepancies are considered largely due to; the equipment used to measure both energy expenditure and power, the sub-maximal workload intensity/duration and the fitness of the participant. While gross efficiency is limited to submaximal intensities eliciting an RER < 1.0, efficiency has been measured up to 80 % of maximum minute power (W_{max}) (Lucia, Hoyos, Perez, Santalla and Chicharro, 2002), indicating that a wide range of intensity measurement is possible.

$$Gross\ efficiency = \left(\frac{Power\ output}{Total\ energy\ expenditure}\right) \times 100$$

Equation 3. Gross efficiency (Mosely and Jeukendrup, 2000)

2.3.2 Net efficiency

To overcome the non-linear relationship seen with gross efficiency, net efficiency provides a potential solution by subtracting RMR (Moseley and Jeukendrup, 2001). Due to RMR being an additional measure of energy expenditure there is however an increased possibility of error and variability within the net efficiency calculation. The length of time and protocol used to determine RMR has a great deal of variety and has been reported to be as much as 50 minutes (20 minutes resting, minimum of 30 minutes recording, Potteiger, Kirk, Jacobsen and Donnelly, 2008), but as little as 20 minutes (Segal, 1987) and 10 minutes (Nieman et al., 2006), with some time periods undetermined based on stability of $\dot{V}O_2$ and $\dot{V}CO_2$ values (Ramires, 2012). Consequently, there is a need to determine a valid and consistent period for RMR measurement. Net efficiency ranges from 24.4 to 31.3 % in physically fit males (Green et al., 2000) and due to baseline correction, is frequently reported to be above the greatest possible physiological efficiency (29 %) (Hill, 1992; cited in Hintzy, Mourot, Perrey and Tordi 2005), this is one of the biggest criticisms of all baseline corrected equations. Although the RMR subtraction should largely correct for the parabolic issue seen in gross efficiency, it is based on the principle that the RMR to maintain homeostasis at rest is equal to the resting metabolic rate during exercise. However, during exercise the essential metabolic rate is likely to change with reductions of blood supply to the gastrointestinal tract, increases in blood flow to the skeletal and cardiac muscle, mobilisation of glycogen storage and increases in ventilation (Mosely and Juekendrup 2001). Despite the issues surrounding net efficiency calculation, it enables a more detailed determination of the source of potential changes in efficiency.

$$\text{Net efficiency} = \left(\frac{Power\ output}{Energy\ expenditure - RMR}\right) \times 100$$

(Mosely and Jeukendrup, 2000)

Equation 4. Net efficiency. Where: RMR, resting metabolic rate.

2.3.3 Work efficiency

The next level of correction for cycling efficiency is work efficiency that addresses two main issues with net efficiency calculation, 1) that RMR is measured in the supine position and not in an upright cycling posture and 2) does not account for the kinetic energy that is required to move the legs in a cyclical motion below which provides mechanical energy. It was argued by Cavanagh and Kram (1985) that accounting for the kinetic energy required to move the legs with unloaded cranks, provides a more accurate representation of force production efficiency. Due to the additional energy correction, work efficiency provides much higher efficiency values (32-33 % Hintzy, Mourot, Perrey and Tordi 2005) compared to gross and net efficiency, further exacerbating the unrealistic representation of mechanical efficiency (Ettema and Lorås, 2009). In addition, work efficiency has been described as less sensitive to change in comparison to gross and net efficiency calculations (Hintzy, Mourot, Perrey and Tordi 2005). The measurement of energy expenditure with unloaded cranks also poses a rather unique and arguably unnatural movement, where participants have to combat the increase in angular velocity during the lowering phase of the cranks; due to the gain in mechanical potential energy at top dead centre. This movement therefore requires additional energy to maintain a consistent cadence to control the angular velocity of the cranks. Expending additional energy not only inflates the subtracted work energy, which artificially improves efficiency, it also likely causes an increase in the inter-participant variation (due to differences in technique and leg mass variation). Since the force to slow the uncoupled cranks is applied in the opposite direction to effective force production, the bearing of the correction is also considered limited (Bini, Hume, Croft and Kilding, 2013).

$$Work\ efficiency = \left(\frac{Power\ output}{EE - Energy\ to\ turn\ unloaded\ cranks}\right) \times 100$$

Equation 5. Work efficiency (Mosely and Jeukendrup, 2000)

2.3.4 Delta efficiency

A final alternative calculation to correct for varying degrees of resting metabolism, cycling position and kinetic energy is delta efficiency. Delta efficiency proposed by Gaesser and Brooks (1975) determines efficiency by the change in power and change in energy expenditure between two different steady-state intensities. Nevertheless, more recently, delta efficiency is calculated as the reciprocal slope of the linear relationship between energy expenditure and work rate (Coyle, Sidossis, Horowitz and Beltz, 1992). Although the delta calculation addresses the issues in net and work efficiency calculations, delta efficiency has been argued to be less valid because the relative contribution of unusable energy decreases at higher exercise intensities (Moseley and Jeukendrup 2001).

$$Delta\ efficiency = \left(\frac{Power\ output_2 - Power\ output_1}{Energy\ expenditure_2 - Energy\ expenditure_1}\right) \times 100$$

Equation 6. Delta efficiency (Gaesser and Brooks, 1975)

2.3.5 Economy

Cycling economy ($W \cdot \dot{V}O_2^{-1} \cdot min^{-1}$) is defined as the ratio of power output ($W \cdot min^{-1}$) to oxygen consumption ($\dot{V}O_2 \cdot min^{-1}$) (Bertucci, 2012) and provides an alternative calculation to assess effective work. This simplified calculation does not take into account macronutrient contribution and so is considered less accurate than efficiency calculation, because of this, cycling economy tends to be reserved for exercise intensities, which induce an RER value > 1.0. Although the anaerobic respiration contribution remains indeterminate, cycling economy allows for the calculation at higher performance intensities (albeit with the anaerobic component unquantified).

$$\text{Economy} = \left(\frac{\text{Power output}}{\dot{V}O_2}\right)$$

Equation 7. Cycling economy. Where: $\dot{V}O_2$, oxygen uptake.

CHAPTER 3: FACTORS INFLUENCING EFFICIENCY AND THE LINK WITH PERFORMANCE

This chapter will summarise and evaluate the current research surrounding the factors that can influence efficiency, and as a result highlight potentially confounding variables for this research. In addition cycling performance will also be reviewed in relation to the theoretical and empirical research surrounding efficiency and performance. See **Appendix 1** for an extensive multi-variable illustration of the factors that can influence cycling efficiency.

3.1 Physical Factors influencing efficiency

3.1.1 Environmental

Core body temperature can increase as a direct result of an increase in work rate, temperature, humidity, subcutaneous body fat and utilizing insulating clothing. Temperature is a recognised factor that can influence muscular function (Ranatunga, 1998) with temperature reported to have a negative linear relationship with efficiency above optimal levels (Daanen et al., 2006). Increases in core body temperature have received the greatest efficiency research interest; most likely due to the cycling race season taking place in warm climates year round in both hemispheres. Segmental and whole body pre-warming/cooling studies have been used to investigate the notion that efficiency is affected by temperature, however discrepancies remain regarding the magnitude and at times the direction of the change (Ferguson, Ball, Sargeant, 2002). The more commonly reported negative association with body temperature and efficiency is currently theorised to be as a result of two separate mechanisms. At a cellular level, it is theorized that an increase in heat above optimal levels can increase the proton-leakage across the inner mitochondrial membrane (Willis and Jackman 1994). Proton-leakage specifically results in a lower ratio of ADP molecules being phosphorylated per O_2 molecule, which adversely affects molecular efficiency. The second theory concerns the body's autonomic response to an increase in core body temperature, whereby cutaneous vasodilation in the peripheral veins aim to increase heat dissipation from the system boundary (Hettinga et al., 2007). Although the exact mechanism remains up for debate, one theory is that reduced venous return to the alveolar compartment reduces blood pressure and reduces the rate that $\dot{V}CO_2$ is expelled, which increases the amount of $\dot{V}CO_2$ present in the blood known as hypercapnia (Wingo, Low, Keller and Crandall, 2008). This increase in $\dot{V}CO_2$ in the veins drives increased ventilation (Serebrovskaya, 1992) and additional/initial cutaneous blood flow (Wingo, Low, Keller and Crandall, 2008) resulting in a higher energy cost to perform the same work or power (Hettinga et al., 2007). Fujii et al., (1985) provided empirical evidence to support this mechanism by inducing voluntary hypocapnia via hyperventilation which resulted in a higher cutaneous blood flow threshold relative to core body temperature. A preliminary study by Bertucci, Arfaoui, Janson and Polidori (2013) supports the cutaneous blood supply theory in direct relation to a reduced efficiency, however further research is required to provide statistical strength, with little conclusive evidence directly confirming a negative association between sub-optimal temperature and a reduced efficiency. Nonetheless, there is evidence to suggest that fluctuations in core body temperature have a direct influence on performance through a reduction in power output. Tatterson, Hahn, Martin and Febbraio (2000) described a 6.5 % reduction in power over a 30 minute time-trial (TT) and Tucker, Rauch, Harley and Noakes (2004) described a 6.5 % reduction in power over a 20 km TT. One reason to explain the reduction in power at sub-optimal temperature has been attributed to a central nervous system regulation of effort, to limit further increases in core temperature (Hettinga et al., 2007). If this is the case, it is likely that efficiency would also be negatively affected due to a reduction in power output. Bailey and O'Hagan (2014) also reported a reduction in TT power of 4 % (albeit not significantly), but reported a significant effect to the pacing strategy as a result of a change in environmental temperature (hot environment; quarterly split mean power decreased with time, cool environment; split power increased with time). The breakdown of the pacing strategy used during the performance TT further supports a power regulation theory whereby the workload is reduced to attenuate heat accumulation. In this thesis laboratory temperature and air convection will be standardized with an air conditioning unit and a large fan to aid heat dissipation and to more closely simulate real-world cycling. Environmental conditions are however, difficult to control in an outdoor field testing environment and therefore conditions will be monitored closely, cutoff thresholds established and differences considered within the analysis.

3.1.2 Pedal cadence

Cadence is a fundamental component of the calculation to derive power output and has a direct link with the kinetic energy cost of the cyclical cycling motion (Broker, 2003). As a consequence, research has explored the link between cadence, efficiency and performance in order to determine the optimal cycling cadence. The concept of preferred cadence has been suggested to not be wholly accurate due to environmental and physical factors often affecting the participants preferred choice such as;

gradient, wind, gearing and competitors (Ansley and Cangley, 2009); due to these factors it has been argued that the drive to determine an optimal performance cadence is restricted to laboratory performance. Optimal cadence in a laboratory environment and from an efficiency perspective would result in a cadence that minimized the metabolic cost of cycling (Ansley and Cangley, 2009). Energetically optimal cadences have been described between 60-70 (rev·min^{-1}) (Takano, 1988; Coast and Welch 1985) with cadences above or below this range being considered to have a higher metabolic cost for the same power output (Swain and Wilcox, 1992). It is important to note that the optimal metabolic efficiency increases slightly with cycling experience, and that a preferred cadence has been reported with a much higher mean range between 80-100 (rev·min^{-1}) (Marsh, Martin and Sanderson, 2000; Foss and Hallén 2005), but as large as 75-107 (rev·min^{-1}) (Leirdal and Ettema, 2011), which is outside of the reported metabolically optimal range. Although the vast majority of the research would agree that lower cadences improve efficiency, partly attributable to an improvement in force effectiveness at lower cadences (Nickleberry and Brooks, 1996; Stebbins, Moore and Casazza, 2014), there is research that contradicts this finding (Sidossis, Horowitz and Coyle, 1992). Consequently it has been argued that what might be more metabolically efficient, might not be a cyclist's preferred cadence as lower more metabolically optimal cadences have been reported to incur higher muscular stress and a greater perception of effort (increased localized sensations of fatigue) (Jameson and Ring 2000; Ansley and Cangley, 2009). It is therefore hypothesised that the negative factors associated with an increased metabolic cost with higher cadences, are outweighed by the positive factors such as reduced muscular stress reducing the feelings of fatigue (Foss and Hallén 2005) and the ability to accelerate (Ansley and Cangley, 2009). As a result, this could have implications for measuring efficiency or economy during performance as opposed to a steady-state noncompetitive environment. It is important to consider the concept of cadence as being multi-dependent, where the optimal metabolic cadence may not be the preferred optimal performance cadence. Despite debate surrounding optimal cadence, the research confirms that oxygen uptake and subsequently energy expenditure and efficiency are significantly influenced by cadence (Ferguson, Ball and Sargeant, 2002). To remove the possibility of cadence as a confounding physical variable within this thesis, cadence was standardized using preferred/habitual cadence that will be maintained throughout testing due to the performance component. While it is useful to maintain cadence within a narrow range as a control measure for testing purposes, it is considered essential to allow for natural variation. Studies which employ a fixed cadence (Stebbins, Moore and Casazza, 2014; Jacobs, Berg, Slivka and Noble, 2013), risk reducing ecological validity as road and track time-trial events, can be quite variable (Lucía, Hoyos and Chicharro, 2001). Where a consistent cadence is difficult to maintain, for instance in field trials, cadence will be added as a covariate to adjust for differences between trials.

3.1.3 Bicycle chain transmission efficiency

Due to the moving parts within bicycle and cycle ergometers, the energy transfer from the pedals to the resultant mechanical energy of the bicycle wheel or flywheel can affect the amount of force transferred and recorded. This is mainly due to frictional transference of energy with specific factors such as; wear and debris between chain and sprockets, sprocket size, chain tension, lubrication and chain offset (non-parallel positioning of chain relative to bicycle). Of the above listed variables only sprocket size (2–5% with smaller sprockets) and chain tension (1.4 %

with maximal tension and up to 19.1% with minimal tension) have been reported to significantly affect frictional losses within chain transmission (Spicer, Richardson, Ehrlich and Bernstein, 2000). In a laboratory setting mechanical efficiency is reasonably stable with minimal and likely consistent chain transmission frictional losses if the same ergometer is used throughout testing and is well maintained. Using the same type of ergometer is particularly important as considerable differences have been stated when comparing between ergometers that use a flywheel and those that do not (Bertucci, Betik, Duc and Grappe, 2012). This difference is attributed to an increased inertial load within the ergometers that use a flywheel making the maintenance of power less physiologically demanding (Hansen, Jorgensen, Jensen, Fregly and Sjogaard, 2002). If comparing efficiency between a laboratory ergometer and a participant's road bicycle it is likely that there are differences in the energy transfer between bicycles. Due to the above factors that can affect the efficiency of the energy transfer, the location of the power measuring device between force application (pedals) to force output (wheel) will also have a bearing on the ratio of recorded force to actual force. To combat potential discrepancies between bicycles and measuring devices, adjustments will be made based on previous reliability testing (Bertucci, Duc, Villerius, Pernin and Grappe, 2005) and laboratory specific testing.

3.1.4 Power output

Gross efficiency is widely accepted to have a positive association with workload (Leirdal and Ettema, 2009); predominantly due to the RMR component of exercising energy expenditure making up a smaller relative proportion as intensity increases (Gaesser and Brooks, 1975; Cavanagh and Kram, 1985). This relationship is said to continue up to 200 W at which it plateaus (Moseley and Jeukendrup, 2001). The plateau in part can be explained by a natural tendency for cadence to increase with work rate (Leirdal and Ettema, 2009), which in turn reduces effective force production (Leirdal and Ettema, 2011), counteracting the improvement in efficiency. Differences between workload intensities is a key reason why efficiency values between studies can vary greatly, particularly when comparing trained verses novice participants (Amati, Dubé, Shay and Goodpaster, 2008; Hopker, Jobson, Carter and Passfield, 2010). Studies that compare absolute intensities ensure that the absolute work is comparable between participants, but do not take into account that an absolute workload intensity could be at a higher relative proportion of a participants W_{max}. Depending on the fitness/cycling experience of the participants, this can also limit the range of the intensities that can be explored to ensure an RER < 1.0 for all participants at all workloads (Hopker et al., 2013). More recently, studies have combined both absolute and relative exercise intensities to counteract the inter-individual differences with absolute intensity measurement (Hopker et al., 2013). The combination of both absolute and relative exercise intensity also allows for the provision to re-assess the relative work load post intervention, ensuring that changes in W_{max} are accounted while having an absolute measure of efficiency for all participants at the same workload. Due to efficiency calculation being limited at the higher intensities, efficiency measurement has rarely been conducted during real-world TT or even simulated laboratory TT's, resulting in limited research surrounding efficiency at a TT power intensity. Regulatory feedback mechanisms vary work load intensities during a TT, and as a result TT pacing is rarely linear when power and time are blinded (Bailey and O'Hagan, 2014). Therefore TT's pose issues for efficiency and economy assessment, as they are non-steady state and can often result in an RER value > 1. Although there are mathematical models to normalize power lasting > 20 minutes (Allen and Coggan, 2010), there currently is no satisfactory method to normalize power < 20 minutes and the influence of varying power on efficiency and economy remains unknown.

3.1.5 Cycling position

Cycling position can broadly be divided into three key positioning components; knee flexion, torso angle (relative to the horizontal) and hand positioning, which are based on the three contact points when cycling; pedals, seat and handlebars (Allen and Cheung, 2012). Knee flexion is perhaps the most important factor for force application and can be altered with crank length, seat tube height, angle and the longitudinal foot position in relation to the pedal (Gonzalez and Hull, 1989). Alterations in knee flexion above and below optimal can alter the range of motion at the knee, hip and ankle (Ericson, Nisell and Nemeth, 1988), with below optimal knee angles reported to cause a greater resultant force but lower force effectiveness, which is likely to lower efficiency for the same absolute work intensity (Bini, Hume and Kilding, 2014). A reduction in effective power due to suboptimal knee flexion is principally theorised due to the length-tension relationship and muscle moment arm lengths within the quadriceps muscles having an impact on the optimal angle to produce force (Jobson, Nevill, George, Jeukendrup and Passfield, 2008). Conversely, Price and Donne (1997) found no effect of changes in knee flexion as a result of alterations in seat height but found a significant improvement in efficiency at steeper seat angles in spite of changes in knee angle. This suggests that seat angle and the positioning of the hips relative to the cranks is more influential for efficient movement than knee flexion alone.

Torso angle has the ability to influence force production, through suboptimal hip angle reducing the force of the gluteal muscles and a reduction in cardiac output (Leyk, Essfeld, Hoffmann, Wunderlich, Baum and Stegemann, 1994; Jobson, Nevill, George, Jeukendrup, Passfield, 2008). However, torso angle did not have an effect on force effectiveness nor gross efficiency in a study by Leirdal and Ettema (2011). Despite increased torso angle having the potential to negatively influence power and efficiency, studies have shown that as long as the position is repeated, efficiency is highly reproducible (Jobson, Nevill, George and Jeukendrup, Passfield, 2008).

Hand positioning is mainly concerned with altering the frontal surface area and drag coefficient, and is therefore more paramount when cycling outdoors and at speeds > 14 $m \cdot s^{-1}$, due to air resistive forces making-up 90 % of total resistive forces (Debraux, Grappe, Manolova and Bertucci, 2011). In a laboratory environment however, the difference in energy cost from a handle bar top and a handle bar drop position have been reported to have no effect on energy expenditure calculations (Ryschon and Stray-Gundersen, 1991). It is important to note that although all three components of body position have the potential to alter efficiency, and could be utilised to ensure the most metabolically efficient cycling position, due to the substantial gains that can be made with a more aerodynamic positon, bicycle set-up is predominantly motivated by reducing aerodynamic resistive forces, with efficiency often a lower priority (Fintelman, Sterling, Hemida and Li, 2014).

Consistent bicycle set-up can be easily ensured in both a testing and field environment, however the exact position of the participant on the bicycle cannot be completely fixed due to small but possible variations in regards to movement on the saddle, elbow flexion, head position and hand positioning (Allen and Cheung, 2012). Despite similar ergometer set-up in the laboratory, the limited but possible movement on a bicycle has anecdotally been reported to result in participants assuming a more upright position in comparison to field positioning (Jobson, Nevill, George, Jeukendrup and Passfield, 2008). This was attributed to the aerodynamic advantages that can be gained in the field condition having little benefit in the laboratory and therefore the more physiologically advantageous up-right position being adopted (Fintelman, Sterling, Hemida and Li, 2014). Although this phenomenon has the potential to confound laboratory and field comparisons the effects of altering torso angle and hand positioning on efficiency have reported negligible findings. Therefore in this thesis the bicycle seat and handlebar position, along with the use of the same pedals will be closely replicated to minimize cycling positional factors.

3.1.6 Body Mass and composition

Cycling is considered a non-weight bearing activity when seated, which reduces the impact of body mass on efficiency in comparison to other activities such as running. Swain (1994) re-analysed data from a previous publication (Swain, 1987) and found that efficiency was not affected by body mass in trained cyclists. However, efficiency was shown to be negatively associated with body mass during stationary cycling in novice participants (Berry, Storsteen and Woodard, 1993). Mass distribution, but specifically leg mass in novice participants was the primary reason attributed to the higher energy expenditure in stationary cycling. Hopker, Jobson, Carter and Passfield (2010) have also investigated lean leg mass in competitive cyclists and found that it was negatively associated with gross efficiency, irrespective of intensity (150 W, $r = -0.59$ and 180 W, $r = -0.58$). This result was attributed to a lower leg mass reducing the kinetic cost of accelerating and decelerating the legs and a higher leg mass having the reverse consequence (Berry, Storsteen and Woodard, 1993). Furthermore, a reduction in mass at the more distal end of the leg (nearer the foot) would reduce the energy cost more, than the same reduction in mass at a more proximal location on the thigh. This is because mass has a higher inertia at more distal ends, due to the greater angular velocity and location to the joint centre (McGinnis, 2004). Total body mass should also be considered in terms of composition, with fat mass being the primary constituent that can reduce mass without having a negative influence on performance power. Currently other than the study by Coyle (2005) which faced substantial criticism, there is little research that assess the influence of a reduced fat mass while maintaining lean mass on participants accustomed to cycling. Therefore, the Coyle (2005) paper will only be used during this thesis for the purpose of body composition reference, and not for changes in efficiency.

3.2 Physiological factors influencing efficiency

3.2.1 Training

Training has been explored to influence efficiency on the principle that it can improve the capacity to utilising O_2 (~20-30%) (Sjogaard, Nielsen, Mikkelsen, Saltin and Burke, 1982), increase work capacity (Gimenez, Cereceda, Teculescu, Aug and Laxenaire, 1982) and improve cycling technique (Coyle, et al. 1991; Jones and Carter, 2000). Research within this area has investigated both comparative and intervention design studies to explore the effect of cycling experience and various training types. Comparative research design has investigated the difference between trained and untrained participants with trained participants being reported to have a

1.4 % higher efficiency across workloads than untrained (Hopker, Coleman and Wiles, 2007). Conversely, Moseley, Achten, Martin and Jeukendrup (2004) reported no efficiency differences between elite and trained recreational cyclists, and Nickleberry and Brooks (1996) also reported no differences between recreational and competitive cyclists suggesting that even a basic level of training is sufficient to reduce the detectable efficiency changes between participants. This lack of difference could be due to the reduced sensitivity of unpaired inter-comparative statistics or could also suggest that training adaptions are minimal after an initial period of training, explaining why a difference was only found between novice and trained participants (Hopker, Coleman and Wiles, 2007). Although comparison studies allow for potentially large training differences between participants, which can span many years; due to the individualistic differences between participants the descriptive data is often unable to explicitly determine if training improves efficiency (Hintzy, Mourot, Perrey and Tordi, 2005). Additionally, investigating the training influence on efficiency in this observational manner is unable to account for possible genetic factors (Joyner and Coyle, 2008) and discrepancies within a trained or competitive cyclists exercise history. The training undertaken in the lead-up to testing could also be a factor where the intensity, mode and duration of training that is conducted in the trained group could influence the results, with Hopker, Coleman and Passfield (2009a) reporting a 1 % gross efficiency improvement over a competitive season. The cycling training season is often divided into several periodized segments where training can vary from baseline endurance to interval sprint training. The most frequent type of cycling training is predominantly endurance based, with endurance training been shown to improve efficiency in untrained female participants by 11 % for gross efficiency, 9 % for net efficiency and an insignificant 2.4 % increase in work efficiency (Hintzy, Mourot, Perrey and Tordi, 2005). This study suggests that endurance training can improve efficiency in untrained participants and suggests that gross efficiency is the most sensitive to change. However, because trained participants tend to be accustomed to endurance training, high intensity training has been suggested to be the most potent training stimulus in comparison to endurance training (Hawley and Stepto, 2001; Laursen and Jenkins, 2002; Jobson, Hopker, Korff and Passfield, 2012). Although the evidence is reasonably convincing for training being considered a key variable to improve efficiency, Hopker, Coleman, Passfield and Wiles (2010) found that the majority of the medium term efficiency gains were achieved after the initial commencement of high intensity training (≤ 6 weeks 1.4 % improvement, ≤ 12 weeks 1.6 % improvement in gross efficiency). This suggests that the improvements commonly reported as a result of a change in training may be achieved relatively quickly and that the rate of improvement soon plateaus. Currently there is little research assessing the long term effect of high intensity training or the speed of decline after high-intensity training ceases. In a recent meta-analysis conducted by Montero and Lundby (2015), it was reported that endurance and high intensity training alone or in combination can improve efficiency in untrained participants, but in trained participants only high intensity training improved efficiency. It is widely accepted that untrained participants have a greater potential to improve their efficiency than trained participants, which is the likely reason why untrained participants had the greater improvement, and why both training types induced an efficiency improvement. While comparative studies suggest that absolute efficiency values are not wholly based on training experience, training intervention studies with both trained and untrained participants have demonstrated that training can improve efficiency. As a result, training intensity, volume and type will be monitored throughout this research and due to the large improvements seen with untrained participants, participants who cycle regularly will be solely recruited to minimise the potential of experimental testing inducing a training effect.

3.2.2 Muscle fibre type

There are three main classifications for the types of muscle fibre, slow-twitch oxidative (Type I), fast-twitch oxidative glycolytic (Type Iia) and fast-twitch glycolytic (Type IIX) (Bottinelli and Reggiani, 2000; Jones, Pringle, and Carter, 2005). Although the fibres are organised according to oxidation and speed of contraction, the classification creates a false dichotomy as there is a great deal of overlap between their metabolic properties (Jones, et al., 2005); which is problematic when trying to identify muscle fibre type and its relation to efficiency. It is widely accepted that Type I fibres make up the majority of an endurance cyclists muscle mass (Kyle, 2003), however debate remains concerning fibre type efficiency with some studies suggesting that Type I fibres are more efficient (Coyle, et al., 1992; Horowitz, et al., 1994), whilst others claiming that they are similarly efficient (He, Bottinelli, Pellegrino, Ferenczi and Reggiani, 2000; Medbo, 2008), and others still that Type II fibres are the most efficient (when cycling at 100 rpm compared to 60 rpm Suzuki, 1979). Discrepancies exist because of a varying perspective over the physiological mechanisms that dominate efficiency, as some take into account absolute energy while others also consider the efficiency of the fuel used to re-synthesise energy (ATP). Currently, the above research has only been able to infer muscle fibre efficiency; predominantly through the use of single muscle biopsies in the Vastus Lateralis muscle (Faria, Parker and Faria, 2005). Another issue is that a single muscle biopsy is assumed to be representative of whole body muscle fibre proportions, which in turn is directly associated with energy expenditure and efficiency calculations (Jones, et al., 2005; Medbo, 2008). Additionally there is also the possibility that recruiting participants who are unfamiliar with cycling (likely due to the invasive nature of a biopsy) increases the variability within efficiency measurement which could be confounding results (Medbo, 2008). Irrespective of the debate, a large proportion of the improvements that are reported in cycling efficiency have been theorised to be as a result of an increase in Type I muscle fibres (Coyle et al., 1992).

3.3 Macronutrient manipulation and supplementation

3.3.1 Macronutrients

Dietary manipulation by altering macronutrient ratios is one approach that has received little attention in the literature with the theoretical possibility to both improve efficiency and conserve CHO energy. Carbohydrate and FAT manipulations have been the primary adjustment nutrients, as they constitute the principal energy sources during endurance cycling; FAT accounting for ~ two thirds of the energy source at 50 % maximal intensity, with CHO taking over as the primary energy source at ~75 % maximal intensity (Maughan and Shirreffs, 2011). Jansson (1982) reported a 5.6 % higher gross efficiency with a five day high CHO diet verses a low CHO diet. Using trained cyclists, Neufer et al. (1987) reported elevated serum glucose levels with the supplementation of CHO prior to testing, and reported a higher work rate in the latter stages of cycling for one hour. In combination, these studies suggest the potential for efficiency to be altered with macronutrient ratios and the potential to influence performance particularly in the concluding stages.

Nonetheless, the above findings are based on small sample sizes; Neufer et al. (1987) utilised ten participants and Jansson (1982) just seven. Cole, Coleman, Hopker and Wiles (2014) recruited 15 trained participants and identified a significant 0.8 % higher gross efficiency with a three day high CHO diet (70 % CHO), opposed to a three day moderate CHO diet (45 % CHO). Interestingly there was no mean difference between the high and low CHO diet (20 % CHO), with efficiency only lower in the low CHO condition during two time points over 120 minutes (25 and 85 min). This suggests that reducing the CHO macronutrient ratio while maintaining a neutral energy balance has the potential to have a negative effect on efficiency, with a high CHO diet having the most likely positive influence. Macronutrients have also been explored in a more supplemental form with CHO ingestion compared to a placebo during 150 minutes of cycling; gross efficiency was again not improved overall, but did show higher efficiency values at two time points during 40 and 150 minutes (Dumke, et al., 2007). There was also an overall reduction in blood glucose in the placebo condition suggesting that glucose availability could explain the reduction in efficiency at the noted time points, and as a result will be measured during cycling efficiency testing within this thesis.

3.3.2 Dietary supplements

The legal definition of a dietary supplement is a product intended to supplement the diet that bears or contains; a vitamin, mineral, herb, amino acid or is used to increase total calorie intake (National Research Council, 2005). The main theorised pathway for a supplement to influence efficiency is via an alteration in RER, by substrate availability modifying substrate oxidation (Brouns, 1989; Graziela, 2003; Coyle et al., 2001; Dumke et al., 2007; Auvichayapat et al., 2008). Increasing fat oxidation is the main motivation for supplements in aiding fat reduction and in doing so could spare CHO, which would be considered beneficial for performance (Dulloo et al., 1999). It is currently unknown if supplements potential cumulative increase in $\dot{V}O_2$ and substrate ratio could affect cycling efficiency. Green tea which contains Catechni Polyphenols are claimed to increase BMR through increased thermogenesis and lipid oxidation (Mukhtar and Ahmad, 2000), with a 4 % increase in RMR (Komatsu et al., 2003), and between a 17 % - 31 % reported increase in fat oxidation (Dulloo et al., 1999; Venables et al., 2008). However, green tea naturally contains caffeine, which is claimed to cause a similar increase in fat oxidation, and there is yet to be conclusive evidence that decaffeinated green tea can significantly affect efficiency. There is reasonably strong evidence to suggest that caffeine increases fat oxidation (Chad and Quigley, 1989; Donelly and McNaughton, 1992; Magkos and Kavouras, 2004), however other studies who found an improvement in endurance have reported no reduction in RER, indicating no increase in measurable fat oxidation (Kovacs et al., 1998; Engels et al., 1999; Jenkins et al., 2008). L-Carnitine also has the potential to increase fat oxidation because this substance shuttles activated long-chain fatty acids (LCFA) from the cytosol, across the inner mitochondria membrane to the mitochondrial matrix for β-oxidation (Brass et al., 1994; Villani et al., 2000). Free and total L-Carnitine are reported to be lower in athletes training for endurance and is supplemented on the premise that it increases fat oxidation during exercise and at rest (Arenas et al., 1991; Abramowicz and Galloway, 2005). Equally many studies investigating the effects of L-Carnitine have failed to show a significant increase in fat oxidation when examining $\dot{V}O_2$ and RER (Brass, Hoppel and Hiatt, 1994; Vukovich et al., 1994) and when monitoring fat mass loss (Villani et al., 2000).

There is also the possibility for supplements to improve efficiency and in turn performance through other pathways such as increasing lactate buffering capabilities in the case of sodium bicarbonate. Currently there is reasonably compelling evidence for sodium bicarbonate in relation to short duration performance with events that result in an elevated blood lactate level (Burke and Deakin 2006; Edge et al., 2005), with endurance athletes also potentially benefitting from bicarbonate supplementation, as they too have elevated blood lactate levels (Oopik et al., 2003). Interestingly, a study that supplemented bicarbonate, mainly looking at the effect on the $\dot{V}O_2$ slow component also calculated gross efficiency (Santalla et al., 2003). While no significant differences were found, bicarbonate did appear to attenuate the reduction in cycling efficiency towards the end of the trial. It is also noteworthy to address that this study was conducted at 90 % of the cyclists $\dot{V}O_{2max}$ intensity, which was shown to increase lactate accumulation quite dramatically. Therefore a high proportion of anaerobic respiration was very likely and called into question the gross efficiency calculations. Inorganic dietary nitrate (NO_3-) is arguably the newest supplement to be suggested to improve performance and efficiency, based on reports that it can reduce the $\dot{V}O_2$ cost of exercise at sub-maximal intensities by ~ 4 % (Vanhatalo et al., 2010) and ~ 3 % (Whitfield et al., 2015). The reason for the reported improvement in efficiency has been suggested to be either linked directly with muscle contraction efficiency within the muscle structure (sarcoplasmic reticulum and or actin-myosin interaction) or during mitochondrial oxidative phosphorylation (Jones, Vanhatalo and Bailey, 2013). Nevertheless an improvement in mitochondrial efficiency has however been discredited by Whitfield et al. (2015) who found no improvement in mitochondrial efficiency to explain the significant reduction in submaximal $\dot{V}O_2$.

It is only relatively recently that supplements have been explored for the primary purpose of altering cycling efficiency, with Quercetin found to have no significant effect (Dumke et al., 2009). Consequently there is limited direct evidence surrounding supplements having a negative effect on efficiency but similarly there is limited research on supplements being able to improve efficiency despite reported performance improvements (Jones, Bailey and Vanhatalo, 2012). Only caffeine currently has reasonable evidence to suggest that it could alter efficiency and so particular attention will be given to limit caffeine consumption prior to testing. Due to the potential influence of participants macronutrient ratios and quantity in the days leading up to efficiency measurement, three day food diaries will be used to ensure similar macronutrient ratios with dietary supplementation restricted during testing.

3.4 Performance

Cycling performance is fundamentally determined by the cyclists ability to produce propulsive forces (power output) and to overcome resistive forces (rolling resistance, aerodynamic drag, crank friction and gravity) (Faria, Parker, and Faria, 2005), while the ability to win is dependent on a combination of physiological, biomechanical, nutritional and psychological factors that are often joined with team tactics (Joyner and Coyle, 2008). Cycling events can range from sprint distances (200m for sprint track qualifying) to multi-stage races lasting several days and even weeks (Tour de France, Giro d'Italia & Vuelta a Espanã), with the average stage race lasting ~ 5 hours (Faria, Parker and Faria, 2005). Typically, the aim of a competitive cyclist is to complete a set distance in the fastest possible time, or in the case of tour racing be the first across the finish line. There are numerous performance models which attempt to both predict performance and determine the key variables to improve performance (Olds et al., 1995). Some models state both physiological and biomechanical factors with Olds (2001) including; $\dot{V}O_{2max}$ (maximal oxygen uptake), fractional utilisation of $\dot{V}O_{2max}$, efficiency and frontal area as the key determinants of performance. Joyner and Coyle (2008) look specifically at the physiological variables and arguably provide the most popular performance model for endurance cycling (**Figure 3.1**). A key theme amongst the majority of performance models are; $\dot{V}O_{2max}$, metabolic thresholds (lactate threshold/submaximal $\dot{V}O_2$) and efficiency/economy (Faria, Parker, and Faria, 2005).

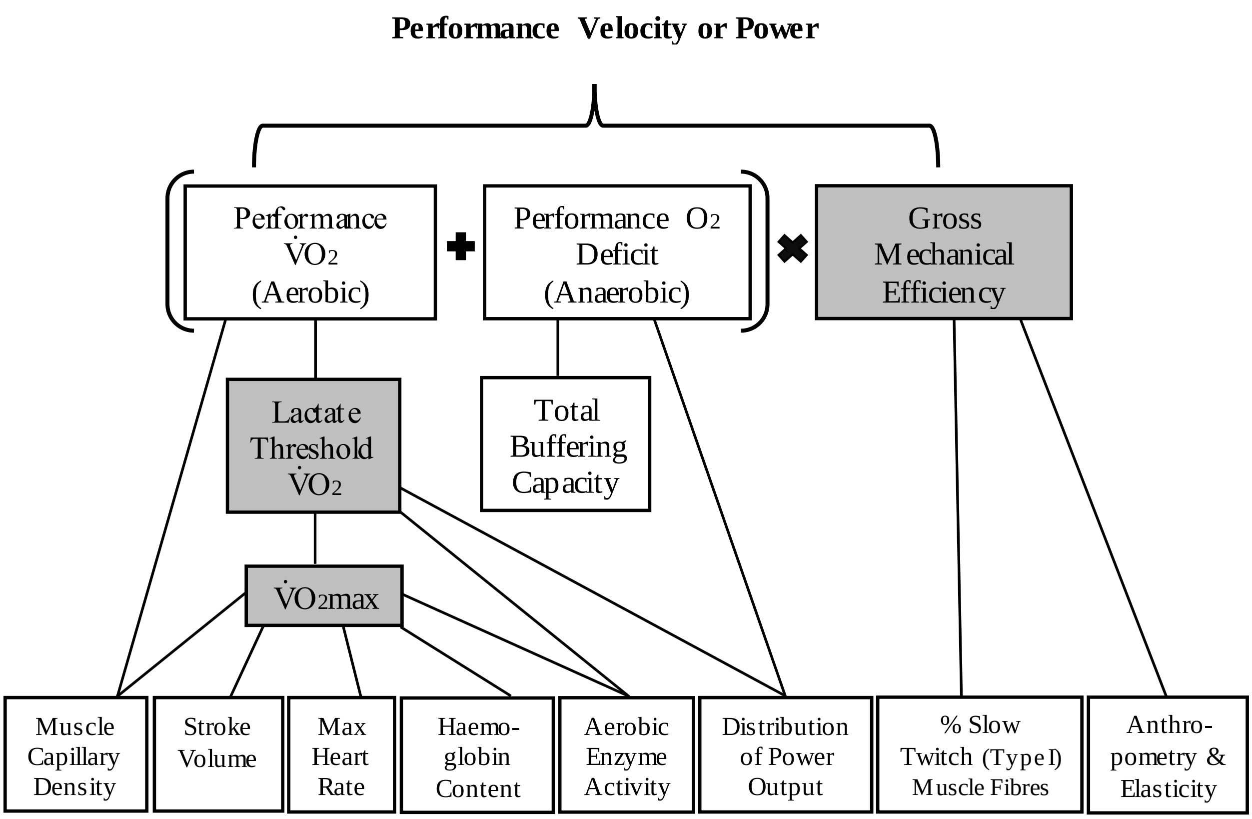


Figure 3.1 Schematic of the determining physiological variables that interact to influence performance (Joyner and Coyle, 2008). Note: Key determinants are indicated with a grey background. Note: $\dot{V}O_2$, oxygen uptake, $\dot{V}O_{2max}$, maximal oxygen uptake.

3.4.1 $\dot{V}O_{2max}$ and performance

Historically one of the most commonly investigated physiological variable in relation to performance is $\dot{V}O_{2max}$ (Jobson, Hopker, Korff and Passfield, 2012). This variable is commonly measured using a graded exercise test to volitional exhaustion, and was linked with performance due to the observation that elite endurance athletes have the highest values (Faria, Parker and Faria, 2005). Maximal aerobic capacity ($\dot{V}O_{2max}$) is defined as the amount of oxygen that can be utilised when exercising maximally and is restricted by tissue oxygen demand, central and peripheral cardiovascular limitations and is frequently presented relative to body mass (Faria, Parker and Faria, 2005). Body mass is often an undervalued component of $\dot{V}O_{2max}$, where a small reduction in fat mass results in a relative improvement in $\dot{V}O_{2max}$, despite no improvements in the magnitude of $\dot{V}O_2$ utilisation. A moderate negative association ($r = -0.554$) has been reported between $\dot{V}O_{2max}$ and body fat % in males (Kriketos, Sharp, Seagle, Peters and Hill, 2000). This suggests that performance could be directly influenced by an improvement in $\dot{V}O_{2max}$ via a reduction in fat mass, yet this is not indicated by Joyner and Coyle's (2008) performance model (**Figure 3.1**). Olds (2001) reviewed and presented numerous studies which explored the relationship with $\dot{V}O_{2max}$ and performance with all but one reporting a highly positive correlation value ($r \sim 0.70$); despite this, $\dot{V}O_{2max}$ is not considered a valid predictor of performance on its own and is frequently combined with lactate threshold and efficiency variables (Craig et al., 1993; Olds et al., 1995). When $\dot{V}O_{2max}$ has been compared with gross efficiency, an inverse relationship has been reported (Lucia, Hoyos, Perez, Santalla and Chicharro, 2002) and it has also been suggested that a greater efficiency appears to compensate for a lower $\dot{V}O_{2max}$ value in highly trained endurance cyclists. It is theorised that where there is a high capacity to supply $\dot{V}O_2$ in the case of having a large $\dot{V}O_{2max}$, there is less of a need for the body to use $\dot{V}O_2$ efficiently. Conversely, in the case where $\dot{V}O_{2max}$ is low there is a greater need for more efficient use of $\dot{V}O_2$ in order to achieve the same work or power output, however there is currently little evidence to support this theory. Due to $\dot{V}O_{2max}$ being limited in part by cardiovascular capacity, a newly proposed approach to explore the inverse relationship is to use pulmonary function tests, specifically measuring vital capacity (VC) (the maximal volume of air breathed out after maximal inhalation) and forced expiratory volume (FEV_1) (volume of forced expired air recorded after one second of expiration) alongside the assessment of $\dot{V}O_{2max}$ and efficiency. Vital capacity and FEV_1 are both very simple measurements that could provide an indication of the size limiting capacity and the airway efficiency, which may be influencing an athlete's predisposition to have either a higher or a lower $\dot{V}O_{2max}$ relative to efficiency. This is yet to be explored within the research and will be used as an exploration of the relationship between $\dot{V}O_{2max}$ and efficiency in the main discussion (**Chapter 11**) of this thesis.

3.4.2 Lactate threshold

Lactate threshold describes the lactate inflection point during incremental exercise where lactate production is higher than lactate use. Lactate accumulation is ascribed to an increase in the rate of glycolysis (glucose conversion to pyruvic or lactic acid) and has superseded the term known as anaerobic threshold (MacRae, 2003). Lactate threshold is considered highly associated with performance (Ghosh, 2004), with very high correlation values (r = 0.91) when associated with 90 minute cycling TT performance power (Bentley, McNaughton, Thompson, Vleck and Batterham 2001). Lactate threshold is also particularly important as a marker of endurance capacity, as the threshold occurs at a higher power output in endurance trained athletes allowing them to sustain a higher percentage of their $\dot{V}O_{2max}$ (Withers, Sherman and Miller, 1981). Ventilatory threshold is believed to provide a similar predictive measure of endurance capacity relative to lactate threshold, but is calculated using gases during incremental exercise rather than blood, and is determined by the point at which ventilation increases exponentially (Gaskill et al., 2001). There are four different methods that can be used to determine threshold, with subjective issues in determining the deflection point present in both lactate and ventilator threshold assessment.

3.4.3 Body composition and performance

Within the Joyner and Coyle (2008) performance model the two categorical variables that link directly to efficiency are proportion of Type I muscle fibres and anthropometry/elasticity. The research suggests that indeed muscle fibre proportion has a direct influence on cycling efficiency (Coyle et al., 1992; Horowitz et al., 1994), but this model also suggests that anthropometry and by extension body composition could also directly influence gross efficiency and in turn performance. This area is yet to be fully explored within a trained population utilising a dietary intervention to manipulate body mass. Body mass also has the potential to have a greater influence on performance if considering the outdoor field environment. The link between field performance and body mass has been described in formulaic terms by Swain (1994).

$$Energy\ cost = (k_r \cdot P \cdot s) + (k_a \cdot A \cdot v^3) + (g \cdot P \cdot i \cdot s)$$

Equation 8. Mass and field performance (Swain, 1994). Where: k_r = rolling resistance coefficient, P = combined mass of cyclist and bicycle, s = bicycle road speed, k_a = air resistance coefficient, A = cyclist's surface area, v = bicycle speed in air, g = acceleration of gravity and i = road incline.

The first component of Swain's (1994) equation explains how the frictional forces between the road and tyre (assuming the same tyre type, air pressure, tread design and material remain the same) are directly proportional to the mass of the cyclist, bicycle and rolling resistance; with greater mass tending to increase the contact area between the road and the tyre. The second component is the cost of pushing the cyclist through air with frontal surface area influenced by cycling position and to a lesser extent the distribution of fat and lean mass (dependent on distribution). The final part is related to gravitational effects on ascents and descents that is directly proportion to the total mass of the cyclist and bicycle. This factor relates to the inertia of the cyclist interacting with gravitational forces and the reluctance of the body and bicycle to change direction and or speed. Using this theory, having a greater mass on a flat level course tends to have an advantage over a lighter cyclist, due to the trend for heavier cyclists to have more lean mass and only marginal increases in rolling resistance, while not being adversely affected by negative gravitational forces and a higher inertia. Conversely, a lighter cyclist would have an advantage over an undulating course due to a lower inertia and higher relative power to weight ratio ($W \cdot kg^{-1}$) (MacRae, 2003). Studies that have compared laboratory and field based performance testing have described that body mass was able to explain 52 % of the variance between the trials (Jobson et al., 2007). The discrepancy between laboratory and field based performance time's highlight the notion that a large proportion of the variation remains unexplained. Previous research comparing efficiency with different ergometers to free cycling suggest that the discrepancy in time could be as a result of a change in efficiency. It seems logical to consider that a proportion of the discrepancy could be due to a change in metabolic efficiency in the field environment, which has been previously linked with differences between ergometers and free-cycling (Bertucci, Betik, Duc and Grappe, 2012).

CHAPTER 4: BODY MASS CHANGE, CALORIE RESTRICTION AND THE LINK WITH CYCLING EFFICIENCY

To date, research is not currently available on elite or even habitualised cyclists in regard to the effect of body mass change. Therefore, in order to fully explore and speculate on the potential effects of calorie restriction on cycling efficiency, this Chapter will explore the efficacy of calorie restriction on an exercising population, with evidence primarily centred from health and obesity research. While there remains little available information on an already exercising population reducing body mass, Although body mass reduction via calorie restriction in an exercising population has primarily been overlooked from a research perspective, reducing fat mass prior to competition is considered standard practice in trained/elite cyclists (Kyle, 2003; Knechtle, Knechtle and Rosemann, 2009). The effectiveness of this process and the influence on changes in body mass, composition and metabolism will be explored in regard to the resultant effect on efficiency and performance.

4.1 Energy balance and body mass change modelling

Energy balance refers to the relationship between energy intake and energy output, where excess intake results in an increase in stored energy (positive energy balance) and a deficit of energy in a reduction (negative energy balance) (National Research Council US Committee, 1989; Landsberg, Young, Leonard, Linsenmeier and Turek 2009). The energy balance equation is a simplified means to describe the theoretical linear relationship between mass gain and mass loss, which is based principally on the first law of thermodynamics (Sadava et al., 2013).

$$Energy\ Intake = Energy\ Output + Storage$$

Equation 9. Energy balance (Landsberg et al., 2009).

Assuming a linear relationship, basic physiological principles can be applied to quantify the magnitude of calorie deficit or excess on the resultant effect of mass change. This was first explained by Wishnofsky (1958) using the information from Bozenraad (1911 cited in Wishnofsky, 1958) that human adipose tissue contains 87 % fat, thus 0.454 kg of adipose tissue is equal to 0.395 kg of fat. Combining the known calorific value of one gram of fat (in the original example 9.5 kcal·g), Wishnofsky (1958) deduced that 0.454 kg of human adipose tissue contains ~3752.5 kcals. This value has since been rounded down to 3500 kcal based on fat containing a lesser 9 kcal·g (Péronnet and Massicotte, 1991). It is noteworthy that this calculation only takes into account the mass change due to fat and water (~90 % of adipose tissue), but does not take into account the protein and triglyceride mass content that is also contained within adipose tissue (~10 %) (Entenman, Goldwater, Ayres and Behnke, 1958; Martin, Daniel, Drinkwater and Clarys, 1994). Utilising the Wishnofsky (1958) calculations and assuming that a reduction in mass is equivalent to a change in fat and water, the formula can be extrapolated to predict the number of kcals required to be in deficit for a desired mass change. Based on a negative energy balance of 500 kcal·day^{-1}, after two weeks (-7,000 kcal) a mass reduction of 0.9 kg would be predicted, after a month (-15,000 kcal) a reduction of 1.93 kg and after six months (-90,000 kcal) a reduction of 11.57 kg. Due to the indiscrimination between either a positive or negative energy balance, mass gain can also be computed with an assumed similar magnitude, but in an opposing direction. (**Figure 4.1**).

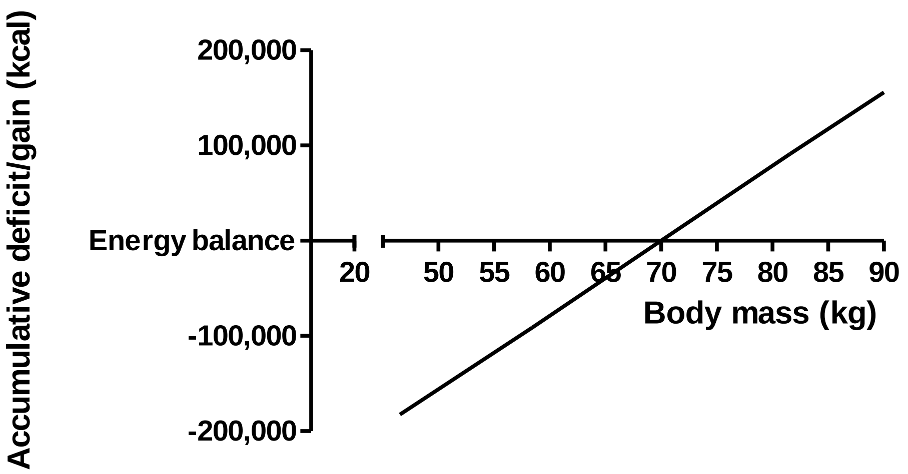


Figure 4.1 Predicted body mass change based on the theoretical linear relationship, with a starting body mass of 70 kg.

While the simplistic energy balance equation (**Equation 9**) is largely correct in principle and research suggests that it can apply for short-term mass change in obese participants (Hall 2008). There are three main failings surrounding the linear model; firstly it suggests that mass reduction and gain are limitless, secondly that lean mass is maintained and thirdly that the same calorie deficit/excess would result in an equivalent and consistent mass change (Hamid, 2009). The main consequence of this computation results in the formula overestimating mass change when used to predict body mass perturbations of medium- to long-term, with greater inaccuracies the longer the duration of the kcal imbalance. A more complex model by Forbes (1987) and adapted by Hall (2007 & 2008) suggest that starting body mass and fat mass have an important influential effect on the required calorific deficit to induce mass reduction. Utilising a parabolic model, a non-obese participant of 70 kg would require a 10 % smaller calorific deficit of ~6943 kcal to induce a 1 kg mass reduction, opposed to ~7709 kcal that would have been previously predicted. Consequently, the adapted equation by Hall (2008) explains that a smaller deficit is required to achieve the same mass reduction for a leaner participant. This is attributed to lean mass having a lower energy density and consisting of a higher proportion of water than adipose tissue. The modified equation was also shown to account for the changes in body mass following semi-starvation techniques in already lean participants, where the linear equation would have grossly overestimated the required deficit (Keys, Brozek, Henschel, Mickelsen and Taylor, 1950).

4.2 Factors affecting body mass change

4.2.1 Body composition

There are considerable differences between the metabolic energy costs of the various tissues in the body. Although the heart, kidneys, brain and liver require a considerable greater number of kcals per kg relative to muscle (13 $kcal \cdot kg d^{-1}$) and fat mass (4 $kcal \cdot kg d^{-1}$) (**Table 4.1)**: Muscle and fat tissue tend to make-up the largest contributions to total mass and therefore proportionally provide the greatest potential to change RMR as a direct result of tissue mass reduction (Hill, Cateracci and Wyatt, 2006). Due to the higher metabolic rate of muscle mass, muscle tissue reduction is expected to have a larger effect on RMR than fat mass reduction. Fat reduction is however reported to have a larger effect on exercising energy expenditure when compared to RMR, attributed to a reduction in inertia and improved heat dissipation (Rosenbaum et al., 2003; Amati et al., 2008). Research also suggests that the rate of fat mass reduction has a tendency to slow, following accumulative and systematic fat mass reduction, which is relative to the total magnitude of reduced fat mass. (Kriketos, Sharp, Seagle and Hill, 2000). The most metabolically efficient body fat proportion has been described by Perriello (2001) as between 7 to 9 % for males, but this is much lower than the current mean ± SD for the male population 23 ± 9.4 %; based on a recent cohort of 3409 males with an average age of 44 years (Flint, Cummins & Sacker 2014). Conversely trained cyclists have been reported to have lower body fat % than the population mean ranging from 7-18 % (Knechtle, Knechtle and Rosemann, 2009), with the upper end of this range providing a large potential for fat mass reduction.

Table 4.1 Contribution of different organs and tissues to total daily energy expenditure.

	Mass		Metabolic rate	
Organ or Tissue	kg	(% of total)	$kcal \cdot kg d^{-1}$	(% of total)
Kidneys	0.3	(0.5)	440	(8)
Brain	1.4	(2.0)	240	(20)
Liver	1.8	(2.6)	200	(21)
Heart	0.3	(0.5)	440	(9)
Skeletal muscle	28.0	(40.0)	13	(22)
Adipose tissue	15.0	(21.4)	4	(4)
Other (skin, gut, bone, etc.)	23.2	(33.0)	12	(16)
Total	70	(100)		(100)

Note: Table from Hill, Cateracci and Wyatt, (2006).

4.3 Hypocaloric diets

Reducing fat mass is a key strategy employed by many cyclists prior to a race in an attempt to improve performance (Knechtle, Knechtle and Rosemann, 2009; Kyle, 2003). This is principally achieved by creating a negative energy balance by either consuming fewer calories and or expending more calories through physical activity (Volek, VanHeest and Forsythe, 2005). Dietary intake can be broadly classified based on energy balance into three main categories; hypocaloric (negative energy balance), isocaloric (neutral energy balance) and hypercaloric (positive energy balance) (Chung et al., 2014). The principle aim of a hypocaloric diet is to reduce mass by reducing fat energy storage. Calorie restriction via a hypocaloric diet is defined as a reduction in calorie intake below usual ad libitum intake without malnutrition (Fontana and Klein, 2007). Reducing dietary energy intake through calorie restriction is perhaps the most common method to induce a negative energy balance as it is one of the easiest, fastest and most effective ways to create a negative energy balance particularly in an already exercising population (Kraemer et al., 1999). The magnitude and duration of the deficit will however affect the rate, sustainability and perhaps more importantly the composition of the mass reduction (Abete, Navas-Carretero, Marti and Martinez, 2012; Trexler, Smith-Ryan and Norton, 2014).

4.3.1 Short-term calorie restriction

Short-term calorie restriction studies (Bakker et al., 2015; Kouda et al., 2006) are classified between 1-14 days (Broom, Hopkins, Stensel, King and Blundell, 2014). Short-term effects of calorie restriction include a rapid reduction in body mass, predominantly attributed to a reduction in stored glycogen, water and foodstuffs within the gastrointestinal tract (Corvilain, et al., 1995; Heymsfield et al., 2012). Glycogen is bound with water in the liver at a ratio of ~ 3-4 g of water for every gram of glycogen (Kreitzman, Coxon and Szaz, 1992). The liver is estimated to contain ~90-110 g of CHO, resulting in the estimated maximal change in mass in the liver to be ~550 g for complete glycogen depletion and assuming the higher water to CHO ratio (4:1) (Gleeson, 2000). Muscle glycogen is also considered likely to be stored with water (Olsson and Saltin, 1970) and muscle tissue is estimated to contain between 300-400 g of glycogen (Gleeson, 2000) dependent on CHO intake, usage, training status and muscle mass (Ahlborg, Bergstrom, Edelund and Hultman, 1967;

Ivy, 1991). Consequently the maximal amount of mass change from muscle glycogen depletion would be between ~1.4-2 kg with a maximal combined whole body glycogen depletion of ~2-2.5 kg. Although complete glycogen depletion has been described by Ruderman, Aoki and Cahill (1976, cited in Cahill, 2006) to take ~ 30 hours following starvation, complete depletion is however unlikely to occur with only a moderate calorie deficit. In addition, the above calculations assume complete excretion of the water bound with glycogen and so provide only an estimation of the maximal mass reduction. Measurable reductions in visceral fat have also been noted with short-term calorie restriction (8 days) utilising magnetic resonance imaging (MRI) albeit with a very low calorie diet (Bakker et al., 2015). Visceral fat specifically has been associated with a greater reduction in the initial stages of moderate calorie restriction in comparison to subcutaneous fat, which is lost more proportionally post the initial effects of calorie restriction and with greater fat reduction (Chaston and Dixon, 2008).

In regard to the effect of the early stages of calorie restriction on energy expenditure, the first component of TDEE to be reduced is the thermic effect of food (TEF) (Rosenbaum et al., 2003). Assuming a direct relationship between kcal intake and TEF with a similar macronutrient ratio; a 20 % reduction in calorie intake (previous isocaloric diet of 2500 kcal·day^{-1}) would result in a 50 kcal·day^{-1} reduction or a 2 % reduction in TDEE. Although TEF is likely to cause a relatively small reduction on TDEE, RMR has long been acknowledged to have a rapid and early response (within a couple of days) to energy restriction (Abete, Navas-Carretero, Marti and Martinez, 2012). Prentice et al., (1991) reviewed a variety of calorie restriction studies and out of 29; only one found calorie restriction to increase RMR (1 week study), one had no change, but the remaining studies had a reduction in RMR ranging from 5-25 %

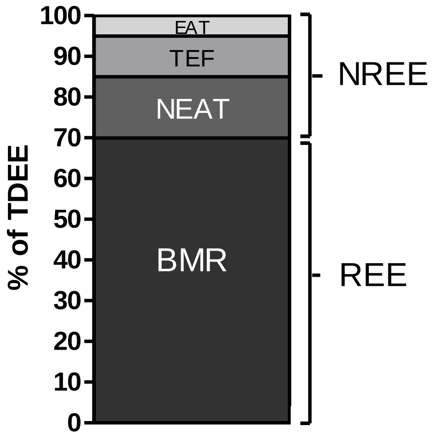
(Parkinson, 1990), with studies of two week duration having a reduction in RMR of ~ 10 %. More recently just four days of slight (intake: 1462 kcal·day^{-1}) verses moderate calorie restriction (intake: 1114 kcal·day^{-1}) inducing a 2 % body mass reduction was shown to cause a 6 and 13 % reduction in BMR respectively, with the greater calorie restriction having the larger effect (Kouda et al., 2006). Assuming a daily energy expenditure of 2500 kcal and RMR consisting of 70 % of TDEE, with a conservative 10 % reduction in RMR (Kouda et al., 2006) would equate to a 175 kcal·day^{-1} reduction in TDEE. Combining the predicted reduction in TEF and RMR it is considered possible to induce a 9 % overall reduction in TDEE over a two week period.

The significant reductions in RMR have been suggested to be because of an improvement in mitochondrial biogenesis, due to an increase in the genes responsible for mitochondrial synthesis and a reduction in damage resulting in more efficient oxygen utilisation (Civitarese et al., 2007). There is also evidence that an increase in proteolysis (protein breakdown), amino acid oxidation and a reduction in protein synthesis provides one of the first metabolic compensatory mechanisms that could also explain a reduction in RMR (Carbone, McClung and Pasiakos, 2012). Although this effect has been reported to be attenuated following continued calorie restriction (Abete et al., 2012), it could have a consequential impact on muscle tissue mass. A reduction in muscle tissue has the potential to reduce RMR, but more so when exercising due to the multiplication of energy expenditure. The above combined effects have the potential to improve cycling efficiency due to a reduction in RMR, muscle metabolism (particularly during exercise) and an increase in amino acid oxidation which is not accounted for in traditional efficiency calculations. Conversely there is also the possibility that short-term calorie restriction could result in a reduction in efficiency, due to a predominance of fat utilisation which requires a higher volume of $\dot{V}O_2$ to oxidise. A greater demand for $\dot{V}O_2$ would either be satisfied from an increased proportion of $\dot{V}O_2$ extraction or increased ventilation, which would incur a higher energy cost (Hopker et al., 2013). In regard to performance, the small benefits commonly associated with having a lower body mass and potentially being more efficient, are likely to be outweighed in the short-term by a reduction in stored muscle and liver glycogen reducing high intensity exercise capacity (Heigenhauser, Sutton and Jones, 1983). Furthermore a reduction in protein synthesis has the possibility to reduce performance power due to a limited recovery from training, albeit a likely small effect during short-term calorie restriction, which is considered to occur in direct proportion to lean mass reduction (Stein et al., 1991).

4.3.2 Medium-term calorie restriction

Medium-term calorie restriction is described between 2-12 weeks (Broom, Hopkins, Stensel, King and Blundell, 2014) and the effects can be attributed to two main and interconnected mechanisms; homeostatic control and the influence of changes in body composition. Changes in body composition play a more active role during medium- to long-term studies as there is a greater potential to change absolute lean mass and fat mass, this in turn would have a larger influence on the components of TDEE (Martin et al., 2007). Because of the link between changes in body mass and TDEE, the changes in energy expenditure are often offset against changes in lean mass (Amati et al., 2008). Goldsmith et al., (2009) reported that metabolic savings of ~ 300-400 $kcal \cdot day^{-1}$ were possible following a 10 % reduction in body mass, after accounting for changes in lean mass. Metabolic savings have been attributed to the detection of a calorie deficit, with homeostatic control mechanisms altering in the opposite direction to the changes in energy balance to either limit mass gain or limit mass reduction (Maclean et al., 2011). This phenomenon is believed in part to explain why body mass tends to plateau following medium-term calorie restriction and why mass reduction tends to be less than predicted (Trexler, Smith-Ryan and Norton, 2014; Byrne, Wood, Schutz and Hills, 2012). It has been speculated that one of the multiple mechanisms attributable for the homeostatic control system can be explained by neuroendocrine adjustments, specifically an extended period of hypothyroidism and hypoleptinemia following calorie restriction (Rosenbaum et al., 2003). Direct improvements in mechanical efficiency at the muscle via a 25 % reduction in glycolytic enzymes (Phosphofructokinase) relative to oxidative enzymes (Cytochrome c oxidase) has also been attributed to an adaptation within the homeostatic control system (Goldsmith et al., 2010). Equally there is increasing and convincing evidence that hypocaloric diets in the medium- to long-term are able to increase life span and reduce disease in a variety of animals (Mair and Dillin, 2008). Although the evidence remains unclear for human's (Cava and Fontana, 2013), the strong empirical evidence from animal studies advocates a measurable downregulation in metabolism, which has the potential to improve cycling efficiency. The exact details of the mechanisms are as yet unknown, but the ageing paradigm is guided by the notion that age is determined by an accumulation of damage (Sohal and Weindruch, 1996). Calorie restriction is therefore believed to slow down the rate of cellular damage through a longer cellular lifespan resulting in a reduction in the rate of cellular reproduction. The mechanism for reducing cellular turnover in the case of energy intake has been termed the nutrient-sensing pathway which is described to be able to assess nutrient status and adjust nutrient-consuming processes such as; growth, metabolism and reproduction of cells relative to energy availability (Gems and Partridge, 2013; Cava and Fontana, 2013).

Maclean, Bergouignan, Cornier and Jackman (2011) describe how all elements of TDEE are affected with calorie deficit (**Figure 4.2**). Although an absolute reduction in; RMR (Martin et al., 2007; Piccolo et al., 2015), NEAT (Levine, 2004), TEF (Miles, Wong, Rumpler and Conway, 1993) and EAT (if comparing similar exercise volume) (Amati et al., 2008) is generally accepted, the magnitude of the change in an exercising population remains relatively unknown. Additionally, **Figure 4.2** also suggests that whole organism efficiency should be improved in the magnitude of all but TEF components of TDEE. It is noteworthy that the metabolic benefits associated with mass reduction are caused specifically through the process of calorie restriction, and are not present if a low body fat is maintained through physical activity (Fontana and Klein, 2007). It is hypothesised that a separate and differing mechanism triggered by calorie restriction results in an overall down regulation and slowing of cellular damage (Civitarese et al., 2007). Consequently a reduction in metabolism via a down regulation in cellular turnover provides a large potential to reduce whole organism energy expenditure and a strong rational for a unique mechanism to improve cycling efficiency.



	Absolute levels	Efficiency
EAT	Variable	⇧
TEF	⇩	?
NEAT	⇩	⇧
BMR	⇩	⇧

Figure 4.2 Effect of calorie restriction and body mass reduction on TDEE (Adapted from Maclean, Bergouignan, Cornier and Jackman, 2011). Note: BMR, basal metabolic rate, NEAT, non-exercise activity thermogenesis, TEF, thermic effect of food, EAT, exercise activity thermogenesis, NREE, non-resting energy expenditure, REE, resting energy expenditure.

4.3.3 Severity of calorie restriction

The severity or magnitude of calorie restriction has been described to be one of the most important factors that influences the rate, composition of mass reduction and the resultant effect on the activation of compensatory homeostatic control mechanisms (Wadden, Byrne and Krauthamer-Ewing, 2006). Slight calorie restriction tends to be described as < 400 kcal·day^{-1} in deficit (Fitzgerald, 2009), moderate calorie restriction commonly induces a deficit between 500-750 kcal·day^{-1} (~80 % of usual intake) (Sinclair, Morley and Vellas, 2012), with low calorie diets (LCD) resulting in a total energy consumption of between 800-1500 kcal·day^{-1} and very low calorie diets (VLCD) providing fewer than 800 kcal·day^{-1} or < 20 % of usual calorie intake (Wadden, Byrne and Krauthamer-Ewing, 2006; Gao, Yan, Zhao, Tao and Zhou, 2015). Severe calorie restriction or VLCD often result in unsustainable mass reduction and have the risk of malnutrition, particularly over prolonged periods (National Research Council US Committee, 1989). Caloric deficits ≥ 1000 $kcal \cdot day^{-1}$ have been noted to result in very little additional fat mass reduction when compared to moderate deficit (500 $kcal \cdot day^{-1}$), with increased adverse reductions in water, electrolytes, minerals, CHO and lean mass (Perriello, 2001). To limit the potential adverse effects of LCD and VLCD, moderate deficits of ~500 kcals (20 % calorific deficit) are recommended to ensure sustainable body mass reduction with lean mass preservation (Trexler, Smith-Ryan and Norton, 2014; Wadden, Byrne and Krauthamer-Ewing, 2006; O'Connor and Caterson, 2010). Moderate calorie deficits for the above reasons tend to be the more popular intervention strategy for medium to long-term calorie restriction interventions (Fontana and Klein, 2007).

4.3.4 Exercise and calorie restriction

Exercise is a branch of physical activity that is often used in combination with calorie restriction to increase calorie deficit. Research suggests that exercise in combination with calorie restriction assists absolute mass change via a direct increase in energy expenditure, but perhaps more importantly is reported to preserve lean tissue (Yoshimura et al., 2014). Preservation of lean tissue has the consequential effect to attenuate reductions in RMR (Stiegler and Cunliffe 2006), with increases in fat oxidation at rest and during exercise also considered additional benefits of combining exercise with calorie restriction (Kriketos, 2000). The weighting of the beneficial effects of combining exercise with calorie restriction are however, largely dependent on the type of exercise. Based on a recent review of 32 controlled trials, Clark (2015) reported that; fat mass was reduced the most when calorie restriction was combined with endurance exercise (effect size: 1.07) and lean mass was best maintained when calorie restriction was combined with resistance exercise (effect size: 1.08). As yet there is little conclusive evidence that prescribing a combination of endurance and resistive exercises with VLCD's has any beneficial effect on body mass, composition or RMR (Donnelly, Pronk, Jacobsen, Pronk and Jakicic, 1991). It is also noteworthy that a reduction in calorie intake has been linked with reductions in energy expended from free-living physical activity (Martin et al., 1985). Therefore, during restricted calorie intervention studies it is important to ensure exercise remains consistent, as changes in the type, volume and intensity could have confounding influences on body composition and factors that would likely influence RMR and efficiency calculations.

4.3.5 Macronutrient ratios

Total mass reduction as a consequence of calorie restriction on average results in ~75 % reduction of fat mass and ~25 % reduction in lean tissue (Weinheimer, Sands and Campbell, 2010). Recent reviews do however suggest that lean mass reduction can be significantly attenuated with both sufficient protein intake (0.8-0.9 $g{\cdot}kg^{-1}{\cdot}day^{-1}$) and above sufficient levels (> 1.05 $g{\cdot}kg^{-1}{\cdot}day^{-1}$ / ≥ 25 % protein) (Trexler, Smith-Ryan and Norton, 2014; Wycherley, Moran, Clifton, Noakes and Brinkworth, 2012). Layman et al., (2003) similarly reported an improved lean mass attenuation with a high protein hypocaloric diet but also found a greater fat mass reduction as opposed to a hypocaloric diet with adequate protein intake (0.8 $g{\cdot}kg^{-1}{\cdot}day^{-1}$). Nevertheless the research remains rather equivocal with Backx et al. (2016) suggesting there is little difference between body mass reduction and lean mass change when comparing adequate (0.9 $g{\cdot}kg^{-1}{\cdot}day^{-1}$) and above adequate (1.7 $g{\cdot}kg^{-1}{\cdot}day^{-1}$) levels of protein intake. In addition small changes in macronutrient ratios (PRO: from 18 to 25 % and from 49 to 42 %) are reported to have little effect on total mass reduction (Lockard et al., 2015; Gardner, Offringa, Hartle, Kapphahn and Cherin, 2015). Based on the above research, a cautious approach to a hypocaloric intervention would require standardisation of macronutrient ratios to ensure limited changes pre, during and post intervention. Therefore a portion control strategy to reduce calorie intake but limit changes in macronutrient ratios would seem a rational option that would minimise food choice disruption, reduce RER fluctuation as a direct effect of macronutrient proportions and arguably increase the sustainability of the intervention (Rolls, 2014).

4.3.6 Free-living body mass rebound

It could be argued that a research led approach to mass reduction utilising calorie restriction techniques that are often combined with some form of laboratory testing, is a rather artificial means of altering a participants dietary habits to manipulate body mass and composition. When research interventions are complete, it is logical to consider that in most cases physiological feedback mechanisms and pre-intervention eating and exercise habits will inevitably return the participant to the original body mass and composition. The notion that only 2 % of participants are able to maintain a reduced mass in the long-term (two years post intervention) was proposed by Stunkard and McLaren-Hume (1959, cited in Wing and Phelan, 2005). However with the clarification of the definition to mass maintenance requiring a > 10 % of intentional body mass reduction maintained one year post intervention, the value has since been increased to ~20 % of participants being able to maintain a reduced body mass (Wing and Phelan, 2005). Despite a substantial increase in the number of participants maintaining a reduced mass, a large proportion of the mass reduced during an intervention is frequently regained. The original hypothesis that humans maintain a preferred body mass and composition stemmed from observations that both animals and humans mass tend to return to pre-intervention values following the cessation of an intervention (Harris, 1990). This resulted in the development of the 'set-point theory' which suggests that an autonomic feedback mechanism, most likely hormone controlled aims to return body mass but more specifically fat mass to the pre-intervention state (Farias, Cuevas and Rodriguez, 2011). Considering that metabolic compensations and the set-point theory are reasonably widely accepted, few studies include follow-up mass changes. Sustained reductions in RMR have been described as long as 12 weeks following severe calorie restriction (Dulloo and Jacquet, 1998), however with a more sustainable moderate calorie restriction it is unlikely that the effects will have a similar longevity. Due to a lack of clarity on the rate of mass regain in an exercising population, follow-up testing will be conducted in this thesis to allow for the monitoring of the participants mass, composition and metabolism to assess if any potential changes in efficiency and performance are maintained. This allows for the attainment of an intervention to also be assessed on the longevity of the outcome, a factor that is often neglected.

4.4 Cycling efficiency and calorie restriction

Despite the potential for efficiency and performance gains, mass reduction has predominantly been studied for the purpose of improving health by reducing fat mass to combat obesity and obesity related diseases (Washburn et al., 2014). Only a small number of studies have directly assessed the effect of body mass reduction on exercise energy expenditure, with fewer still calculating efficiency, as the majority of obesity led research has been guided by the notion that RMR is the predominantly effected component of TDEE (Apfelbaum, Bostsarron and Lacatis, 1971). To the authors knowledge only one study which has been heavily criticised using a professional cyclist has eluded to reductions in body mass overtime being attributed to an improvement in efficiency (Coyle, 2005). As a consequence of the ubiquitous obesity perspective, the existing calorie restriction research (Poole and Henson, 1988; Amati et al., 2008) has focussed primarily on overweight and obese participants who infrequently exercise.

Poole and Henson (1988) were one of the first to explore the effect of caloric restriction on gross and work efficiency. They reduced body mass by 5 % in 13 moderately obese women (average 4 kg reduction) over three weeks with a LCD consisting of 800 $kcal \cdot day^{-1}$. Although they did not find a significant change in gross or work efficiency using four minute work stages on a cycle ergometer, RMR when inferred from absolute $\dot{V}O_2$ was significantly reduced at rest and zero watt cycling, but not during resisted exercise. A later study by Rosenbaum et al., (2003) reduced body mass by 10 % (N = 30), which caused a significant 27 % relative improvement in net efficiency when cycling at 10 W and a nonsignificant 10 % relative change at 50 W, while RMR remained reasonably unaffected. The effect of a 10 % mass gain was also explored albeit with less participants (N = 8), where a significant 20 % reduction in net efficiency was reported at 10 W and a 5 % reduction at 50W. Goldsmith et al., (2010) reported similar effects following both a 10 % increase and 10 % decrease in body mass, with a 15 % improvement in net efficiency at 10 W with mass reduction and a 38 % decrease in efficiency at 10 W with mass gain. It was proposed that a mechanism active during very low intensity exercise was most likely responsible for the efficiency improvements, due to a narrowing of changes in efficiency values at the higher 50 W intensity. In an attempt to isolate if the mechanism was biomechanical or physiological, Rosenbaum et al., (2003) estimated the mass reduced from the lower limbs and added exogenous weights to the thighs of the 10 % mass reduction group. The results indicated that changes in lower extremity mass accounted for ~ 60 % of the changes in energy expenditure when cycling at 10 W and ~ 40 % at 50 W. Although there are inaccuracies with estimating the magnitude and distribution of mass change and the resultant magnitude and location of the exogenous mass; the findings suggest that a combination of both biomechanical and physiological mechanisms associated with exercising energy expenditure, were responsible for the efficiency improvements. This therefore puts into question the initial proposal that RMR is the dominant mechanism for reducing energy expenditure whilst exercising. In addition, Rosenbaum et al. (2003) provides support for the notion that the process of mass reduction (calorie restriction) may be a key influencing factor responsible for inducing changes in physiological mechanisms during exercise. Since Poole and Hensons' (1988) and Rosenbaum's (2003) publications it has been reported that at least five minutes should be allowed for steady state $\dot{V}O_2$ and $\dot{V}CO_2$ to be achieved; rendering their calculations of efficiency potentially erroneous and unreliable as stability of $\dot{V}O_2$ and $\dot{V}CO_2$ is a pre-requisite for accurate efficiency calculations (Wasserman et al., 2005).

To the author's knowledge Amati et al., (2008) is the only paper that has investigated both the singular and combined effects of calorie restriction and exercise training on gross efficiency. Despite reporting a significant gross efficiency improvement in the exercise (4.7 %) and combined group (9 %), they failed to find a significant improvement in the calorie restriction group (~ 4 %). The nonsignificant finding was likely due to a grouping bias where the calorie restriction group only represented 17 % of the total sample size (N = 64). It is also noteworthy that the proportion of Type I muscle fibres decreased in both of the conditions with calorie restriction, and it was only in the exercise training group that a greater proportion of Type I muscle fibres were found albeit non-significantly. This suggests that gross efficiency could be significantly improved irrespective of the percentage of Type I muscle fibres, indicating that other key physiological mechanisms are likely responsible for the efficiency improvement. Further criticisms of the study concern; the absence of a control group, an alteration of macronutrient ratios in groups involving dietary intervention (< 30 % fat intake), insufficient dietary intake standardisation prior to testing and the magnitude of calorie deficit ranging from 500-1000 $kcal \cdot day^{-1}$.

Currently, the research concerning the effect of body mass reduction through calorie restriction have ensured a period of mass stability prior to testing to limit the likelihood of increased protein oxidation. As a result the present findings are limited to conclusions concerning medium to long-term body mass reduction and not the direct effect of calorie restriction on efficiency. The above research has also used participants with low activity levels, with the majority being classified as sedentary. This has not only limited the scope of the investigations to low exercise intensities between 10-105 W (Rosenbaum et al., 2003 & Goldsmith et al., 2010); 10-50 W; Poole and Hensen 1988; 30-105 W and Amati et al., 2008; 20-75 W), but resulted in a wide range of efficiency values (7-19.0 %) allowing for the potential magnification of relative efficiency changes. By using participants unaccustomed to cycling it is difficult to control for the possibility of a learning or training effect during experimentation; although Amati et al., (2008) did attempt to overcome this by performing repeated tests pre- and post-intervention with some of their participants. As a result trained cyclists would reduce some of the unknown factors and increase the range of absolute power output, improving the application of calorie restriction studies to the changes in cycling efficiency research. Utilising trained cyclists would also allow for the valid exploration of the effect of any potential changes in efficiency on cycling performance, with an intervention not theorised to improve absolute power output, unlike numerous training studies.

4.5 Performance implications

Based on physiological principles of calorie restriction, reductions in absolute peak power and endurance performance are considered to be probable in the short-term (Perriello, 2001). In the short-term the three mechanisms believed responsible for a performance decrement are reduced muscle and liver glycogen stores, dehydration and a reduction in lean mass (Perriello, 2001). Reductions in lean mass in particular have been associated with an absolute reduction in maximal power and $\dot{V}O_{2max}$ (Weiss et al., 2007). It has also been noted that calorie restriction can slow the recovery process, hampering the possibility of performance gains during the training season and recovery after competition (Burke, Loucks and Broad, 2006). Reducing body mass during the competitive season is therefore not recommended due to these negative effects, but it is frequently noted that athletes find it difficult to maintain competitive body mass (O'Connor and Caterson, 2010). Weight cycling is a practice which allows athletes to reduce body mass during the competitive season, often involving several short periods of calorie restriction to achieve a desired body mass/composition, that is usually combined with a short period of re-feeding prior to competition (Saarni, Rissanen, Sarna, Koskenvuo and Kaprio, 2006). Although the process of calorie restriction in the short-term is likely to have a negative effect on performance power; the medium-term effects often result in reduced total body mass, subcutaneous fat tissue, RMR and increased fat oxidation at higher absolute intensities (Rosenbaum et al., 2003). These beneficial effects could likely improve performance through a direct improvement in efficiency in a laboratory environment. Moreover in an outdoor field environment there is a greater potential to improve performance, due to improved biomechanical factors combining with physiological. Body mass reduction has the possibility to reduce; frontal area (albeit only very slightly), the force required to accelerate and decelerate the total mass (bike and rider) and the force required to maintain velocity up-hill (Kyle, 2003). This is supported by the research of Jobson et al. (2007) where body mass/size was attributed as the dominant variable that influenced TT performance in the field environment, when compared to stationary laboratory cycling. The collective term for the main biomechanical benefits, tend to be broadly summarized to an improved power-to-weight ratio (Garthe, 2011), which when combined with physiological factors could improve efficiency (Amati et al., 2008), thermoregulation and have a CHO sparing effect. The potential for performance gains are however, dependent on the rate of the initial calorie restriction to ensure minimal lean tissue loss (Garthe, Raastad and Sundgot-Borgen, 2011) and that prior to performance an isocaloric diet is consumed to ensure adequate glycogen storage and hydration (Perriello, 2001). Thus gradual and slow rates of mass reduction are recommended in athletic groups, particularly in the short-term as research assessing the long-term effects between slow and fast rate mass reduction show little differences in performance (O'Connor and Caterson, 2010). Despite a strong physiological basis to suggest certainly in the short-term calorie restriction would be disadvantageous to performance, currently there is little research to determine the magnitude of the effect of moderate calorie restriction in either the short- or medium-term on cycling efficiency and performance.

CHAPTER 5: Rationale, aims and objectives

5.1 Rationale

Cycling efficiency is considered a key determinant of performance (Ettema and Lorås, 2009; Gaesser and Brooks, 1975; Horowitz et al. 1994; Korff et al. 2007; Olds et al. 1995) based on the theory that a higher efficiency either allows for a reduction in total energy to achieve the same amount of work, thus conserving energy or allowing a higher work rate for the same amount of energy, resulting in an improved endurance capacity (Lucia et al. 2002). Efficiency has been argued to have a direct influence on the $\dot{V}O_2$ cost relative to power, (Joyner and Coyle, 2008) with efficiency likely able to explain ~30 % of the variation in performance power (Jobson et al., 2012). Despite this, efficiency has been underrepresented in comparison to the extensive research linking $\dot{V}O_{2max}$ and lactate threshold parameters to performance. The performance models that include efficiency make little acknowledgement of the effect of race distance, with efficiency likely having a greater influence on performance in longer endurance events as the saving of energy or time is accumulative (Jobson et al., 2012). Jeukendrup et al. (2000) calculated that a 1 % improvement in efficiency over a 40 km cycling TT, would translate to a 63 second reduction in time. This is classed as a significant amount as Wiles et al., (2006) used 2004 Olympic times to demonstrate that competitive races have been won by much smaller margins. Even though there is a strong theoretical link, few intervention studies demonstrating an improvement in efficiency have confirmed a performance improvement as a direct result of efficiency change. Jobson et al., (2012), reported that only two studies have attempted to determine a direct link with performance. Horowitz, Sidosis and Coyle (1994) approached the efficiency and performance link by classifying the participant's fibre type and separating participants based on a fibre Type I % above or below 56 %. They described that a greater proportion of Type I fibres resulted in both a higher average TT performance power along with a higher overall efficiency. Despite the seemingly symmetrical link between a higher power output and efficiency it does not provide conclusive evidence of an inherent link between the two variables, particularly because of the known linear relationship between power and efficiency. More recently Passfield and Doust (2000) found a high positive correlation (r = 0.91) with the change in efficiency and change in 5 minute sprint performance power following one hour of submaximal cycling (60 % W_{max}). Although this finding indicates that efficiency and sprint performance are both affected by previous endurance performance, it does not necessarily provide evidence that they are intrinsically linked. One hour of cycling would have reduced carbohydrate stores (muscle and liver glycogen), which can have both a negative effect on sprint performance and efficiency through a greater reliance on FAT for fuel. Furthermore, as sprinting utilises a high proportion of the anaerobic energy pathway, it could be argued that the performance measure was not representative of endurance cycling. A more relevant performance measure based on its popularity at both an amateur and professional level, would be a 10 mile or 16.1 km self-paced TT. Endurance centred laboratory performance measures arguably provide the most logical and controlled method to quantify the link with efficiency. However, field performance would provide a more ecologically valid link albeit at a cost of reducing control over confounding variables (environmental [temperature, humidity, wind speed/direction and precipitation], cadence and terrain). Consequently, due to the potential positive outcomes of using both environments, this thesis has measured both laboratory and field measures of cycling efficiency and performance in order to further explore the relationship.

There is yet to be an investigation into the short- and medium-term effect of calorie restriction on trained cyclist's efficiency. Due to the potential negative health and performance effects associated with large calorie deficits, a moderate calorie deficit to elicit a 500 $kcal \cdot day^{-1}$ (~20 %) reduction in daily intake was considered the most viable option, using portion control to ensure similar macronutrient ratios. A moderate calorie deficit over a short duration is likely to cause only small changes in body composition and so a sensitive and reliable measure of body composition was considered beneficial. Consequently prior to the prescription of a calorie deficit, the within- and between-day variability of body composition measures were also considered valuable. Additionally for the purpose of sample size estimations and the determination of the smallest worthwhile change, the variability of; RMR, efficiency, TT performance and blood parameters will also be established. An issue with exploring the acute effect of calorie restriction is the potential for there to be an increase in protein oxidation. Blood Urea Nitrogen (BUN) along with performance associated blood parameters will also be measured to establish a baseline and potential physiological insights, if changes in efficiency and performance occur.

Laboratory efficiency is all too often assumed to link directly with field efficiency measures, despite differences in biomechanical and environmental variables. Hence this thesis will aim to explore if it is possible to conduct efficiency measurement in an outdoor environment and compare with laboratory based stationary cycling. Research into cycling efficiency literature also raised the issue that $\dot{V}O_{2max}$ tends to be inversely related with cycling efficiency. Thus whilst collecting this data the interlinking relationship with $\dot{V}O_{2max}$, efficiency and performance, along with the hypothesis that lung volume could have an influential effect on cycling efficiency, will be explored in **Chapter 11** where data across studies can be summed together to strengthen the data sample.

5.1.1 Unpublished research

Gross efficiency and tracked body mass change data recorded across two studies for the purpose of a doctoral thesis by Hopker (2009), were re-examined to determine if there was an observable change in efficiency when comparing the highest and lowest body mass trials. Duplicate entries from the studies were removed, leaving 32 unique male trained participants to be included in the retrospective analysis. The highest and lowest mass values were selected out of either five laboratory visits collected over the course of a year or out of three visits over the course of 12 weeks during a training intervention study. Efficiency was measured across a number of intensities starting from 150 W for a period of eight minutes, increasing by 30 W per stage until an RER > 1.0 was recorded. The average change in body mass, comparing the highest and lowest values (mean ± SD) resulted in a -1.06 ± 0.90 kg reduction. Individual changes are presented in **Figure 5.1**, with 21 participants having an improvement in efficiency and 11 having a reduction in efficiency. Gross efficiency changed from 20.5 % to 21.4 % equating to a relative 4.39 % significant improvement ($P < .01$) (averaged across all viable workloads). This change is similar to the ~ 4 % improvement in efficiency as a result of calorie restriction reported by Amati et al. (2008), and explains a large proportion of the relative 5.1 % improvement in efficiency across a competitive cycling season (Hopker, 2009). The retrospective analysis did however fail to show a significant relationship between body mass and efficiency change ($r = 0.185$, $P > .05$). Due to the original research purpose, training variability present across a competitive cycling season and across an intervention study are likely to have confounded the relationship between body mass and efficiency. It has also been previously discussed that the magnitude, method and duration of energy deficit has implications for both body composition and homeostatic control mechanisms. It is therefore unknown if the participants mass reduced gradually or in the immediate period prior to testing and if training variability was responsible for the reduction in mass. It is important to note that the vast majority of the participants during testing were considered mass stable, with the average mass change below 1 kg. This suggests that there is a potential to increase the magnitude of body mass change if directly targeted that could cause a greater efficiency change. Consequently, the question remains as to whether efficiency can be improved as a direct result of dietary manipulation utilising calorie restriction to induce body mass reduction in participants accustomed to cycling.

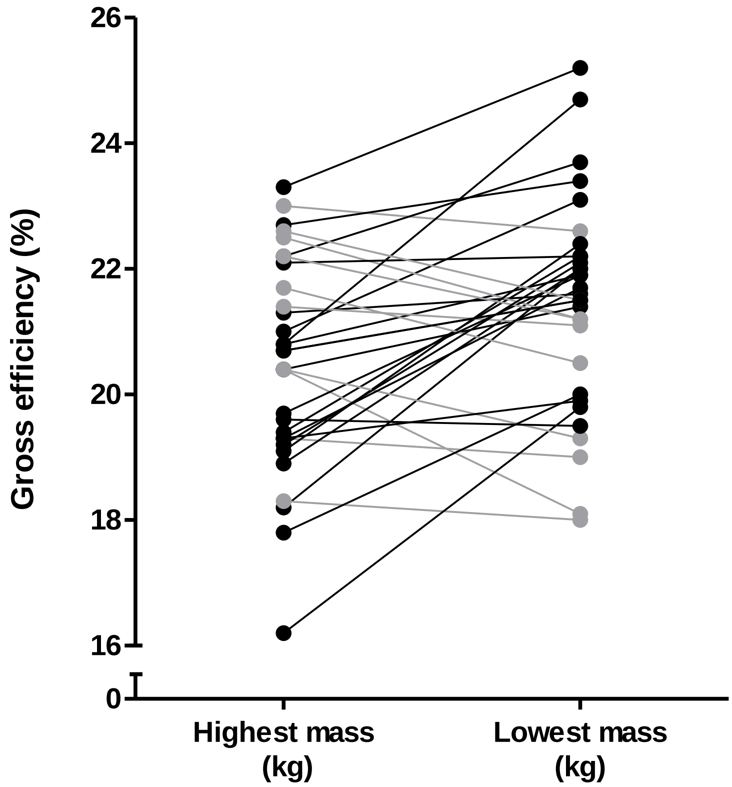


Figure 5.1 Individual body mass change in relation to gross efficiency change, utilising the highest and lowest body mass measured over the course of testing. Note: —●— = improved efficiency, —●— = reduced efficiency.

5.2 Aims

- To establish the variability of the key variables; energy expenditure, body composition and TT performance.
- To explore the effect of short- and medium-term body mass reduction on cycling efficiency in participants accustomed to cycling.
- To investigate the link between cycling efficiency and performance in both a laboratory and field environment.

5.3 Objectives

- Within-day variability of air displacement plethysmography will be compared to skinfold measurement.

- Between-day variability will be assessed three times over three weeks in; gross, net efficiency, RMR, TT performance power, venous blood analysis, body mass and composition, while participants are mass stable.

- Short-term body mass reduction will utilise a randomised crossover design with two weeks of calorie restriction aiming for a 500 $kcal \cdot day^{-1}$ deficit, using portion control to investigate the effect on cycling efficiency, performance and body composition.

- Laboratory and field efficiency will be measured in a randomised order at an absolute, relative and performance intensity, comparing stationary laboratory cycling with free cycling on a closed road circuit.

- Medium-term body mass reduction will utilise a six week dietary intervention period followed be a six week follow-up period with a control group. Field performance will also be measured pre and post intervention in a selection of participants.

CHAPTER 6: GENERAL METHODS

This chapter will outline the general methods that were applied to all data collection following formal approval from Canterbury Christ Church University Ethics Committee. All laboratory practices and protocols were in accordance with the British Association of Sport and Exercise Sciences (BASES) guidelines and Canterbury Christ Church sport science Laboratory procedures.

6.1 Participant recruitment

Participants were recruited via e-mail from local cycling clubs and face to face recruitment at cycling club meetings.

Participant criteria:

- Male cyclists aged between 18-60 years.
- Have been cycling regularly for at least two years.
- Have had no interruption to their training within the past six months due to injury.
- Have verbally confirmed that they were weight stable for the last three months.
- Have no medical condition that will impair their ability to perform all tests.
- Must not be diagnosed with metabolic syndrome.
- Must not be taking any medication.
- Must be a non-smoker.
- Must not be using any performance enhancing substances or be willing to suspend their consumption for the duration of testing.

Participants accepted onto a calorie restriction intervention required a minimum estimated body fat of ≥18 %, determined by skinfold analysis. This ensured that on completion of the research that participants in a calorie restriction study or group would have a minimum of 16 % body fat, which is within the body fat range of 8-21% described by Whaley, et al., (2006) as having normal health risks. This was set to ensure ethical approval and therefore limits the findings to cyclists within a close range of 18 % body fat and above.

The study design and testing protocol were e-mailed prior to the participant provisionally agreeing to take part in a study and their first visit (**Appendix 2**). The protocol was then explained and discussed with the participant including the potential risks, benefits and notified that they could withdraw at any time before they filled out a health questionnaire and signed an informed consent (**Appendix 3** and **Appendix 4** respectively).

6.2 Pre-testing controls

Prior to each visit participants were asked to refrain from strenuous exercise for 48 hours, caffeine for 24 hours and to arrive in a fully rested and hydrated state (Pringle and Jones, 2002; Jenkins et al., 2008).

6.2.1 Dietary

Before testing participants completed a 72 hour food diary, either hand written (**Appendix 5**) or on a free electronic nutrition and activity package (MyFitnessPal, 2015). Macronutrients in grams were converted to kilocalories (kcal) using the following conversion: CHO = 3.75 kcal/g, FAT = 9 kcal/g, PRO = 4 kcal/g (Collins, Hunking and Stear, 2011). To date MyFitnessPal has not specifically been validated against traditional dietary software (Jospe, Fairbairn, Green, and Perry, 2015). A similar online software has been compared to 24 hour dietary recall and reported only small mean differences in kcal intake (16 and 105 $kcal \cdot day^{-1}$) across two sample days with 50 participants, although some individual differences were present (Carter, Burley, Nykjaer and Cade, 2013). MyFitnessPal (2015) is also the most frequently used dietary online based software reported to be currently used by 32.4% of dieticians surveyed that monitor the dietary intake of athletes (Jospe, Fairbairn, Green, and Perry, 2015). MyFitnessPal (2015) was used above more traditional software as it benefits from increased accessibility via a mobile phone application, allowed for real time monitoring and has the largest food database (> 5 million foods) compared to Nutritics (2016, > 10,000 foods) and CompEat (2016, > 6000 foods), increasing the the accuracy when determining calorific content between different brands. Furthermore mobile diet applications have been demonstrated to increase engagement verses written food diaries and web based records (Turner-McGrievy et al., 2013). To ascertain validity, 50 separate foods (equivalent to ~ 12000 kcals) were analysed based on 100g of each food with Myfitnesspal (2016) and Nutritics (2016) software. Limits of agreement compared the databases kcals, grams of carbohydrate, protein and fat. The error for the total kcals between online databases was 0.012 % and the limits of agreement were 0.365 % ($P > .05$), the carbohydrate and fat in grams were comparable ($P > .05$). Protein in grams was significantly lower with Myfitnesspal ($P < .05$) but equated to 0.75 g difference per 100 g or 3 kcals, which is considered a very small margin.

6.2.2 Training

Training sessions were predominantly recorded with electronic software packages; Garmin Connect (2015), STRAVA (2015) and Training Peaks (Peaksware, 2015) or were recorded with a written activity diary when preferred (**Appendix 6**). Data was collated in weekly segments to assess differences in distance (km), time (mins), speed ($km \cdot h^{-1}$) and elevation (m). This data was collected during testing phases and where possible in the six weeks preceding the participant's commencement of the study. Participants were instructed to replicate their exercise and nutrition as closely as possible before each subsequent trial. Particular emphasis was given to ensure participants consume the same meal two hours prior to testing.

6.3 Environmental conditions

The conditions within the laboratory and field environment were recorded prior to all testing. Temperature was controlled in the laboratory with an air conditioning unit, while humidity and barometric pressure were recorded (Testo 625, Germany; F.D. & Co. Ltd. Watford, UK). In the field environment temperature, humidity and barometric pressure were recorded immediately prior to testing with data from a local weather station providing within test conditions (World Weather Online, 2015). See individual study methodology for mean ± SD of the environmental conditions.

6.4 Body mass and stature

Free standing height was measured using a fixed stadiometer with a resolution of 0.001 m (Seca 220, Hamburg, Germany) with feet together, heels and upper part of the back touching the back plate and head placed in the frontal plane (Norton et al., 2000). Participants was asked to void their bladder prior to body mass measurement using balance beam scales with a resolution of 0.01 kg (Seca, 761, Hamburg, Germany).

6.5 Lung volume and function

Vital capacity (VC) in litres and forced expiratory lung volume (FEV_1) in litres over one second were measured using an open-circuit mechanical spirometer (Vitalograph Ltd, Maids Morton, UK). Participants wore a nose clip and conducted a familiarisation test before they were asked to exhale maximally, the tests was repeated three times and the highest VC and FEV_1 values were selected (Quarijer, Tammeling, Cotes, Pedersen, Peslin and Yernault, 1993).

$$FEV\ \% = \frac{FEV.s^{-1}\ (L)}{VC(L)}$$

Equation 10. FEV % (Alison, 2007). Where: FEV, forced experiatory volume and VC, vital capacity.

6.6 Body composition

Body density was assessed with two indirect measurement techniques that both use a two compartment model; lean mass and FFM.

6.6.1 Air-displacement plethysmography

The air-displacement plethysmography device (BOD POD, life Measurement, Inc, Concord, CA) was calibrated with 20 kg weights and a standardised calibration cylinder (50.039 L) prior to every test. Participant's age (yrs) and height (cm) were entered into the control panel and weighed using the supplied scales. All participants wore standardised Lycra swimming shorts and a swimming cap. Body volume (cm^3) was calculated three times and an average was taken to determine body density ($g.cm^3$).

$$Body\ Volume\ (L) = Measured\ body\ volume - surface\ area\ artifact + 40\ \%\ TGV$$

Equation 11. Bod pod body volume (Dempster & Aitkens, 1995). Where: TGV, Thoracic Gas Volume.

$$Body\ density\ (gcm^3) = \frac{Mass\ (g)}{Volume\ (cm^3)}$$

Equation 12. Body density (Siri, 1956).

6.6.2 Skinfold measurement

Ten skinfold sites were identified and measured; Bicep, Tricep, Subscapular, Surprailiac, Suprapinale, Abdominal, mid-Axillary, Chest, Thigh and medial Calf (Norton et al., 2000; Knechtle, Knechtle and Rosemann, 2011). All sites were marked with a cross, with measurements taken by using the thumb and index finger perpendicular to the skinfold site halfway between the crest and base of the fold (Whaley et al., 2006). The skinfold callipers (Harpenden Skinfold Callipers, Baty

International, West Sussex, UK) were applied 10 mm inferior to the centre of the cross and recorded after two seconds with dial graduation of 0.2 mm and compressibility of 10 gms/mm^2. All measurements were taken on the right side of the participants by myself, a trained Level 1 Anthropometrist (International Society for the Advancement of Kinanthropometry, [ISAK]) (except for study 1 [**Chapter 6**] which was conducted post training but prior to accreditation). Each site was taken in rotation and then repeated, if the second measurement differed more than ± 5 % a third measure was taken. An average was used for two measures and a median if three measures were recorded. The age of the participant at the beginning of the study dictated the equation used throughout.

$$Body\ density = 1.10938 - (0.0008267 \times \Sigma\ Chest, Abdominal, Thigh) + \{0.0000016 \times (\Sigma\ Chest, Abdominal, Thigh)^2\} - (0.0002574 \times age)$$

Equation 13. Equation to calculate body density using three skinfold sites for males aged 18-61 (yrs) (Jackson & Pollock, 1978).

$$Body\ density = 1.112 - (0.00043499 \times \Sigma\ \text{skinfolds}) + \{0.00000055 \times (\Sigma\ skinfolds)^2\} - (0.00028826 \times age)$$

Equation 14. Equation to calculate body density using seven skinfold sites for males aged 18-61 (yrs) (Jackson & Pollock, 1978). Note: Where the sum of the skinfolds are; Chest, mid-Axillary, Tricep, Subscapular, Abdominal, Suprailiac and Thigh.

Age (yrs):

17-19: $Body\ density = 1.1620 - (0.0630 \times LOG\ \Sigma\ skinfolds)$

20-29: $Body\ density = 1.1631 - (0.0632 \times LOG\ \Sigma\ skinfolds)$

30-39: $Body\ density = 1.1422 - (0.0544 \times LOG\ \Sigma\ skinfolds)$

40-49: $Body\ density = 1.1422 - (0.0544 \times LOG\ \Sigma\ skinfolds)$

≥50: $Body\ density = 1.1715 - (0.0779 \times LOG\ \Sigma\ skinfolds)$

Equation 15. Age dependent equations to calculate body density with four skinfold sites for males (Durnin and Womersley, 1974). Note: Where the sum of the skinfolds are; Bicep, Tricep, Subscapular and Suprailiac.

6.6.3 Densitometry

Densitometry is the process of using body density to derive body composition as a percentage of body fat. The Siri (1956) equation was used to convert body density from both skinfold and air-displacement plethysmography measurements into an estimated body fat %.

$$Body\ fat\ \% = \left(\frac{4.95}{density} - 4.50\right) \times 100$$

Equation 16. Densitometry (Siri, 1956)

6.7 Respiratory gases

Two breath-by-breath indirect calorimetry devices were used; an Oxycon Pro (Jäeger, Carefusion, Hoechberg, Germany) which is a laboratory based metabolic cart system and an Oxycon Mobile, a portable version consisting of two small modules (Jäeger, Carefusion, Hoechberg, Germany). Both devices provided measurement of oxygen uptake ($\dot{V}O_2$, $L \cdot min^{-1}$), carbon dioxide production ($\dot{V}CO_2$, $L \cdot min^{-1}$) and respiratory exchange ratio (RER). Calibration procedures were similar with devices having a minimum warm-up period of 30 minutes, with temperature, humidity and barometric pressure manually input to the software package. The main difference between the two devices is the Oxycon Pro uses the paramagnetic principle and infrared absorption method for $\dot{V}O_2$ and $\dot{V}CO_2$ measurement respectively, whereas the Oxycon Mobile uses an electrochemical cell for $\dot{V}O_2$ and thermal conductivity for $\dot{V}CO_2$ (Diaz et al., 2008). The devices were calibrated with certified calibration gas mixtures (Oxycon Pro: 5 % CO_2, 14 % O_2 and 81 % N_2, Oxycon Mobile: 5 % CO_2, 16 % O_2 and 79 % N_2). Both devices measure volume with the same tripleV, turbine set-up and were calibrated with a three litre syringe (Carefusion, Hoechberg, Germany). The facemask was connected to the skin of the participant with head gear and it was verified that there was no leakage of air. The Oxycon Mobile modules were attached with the supplied harness on the back of the participants with live data being transmitted telemetrically while simultaneously recording data on to a memory card (see **Appendix 7** for laboratory set-up). All data was recorded breath-by-breath and averaged over 10 second intervals. The Oxycon Pro has been previously validated against the gold standard Douglas bag method (Rietjens, Kuipers, Kester and Keizer, 2001; Carter and Jeukendrup, 2002). The Oxycon Mobile has also been validated against the Douglas bag method (Rosdahl, Gullstrand, Salier-Eriksson, Johansson and Schantz, 2010) as well as against the Oxycon Pro, with $\dot{V}O_2$ and $\dot{V}CO_2$ reported to be similar during steady state exercise (Perret and Mueller, 2006). Interclass correlations of ~0.8-0.9 have been reported when comparing between devices, with no significant differences reported (Akkermans et al., 2012).

6.8 Resting metabolic rate

Resting metabolic rate (joules·sec^{-1}) was assessed with the participants in a quiet thermo-neutral environment on a massage table in the supine position. A face mask was used to collect breath-by-breath data with indirect calorimetry measurement. The face mask has been shown to be more comfortable and precise at measuring RMR (r = 0.992) than a mouthpiece (r = 0.977) when compared to the ventilated hood attachment (Sega, 1987). The initial duration was for 30 minutes during study 1 (**Chapter 7**) and 2 (**Chapter 8**) but was reduced to 20 minutes for study 4 (**Chapter 10**). Resting metabolic rate was determined by the average $\dot{V}O_2$ and $\dot{V}CO_2$ values between minutes 10-20 and was also used for the purpose of net efficiency calculation. The equation used to derive energy expenditure was established from an updated non-protein equivalent table presented in Péronnet and Massicotte (1991). This equation was used over the Lusk tables (1924 & 1928) and Brouwer (1975) (cited in Moseley and Jeukendrup, 2001) calculations as it was the most current, provided greater divisions between the increments and is used in recent efficiency research (Hopker, 2013).

$Energy\ Expenditure\ (J{\cdot}s^{-1})$

$$= \{1.156 \times (\dot{V}CO_2 \div \dot{V}O_2) + 4.037\} \times \{\dot{V}O_2 \times (4.186 \div 60)\} \times 1000$$

Equation 17. Energy expenditure equation (Péronnet and Massicotte, 1991).

Where $\dot{V}CO_2$ = carbon dioxide output and $\dot{V}O_2$ = oxygen uptake.

6.9 Power measurement

6.9.1 Laboratory

All laboratory tests were conducted on an SRM cycle ergometer (Schoberer Rad Messtechnik, Welldorf, Germany) that was calibrated according to manufacturer's instructions and fitted with the participant's clipless pedals. On the first visit of every study the participants' road bicycle was measured (**Figure 6.1**), applied to the ergometer and recorded for future testing. Zero power offsets were reset immediately prior to testing. Power output (Watts) was recorded in 1 second intervals and averaged over one minute. The accuracy of the scientific eight strain gauge SRM ergometer is reported by the manufacturer to be 0.5 % (Gardner et al., 2004), but experimentally reported to have an error of 2.36 % (Martin, Milliken, Cobb, McFadden and Coggan, 1998). This has been validated and considered acceptable (< 5 %) against the gold standard Monark Ergometer (Jones and Passfield, 1998).

Figure 6.1 The location of the road bicycle measurements. A = Top of seat to pedal centre in 6 o'clock position. B = Middle of saddle in line with seat post to centre of handlebars (tops). C = Centre of handlebars to floor. D = Crank centre to floor.

6.9.2 Field

An eight-strain-gauge rear wheel PowerTap device (PowerTap Pro, CycleOps, Madison, USA), and display computer (Joules, CycleOps, Madison, USA) were fitted to the participants road bicycle prior to field testing. Tyre pressures were standardised to 120 psi with a track pump (Joe Blow Sport, Topeak Inc., USA) (Grappe, Candau, Barbier, Hoffman, Belli, Rouillon, 1999) and power offsets were zeroed by freewheeling prior to testing. The PowerTap wheel has been reported to read systematically higher powers by 2.7 % when compared to the SRM ergometer cranks in field conditions (Bertucci et al., 2005). Nevertheless, Duc, Villerius, Bertucci, Grappe (2007) determined that the PowerTap device was valid, due to the over estimation being systematic and a CV of 2.5 % reported during steady-state cycling verses 2.4 % with SRM cranks. To correct for the differences between the devices, power output recorded with the PowerTap wheel was reduced by 2.7 % prior to efficiency and economy calculations. This correction was also in accordance with simultaneous SRM and PowerTap measurement using a road bicycle on a treadmill in the laboratory (see **Appendix 8**).

6.10 Heart rate

A heart rate monitor (Polar Wearlink, Polar Electro Oy, Kempele, Finland) that was moistened prior to fitting was worn around the chest throughout testing. Resting heart rate (HR_R, beats·min^{-1}), exercising heart rate (HR_E, beats·min^{-1}) and maximal heart rate (HR_{max}, beats·min^{-1}) were downloaded in one second data and averaged over one minute.

6.11 Maximal testing

An incremental exercise test to volitional fatigue was performed to determine the highest W_{max} and maximal oxygen uptake ($\dot{V}O_{2max}$) averaged over one minute. Two of the following three criteria had to be met for it to be determined that the participant reached $\dot{V}O_{2max}$. 1) The highest heart rate averaged over a minute within ±2 beats·min^{-1} of the age-calculated theoretical maximal heart rate, determined as 220 minus age. 2) RER ≥ 1.1. 3) A visible plateau in the participants $\dot{V}O_2$ (increase < .05 L·min^{-1}) in the last 30 seconds of the test. The protocol began at 150 W for 5 minutes and increased by 5 W every 15 s until a cadence > 60 (rev·min^{-1}) could no longer be maintained despite standardised verbal encouragement (Cole, Coleman, Hopker, Wiles, 2014). Participants were allowed to select their preferred cadence, had the use of a fan which was set at a standardised speed (Woods air movement Ltd, Colchester, UK) and were instructed to remain seated throughout. Incremental exercise testing has been shown to be a sensitive and reliable measure of W_{max} due to a within participant coefficient of variation of just 1.32 % and an interclass correlation coefficient of 0.99 (Balmer, Davison and Bird 2000).

6.12 Blood sampling

All blood samples were taken during a standardised five minute recovery period after steady-state efficiency and prior to time-trial commencement. Finger prick samples were only collected on laboratory testing days when efficiency and performance were measured. The skin was prepared with an alcohol swab to ensure that the sample was not contaminated and to reduce the risk of infection. Once the alcohol had evaporated a single-use disposable lancet (accu-Check, Safe T Plus, Roche, UK) was used to bring blood to the surface. The first drop of blood was always discarded and a 75 μl sample of blood collected in a capillary tube (Micro-Haematocrit Tubes, Brand, Wertheim and Germany). The sample was immediately syringed into a single-use disposable cartridge (EC8+, Abbott, Illinois, USA) and placed in a portable clinical analyser (PCA) (i-STAT, Portable 200, Abbott, Illinois, USA). Following the insertion of the cartridge a calibration solution is immediately released and the cartridge biosensors monitored throughout the process of rehydration, calibration and analysis. In the event that a response falls outside of the predetermined limits the software excludes the outcome from the specific biomarker (Jacobs, Vadasdi, Sarkozi and Colman, 1993). The PCA provided instantaneous measurement (150 sec) of the participants: sodium (Na^+), potassium (K^+), chloride (Cl^-), total carbon dioxide (TCO_2), blood urea nitrogen (BUN), glucose (Glu), haematocrit (Hct), acidity (pH), partial pressure of carbon dioxide (PCO_2) and Haemoglobin (Hb). The PCA was tested against strict national quality standard, requiring test results to be within 95 % confidence intervals compared to conventional laboratory tests. Na^+, K^+ and PCO_2 were within national standard and although pH, Hb and Hct were outside of the criteria, the differences were so minor that they were less than that which was considered clinically significant (Schneider, Dudziak, Westphal and Vettermann, 1997). Total dissolved carbon dioxide, Cl^-, BUN and Glu had correlation values between 0.98-0.92 and were also reported to be reliable when compared with standard laboratory testing (Dascombe, Reaburn, Sirotic, Coutts and 2007; Baier et al., 2003). These markers were used to provide a more comprehensive description as to the participant's physiological state immediately prior to a time-trial as well as further explore the physiological effect of the interventions.

6.13 Laboratory efficiency measurement

For accurate and valid efficiency measurement the exercise intensity must be constant to elicit steady-state energy expenditure while respiring with a respiratory exchange ratio (RER) ≤ 1.00 (de Koning, Noordhof, Uitslag, Galiart, Dodge, Foster, 2013). Therefore, participants cycled on the SRM ergometer with pre-defined submaximal absolute and relative exercise intensities; 150 W, 50 % and 60 % W_{max} for eight minutes respectively in study 1 and 2, with the 50 % intensity being omitted for study 3 and 4 (Hopker et al., 2013). $\dot{V}O_2$, $\dot{V}CO_2$, and power (W) were averaged from the last two minutes of each stage. Energy expenditure and efficiency were calculated using **Equation 3, 4 and 17**.

6.14 Laboratory time-trial testing:

Time-trial (TT) testing, defined as a closed-loop exercise, is considered a highly reproducible exercise test that reflects a more realistic scenario of competition compared with time-to-exhaustion testing (Correia-Oliveira, Bertuzzi, Dal'Molin Kiss and Lima-Silva, 2013). Simulated laboratory based 16.1 km TT's were conducted following efficiency and blood sampling. A familiarisation TT was conducted prior to performance measurement as recommended by Zavorsky et al., (2007) to reduce variability between the first and subsequent trials. Participants began the 16.1 km self-paced TT on the SRM ergometer in free test mode and specified; a rolling start, data-restriction (only distance (m) visible) and were instructed to remain seated. Conducting TT's in the laboratory allowed for the assessment of mean power (W_{mean}) and the calculation of cycling economy (CE) by averaging power output and $\dot{V}O_2$ over the entire TT. Mean power during repeated laboratory based TT's have been reported to be a consistent measure of performance (CV = 1.9 - 2.1%) (Sporer and McKenzie 2007).

$$Cycling\ economy\ (W{\cdot}LO_2{}^{-1{\cdot}}min^{-1}) = \left(\frac{Work\ rate\ (W{\cdot}min^{-1})}{\dot{V}O_2\ (L{\cdot}min^{-1})}\right)$$

Equation 18. Cycling economy (Faria et al., 2005). Where; $\dot{V}O2$ represents oxygen uptake.

6.15 Field testing

Field tests were conducted with permission at Fowlmead Country Park, Deal, Kent, 14 meters above mean sea level on a 1.359 km closed-road circuit measured with a counter measuring wheel on the racing line (Stanley, Berkshire, UK) and ridden in a clockwise direction (see **Figure 6.2** for a graph depicting changes in altitude over the course of a lap). The participant's road bicycle was fitted with a rear wheel power device (PowerTap Pro, CycleOps, Madison, USA) and display computer (Joule GPS Promotion, CycleOps PowerTap, Madison, USA). Both tyre pressures were standardised (120 psi) (Grappe et al., 1999) and power offsets zeroed. Following a 30 minute equipment warm-up period with an external power supply (Portable Power Station, 12v, Streetwize, Manchester, UK) the Oxycon Mobile was calibrated in the same manner as the laboratory tests immediately prior to testing. The facemask was attached with headgear, analyser placed in a harness with both modules resting on the back of the participant and cycling helmet secured (see **Appendix 9**). Participants were previously familiarised with the circuit and completed three laps self-regulating power at 150 W and three laps at 60 % W_{max}. Following a five minute rest period the participants began the TT with a rolling start and completed 16.1 km (11.85 laps) as fast as they could with time, power and speed data obscured. The start and finish lines were indicated with cones and a manual lap counter indicated the number of laps left (Canterbury Christ Church University, in house, UK). Participants were instructed to remain seated throughout the TT. Efficiency and economy sampling were conducted with the same criteria as the laboratory testing.

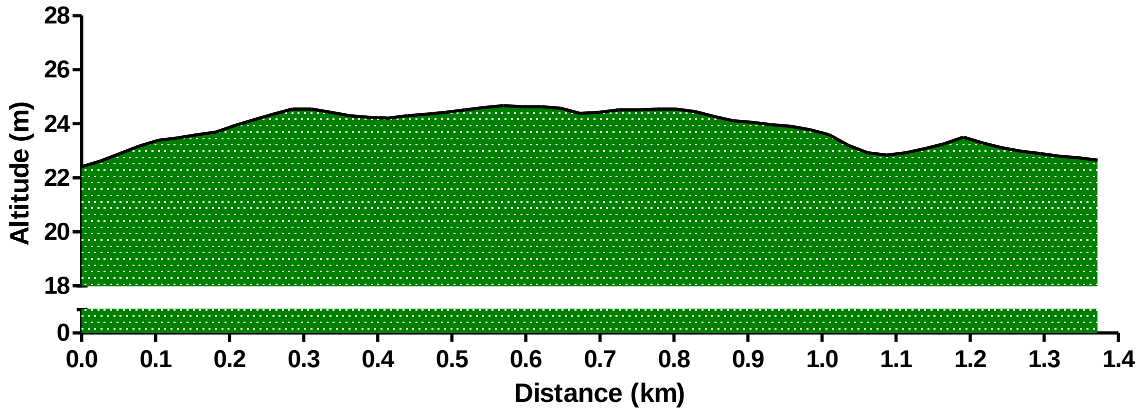


Figure 6.2 The altitude of a single lap on the closed-road circuit relative to mean sea level.

6.16 Data analysis

Descriptive and analytical statistics were calculated using Excel (Microsoft, version 15.0.4737.1003), SPSS (IBM, version 22) and graph pad prism (version 5.0). All data are reported as mean and standard deviation (SD) unless otherwise stated and the Shapiro-Wilk test assessed normality. An alpha level of significance for all tests was set at 95% ($P \leq 0.05$).

CHAPTER 7: VARIABILITY OF BODY COMPOSITION ASSESSMENT, BLOOD PARAMETERS, ENERGY EXPENDITURE AND TIME-TRIAL PERFORMANCE.

7.1 Introduction

Establishing the reliability of measurement is pivotal in the determination of appropriate assessments in sport and exercise science. In the context of this thesis, the generation of reliability data can also help to inform study design and ultimately enhance the interpretation of study results in the drawing of conclusions from data.

There are a number of sources of variability in measurements that need to be considered by the researcher in the context of this current work 1) mechanical error, 2) biological error and 3) experimenter/tester error. Although sometimes difficult to differentiate between these sources, identifying the overall variability (often referred to as noise) can allow the experimenter to identify if particular measurements would be appropriate to include in subsequent investigations. Noisy or unreliable measures may have substantial constraints in terms of the numbers of participants required to objectively ascertain if there are differences (or no differences) when conducting cross sectional or longitudinal studies. Utilising more reliable equipment/techniques to derive data may reduce the 'costs' in terms of participant and laboratory staff time during data collection, thus where possible from a resourcing and ethical standpoint systems or techniques should be evaluated to ensure that data collection is optimised where possible.

For the purpose of this thesis there are three broad areas to investigate in terms of reliability; body mass and body composition, blood parameters, and the assessment of laboratory efficiency and economy. Although there are numerous studies published on reliability, alterations in participant category (age/fitness/competitive level etc.) (Hopker et al., 2007), specific laboratory equipment (Hopker et al., 2012), and laboratory technical staff (Perini, de Oliveira, Ornellas and Oliveira, 2005) may alter the reliability coefficients generated, thus a conservative approach is often taken to derive this data in a manner which would mirror data collection at a later stage of an investigation.

Body mass and composition:

Body mass (kg) has a very low equipment variability due to the often mechanical nature of the measurement, whereas within-day body mass fluctuations are well known to occur with hydration, stomach, bowl and bladder contents (Fairburn and Cooper, 2014) and can be manipulated by as much as 2.27 kg (Cotugna, Snider and Windish, 2011). Within-day body mass can be standardised by testing at similar times of day and controlling food and water intakes prior to participant assessment.

The variability and reliability of methods to assess body composition vary substantially based on the methods used and their limitations. Air-displacement plethysmography (utilising devices such as the Bod Pod) limits inter-tester error but, is susceptible to variations in total water content, air movement within the laboratory environment and participant cooperation to breathe consistently and minimise movement. These are clearly identified in the instruction manual for these devices, however these can be more difficult to 'control' prior to and during assessment (Bod Pod, 2013). Skinfold measurement as an alternative technique to assess body composition is less affected by total hydration, but has a higher inter-tester variability (McRae, 2010) and only accounts for subcutaneous adipose tissue fluctuations. One of the major uses for the assessment of body composition is in the reduction of body mass (usually to reduce body fat) in athletes and the general population, however changes in body mass can also alter hydration status of an individual. Total body water is reasonably stable under isocaloric conditions, however a hypocaloric diet which induces a negative energy balance is likely to reduce total water storage through an increase in glucogenolysis. Glucogenolysis is the biochemical process of breaking glycogen polysaccharides into glucose molecules which results in excess water being excreted (~3 to 4 grams of water for every gram of glycogen, Olsson and Saltin, 1970), causing a temporary reduction in body mass (Kreitzman, Coxon and Szaz, 1992). This reduction in total water storage can doubly effect Bod Pod estimations of fat (kg), as mass is used in both the body density equation and conversion of a percentage to kg. Skinfold body fat % is calculated without mass and is only affected when converting body fat (%) to fat mass (kg). There is also evidence to suggest that visceral adipose tissue is utilised preferentially over subcutaneous fat during the early stages of both moderate and severe calorie restriction (Chaston and Dixon, 2008). This is an issue which is more pertinent to skinfold assessment but not excluding Bod Pod measurements, with a lack of sensitivity to detect specific changes in visceral fat other than through total mass changes. Technical error of the measurement (TEM) is the most commonly reported determination of imprecision within anthropometry (Ulijaszek and Kerr, 1999) and is important to establish prior to dietary manipulation.

Blood parameters:

Basic metabolic blood panels are commonly used to assess patient health; specifically kidney function, acid/base balance, electrolyte, blood sugar and calcium levels (Daniels, 2010). Traditional testing usually requires the collection of 5 mL of blood with results available within 24 hours, there are analysis systems that offer faster analysis times (e.g. Portable Clinical Analyser [PCA]) requiring small volumes of blood (75 μl) allowing for quick and affordable multiple parameter analysis, making metabolic blood assessment more accessible and viable in sport science Laboratories. Not only is it beneficial to monitor the health of participants during an intervention study, it could also provide a metabolic insight in to the effect of calorie restriction on an exercising population, and further more could be used to predict changes in performance. Calorie restriction has been reported to affect measures of Hct, Hb, K+ and BUN (Kreitzman, Coxon and Szaz, 1992; Hall and Everds 2014), with other factors such as; dietary macronutrient intake (Kreitzman, Coxon, and Szaz, 1992), dehydration (Billett, 1990) and training volume and intensity (Metheny, 2012) also having the potential to confound results. The majority of reported validity research with the PCA have not stated the exercising habits of the participants and commonly use patients admitted to intensive care units, operating rooms and accident and emergency centres (Jacobs, Vadasdi, Sarkozi and Colman, 1993; Schneider et al., 1997; Baier et al., 2003). The specific variability of each blood parameter measured with the PCA on a weekly basis in healthy participants is unknown, as the main clinical focus has been to validate the PCA with standard laboratory equipment and not to assess natural fluctuation.

Efficiency and Economy measurements:

The primary dependent variable in this thesis is energy expenditure in the form of gross efficiency, net efficiency and cycling economy. Gross efficiency coefficient of variation (CV) has been reported to be between 1.5 % (Hopker et al., 2012) and 4.5 % (Hopker et al., 2007), this 3 % discrepancy can have substantial implications for estimated sample sizes and is thought to be predominantly due to equipment differences (Douglas bag verses online gas analysis systems) with participant training status also having a likely effect. There are other numerous factors that have been demonstrated to influence the efficiency values obtained in the laboratory and must be controlled during assessment such as; pre exercising diet (Cole et al., 2013), exogenous carbohydrate supplementation (Dumke et al., 2007), exercise intensity (Hopker et al., 2013), cadence (Jacobs, Berg, Slivka and Noble, 2013), bicycle/ergometer set-up (Faria, Parker and Faria, 2005) and laboratory environmental conditions (Hettinga et al., 2007). These factors are also likely to influence the raw power output generated during any simulated time-trial performance, and again these have been noted in numerous papers (Bini, Hume and Croft, 2011; Peiffer and Abbiss, 2011; Correia-Oliveira, Bertuzzi, Dal'Molin Kiss and Lima-Silva, 2013). A study that has controlled these factors have demonstrated CV's of ~2% for performance power output in the laboratory (Smith et al., 2001).

The collection of data for this thesis is utilising some equipment and techniques that reliability data have not been previously reported. With the variability of some measures also reliant on 'experimenter/tester error' the aim of this study was to determine the TEM and CV for skinfold and Bod Pod assessment as well as between-day CV for blood parameters, TT power, RMR, gross efficiency, net efficiency and economy.

7.2 Methods

7.2.1 Within-day repeated measures

Twelve exercising participants (age 27 ± 5 yrs; height 1.75 ± 0.09 m, body mass 71.64 ± 10.42 kg) gave their written informed consent to participate in the within-day investigation and satisfactorily completed a health questionnaire. Participants were asked not to exercise strenuously 24 hours before, not to eat two hours before and void their bladder immediately prior to testing. Free standing height (Seca 220, Hamburg, Germany) and body mass (Seca, 761, Hamburg, Germany) were recorded at the beginning of the visit. Ten site skinfold and Bod Pod assessment were conducted in a randomised order and repeated three times, resulting in three skinfold measurements per site and nine separate whole body volumes. All participants wore standardised Lycra swimming shorts and a swimming cap for Bod Pod measurements. Skinfold body density was calculated using three separate equations: Jackson and Pollock (1978) 3-site, 7-site and Durnin and Womersley (1974) 4-site. The Siri (1956) equation was used to convert both skinfold and Bod Pod densities to body fat (%) (see **Chapter 6** for skinfold equations).

7.2.2 Between-day repeated measures

Seventeen male cyclists (age 42 ± 9 yrs, height 1.79 ± 0.07 m, body mass 81.7 ± 9.5 kg) were recruited from local cycling clubs, gave their written informed consent to participate in the between-day investigation and satisfactorily completed a health questionnaire. Participants conducted a $\dot{V}O_{2max}$ visit and three visits where steady state efficiency and 16.1 km TT's were undertaken during each subsequent visit one week apart. Participants were instructed to maintain their body mass and usual training across the four week period.

Anthropometry:

Free standing height and body mass were recorded at the beginning of every visit. Ten site skinfold and Bod Pod assessments were conducted prior to cycling in a randomised order. Skinfold body density was calculated using the same three skinfold equations described in the within-day measures.

$\dot{V}O_{2max}$:

An incremental exercise test to volitional fatigue was performed on an SRM cycle ergometer (Schoberer Rad Messtechnik, Welldorf, Germany) that was adjusted to participant's road bike geometry and fitted with compatible clipless pedals. The protocol began at 150 W for 5 minutes and increased by 5 W every 15 s until a cadence > 60 ($rev \cdot min^{-1}$) could no longer be maintained (Cole, Coleman and Wiles, 2014). Gases were recorded via indirect calorimetry (Oxycon Pro, Jäeger, Carefusion, Hoechberg, Germany) and a heart rate monitor was warn throughout (Polar Wearlink, Polar Electro Oy, Kempele, Finland). Power output (Watts) was recorded in one second intervals and gas data averaged over 10 seconds. Maximum minute power and $\dot{V}O_{2max}$ were determined by the highest average W and $\dot{V}O_2$ over one minute.

Resting metabolic rate:

Participants laid in the supine position wearing a heart rate monitor in a quiet thermo-neutral environment with a facemask connected to the Oxycon Pro collecting breath-by-breath data for 30 minutes. Oxygen uptake and $\dot{V}CO_2$ data were sampled between minutes 10-15, 15-20, 20-25, 25-30, 10-20 and 20-30 for the determination of the least variable time measurement. Energy expenditure values were determined with **Equation 17**.

Efficiency and time-trial:

Participants cycled at three steady-state intensities for eight minutes each; 150W, 50 % and 60 % W_{max} (Hopker et al., 2013). During a standardised five minute recovery period after steady-state cycling but prior to the commencement of the TT a finger prick blood sample was analysed with a PCA (i-STAT, Portable 200, Abbott, IL, USA). This provided a measure of the participants: sodium (Na^+), potassium (K^+), chloride (Cl^-), total carbon dioxide (TCO_2), blood urea nitrogen (BUN), glucose (Glu), haematocrit (Hct), acidity (pH), partial pressure of carbon dioxide (PCO_2) and Haemoglobin (Hb). The 16.1km self-paced TT detailed; a rolling start, data-restricted to distance covered (m) and for participants to remain seated. $\dot{V}O_2$, $\dot{V}CO_2$ and power were averaged during the last two minutes of each stage and for the duration of the TT. Gross efficiency, net efficiency and economy were calculated as outlined in **Chapter 6**.

7.3 Data analysis

Descriptive and analytical statistics were calculated using Excel, SPSS and Graph Pad Prism. The data was visually checked for the presence of outliers and Shapiro-Wilk test used to assess normality. Technical error of the measurement (TEM) and TEM % were calculated comparing; the first and second skinfold measurements for all ten sites (mm), for the 3-site, 7-site and 4-site equations that were used to calculate body density (g.cc) and when converted to estimated body fat % and fat in kg using the Siri (1956) equation. Technical error of the measurement was also calculated for Bod Pod repeated measurements of volume, density (g.cc), estimated body fat % and kg. Within-day repeated measurement of typical errors were presented as CV % using all three of the repeated observations to determine the least variable method of fat % and mass (kg).

$$TEM = \sqrt{\frac{\Sigma D^2}{2N}}$$

Equation 19. Technical error of the measurement equation (Ulijaszek and Kerr, 1999). Where: D is the difference between repeated measurements and N is the number of individuals measured.

$$TEM\ (\%) = \left(\frac{TEM}{VAM}\right) \times 100$$

Equation 20. Technical error of the measurement as a percentage (Perini, de Oliveira, Ornellas and Oliveira, 2005). Where: VAM is the variable average mean (calculated firstly within each repeated skinfold for each participant and then averaged overall).

$$CV\ \% = \left(\frac{SD}{Mean}\right) \times 100$$

Equation 21. Within day coefficient of variation calculation, adapted from Sheskin (2003).

Between-day repeated measures:

Repeated measures ANOVA's with repeated standard contrasts were performed on all of the data with multiple trials. Data was assessed with the Mauchly's test of sphericity with a threshold of ≤ .05, where data was found to have significant sphericity the Greenhouse-Geisser correction was used. Post-hoc pairwise comparisons were used to determine the specific location of any significant differences. Typical error as a coefficient of variation (CV %) and lower and upper confidence intervals were calculated using log transformed data with a spreadsheet by Hopkins (2011). Pearson's product moment correlation analysis assessed the agreement between the mean skinfold and Bod Pod estimations of body fat %.

7.4 Results

7.4.1 Within-day repeated measures

Seven out of ten of the skinfold sites had a TEM % < 5 % resulting in the measurements being deemed taken by a skilful anthropometrist, with three just outside this range classifying the skinfolds well within the acceptable limits for a beginner anthropometrist (< 7.5 %) (Perini, de Oliveira, Ornellas and Oliveira, 2005) (see **Table 7.1**). The Durnin and Womersley (1974) 4-site equation resulted in the lowest TEM % and CV % when comparing body density and throughout the estimation of body fat % and mass (kg) using the Siri (1956) densitometry equation (see **Table 7.2**). Bod Pod total volume had a lower TEM % and CV % when compared to all individual skinfold measures, but had a TEM % and CV % three times greater after density calculation and more than double when the Siri equation was used to estimate body fat % and mass (kg) (see **Table 7.3**). The 4-site skinfold equation showed the highest agreement with the Bod Pod's mean estimation of body fat % and mass, with only a -0.24 kg lower estimate of fat mass.

Table 7.1 Within-day site specific skinfold data.

Skinfold site	Mean ± SD (mm)	TEM (%)	CV (%)
Biceps	5.3 ± 2.6	5.65	3.49
Triceps	12.2 ± 6.2	1.57	0.90
Subscapular	10.5 ± 4.8	2.48	1.75
Supra iliac	14.5 ± 8.8	3.67	1.80
Supraspinale	9.8 ± 4.3	4.48	1.99
Abdominal	16.3 ± 6.4	5.82	2.44
Mid-Axilla	7.9 ± 4.7	4.78	3.21
Chest	8.1 ± 4.4	5.69	2.34
Thigh	16.5 ± 8.6	3.91	1.55
Medial Calf	8.6 ± 3.6	3.05	1.78
Sum of 10	109.85 ± 1.45	1.74	1.20

Note: SD, standard deviation, TEM, technical error of the measurement, CV, coefficient of variation.

Table 7.2 A within-day comparison of body density, body fat % and body fat (kg) calculated with 3, 4, and 7 skinfold site equations.

	Equation	Mean ± SD	TEM (%)	CV (%)
Density (g.cc)	3 site	1.06359 ± 0.01664	0.06	0.05
	4 site	1.05658 ± 0.01646	0.04	0.04
	7 site	1.06265 ± 0.01626	0.05	0.04
Body fat (%)	3 site	16.64 ± 7.31	0.28	1.51
	4 site	19.87 ± 7.32	0.21	1.12
	7 site	16.72 ± 7.06	0.24	1.24
Body fat (kg)	3 site	11.51 ± 4.86	0.19	1.51
	4 site	13.67 ± 4.66	0.15	1.12
	7 site	11.76 ± 5.34	0.17	1.24

Note: SD, standard deviation, TEM, technical error of the measurement, CV, coefficient of variation.

Table 7.3 Within-day Bod Pod data showing volume, density, fat % and fat mass.

Bod Pod	Mean ± SD	TEM (%)	CV (%)
Volume (L)	65.59 ± 0.16	0.22	0.24
Density (g.cc)	1.05416 ± 0.00248	0.21	0.24
Fat (%)	19.66 ±0.56	0.69	3.82
Fat mass (kg)	13.91 ±0.40	0.48	3.80

Note: SD, standard deviation, TEM, technical error of the measurement, CV, coefficient of variation.

7.4.2 Between-day repeated measures

All seventeen participants completed the initial $\dot{V}O_{2max}$/ W_{max} protocol ($\dot{V}O_{2max}$ 51.4 ± 8.4 ml·kg·min^{-1}, W_{max} 371.0 ± 42 W·min^{-1}, relative W_{max} 4.57 ± 0.65 W·kg^{-1}·min^{-1}) and the four other subsequent trials. Based on data from the $\dot{V}O_{2max}$ test, the participants were classified as 'club level' according to W_{max} (Ansley and Cangley, 2009). Performance characteristics averaged across trials 2-4 are presented in **Table 7.4**. Laboratory environmental conditions were; temperature 18.1 ± 1.1 °C, humidity 64.7 ± 7.7 % and barometric pressure 753.5 ± 8.9 mmHg.

Table 7.4 Between-day performance characteristics averaged across three repeat trials (trial 2-4).

	150W	**50%**	**60%**	**TT**
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
HR_{max} (%)	59.78 ± 6.20	68.68 ± 6.08	78.66 ± 9.39	91.9 ± 3.17
Power (W)	150 ± 4	187 ± 18	222 ± 24	279 ± 36
GE (%)	22.10 ± 2.17	22.73 ± 2.18	22.76 ± 1.80	…
NE (%)	26.44 ± 3.37	26.06 ± 2.84	25.52 ± 2.33	…
EC (W·LO_2)	77.19 ± 9.05	78.66 ± 7.52	78.88 ± 6.31	80.18 ± 8.38
RER	0.92 ± 0.04	0.92 ± 0.04	0.92 ± 0.03	0.95 ± 0.04
RMR (j·s^{-1})	…	…	…	106.16 ± 18.41

Note: SD, standard deviation.

Anthropometry:

Body mass (81.4 ± 9.5 kg) did not significantly change across the group when compared across all four trials, with the largest difference between trials 3 and 4 of only -0.09 kg ($P < .05$). Skinfold estimated fat % was significantly different ($P = 0.003$) with the majority of the differences linked to trial 1 (22.31 ± 5.17 %), with trial 2 (21.75 ± 4.93 %), trial 3 (21.75 ± 1.28 %) and trial 4 (21.39 ± 1.21 %) significantly different (P = .041, P = .048, P = .003 respectively) as well as differences between trial 3 and 4 (P = .010) (**Figure 7.1**). Bod Pod estimated fat % also showed significant differences between the four trials (P = .016), with trial 1 estimating significantly higher than trial 3 (P = .014) and 4 (P = .047) and trial 2 estimating significantly higher than trial 3 (P = .034) (**Figure 7.2**). A high positive correlation (r = 0.754, P < .001) was present between skinfold and Bod Pod estimated fat % (**Figure 7.3**).

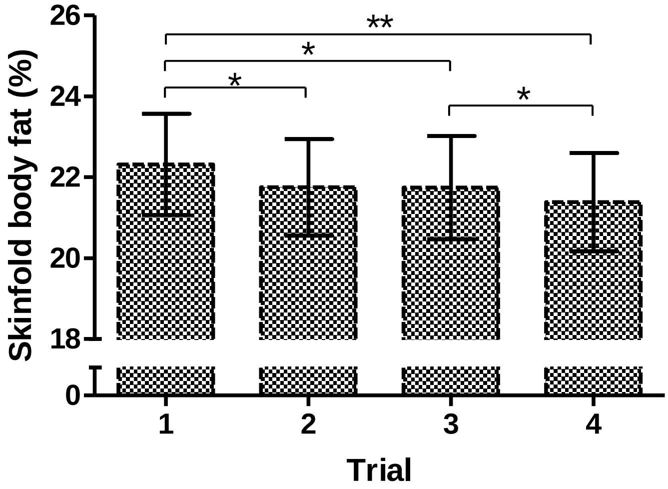


Figure 7.1 Comparing the stability of body fat % estimated with skinfold over four repeated trials. Note: * = P < 0.05 and ** = P < 0.01.

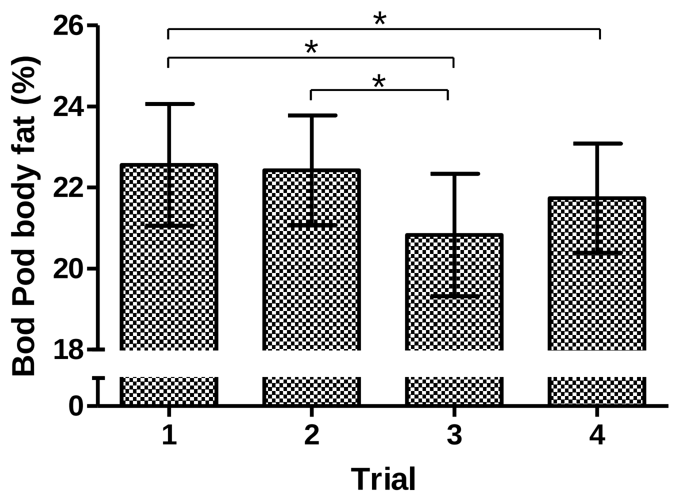


Figure 7.2 Comparing the stability of body fat % estimated with Bod Pod techniques over four repeated trials. Note: * = P < 0.05.

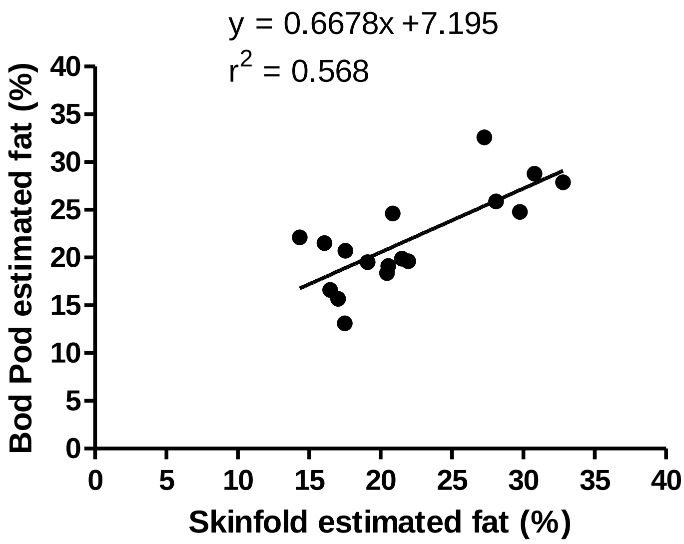


Figure 7.3 The relationship between mean skinfold and Bod Pod estimations of body fat (%) across four trials ($P < .001$).

Body mass had a low and reasonably consistent typical error across all four trials (CV < 1 %). The Bod Pod had greater typical error fat % estimations across trials with greater variance and a larger range of confidence intervals around the typical error than skinfold fat estimation (**Table 7.5**).

Table 7.5 The typical error of body mass and composition.

	Trial 1-2	**Trial 2-3**	**Trial 3-4**
	CV % (CI)	CV % (CI)	CV % (CI)
Body mass (kg)	0.82 (0.64-1.17)	0.54 (0.42-0.76)	0.82 (0.64-1.16)
Bod Pod fat (%)	7.50 (5.80-10.80)	10.95 (8.44-15.87)	11.38 (8.77-16.50)
Skinfold fat (%)	3.24 (2.52-4.62)	3.04 (2.36-4.33)	1.63 (1.27-2.32)
Sum of 10 (mm)	5.34 (4.14-7.65)	4.23 (3.28-6.04)	2.04 (1.59-2.91)

Note: CV %, coefficient of variation, CI, confidence interval.

There was no significant difference between trial 2, 3 and 4 RMR ($j \cdot s^{-1}$) values when sampled between 10-15 min, 15-20 min, 20-25 min and 20-30 min ($P > .05$). There was a difference between RMR sampled between 25-30 min and 10-20 minutes ($P > .05$), with differences both present between trial 2 and 3 ($P = 0.007$, $P = .042$ respectively) (**Figure 7.4**). The least variable sampling time based on CV % was between 10-20 minutes comparing trial 2 and 3 and between 25-30 minutes comparing trial 3 and 4. Sampling RMR from 10-20 minutes was the least variable when considering all three trials (11.03 and 9.66 %) (see **Table 7.6**).

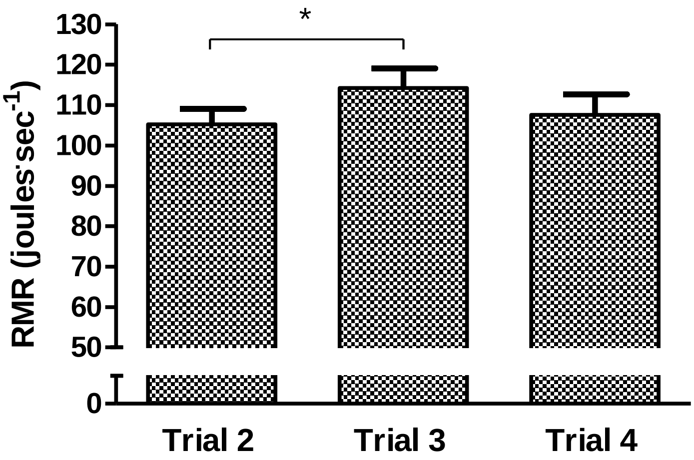


Figure 7.4 Mean Resting metabolic rate (RMR) sampled from 10-20 minutes across trials. Note * = $P < .05$.

Table 7.6 The typical error of Resting metabolic rate (RMR) sampled at different time intervals.

	Trial 2-3 CV % (CI)	**Trial 3-4** CV % (CI)
RMR 10-15mins	11.19 (8.62-16.22)	9.71 (7.44-14.24)
RMR 15-20mins	12.37 (9.52-17.98)	9.83 (7.53-14.42)
RMR 20-25mins	13.05 (10.04-18.99)	9.51 (7.29-13.95)
RMR 25-30mins	12.73 (9.26-21.03)*	9.45 (6.56-17.61)
RMR 10-20mins	11.03 (8.50-15.99)*	9.66 (7.41-14.18)
RMR 20-30mins	13.23 (9.62-21.89)	9.86 (6.87-18.44)

Note: CV %, coefficient of variation, CI, confidence interval, * = $P < .05$.

Energy expenditure comparisons:

There were no significant differences in gross efficiency between trials 2-4, in the absolute 150 W workload or relative 50 % and 60 % W_{max} intensities ($P > .05$)

(**Figure 7.5**). Gross efficiency tended to increase as workload increased but with the exception of gross efficiency at 60 % W_{max} in trial 2, which had a marginally lower gross efficiency (22.73 ± 1.56 %) when compared to the 50 % intensity (23.00 ± 2.22 %). Typical error within gross efficiency measurement reduced as the workload increased, with gross efficiency at the 60 % intensity having the smallest typical error across all trials when compared to the 150 W and 50 % intensities (**Table 7.5**). There was a significant difference between net efficiency at the 150 W workload ($P = 0.033$) with a significant reduction in net efficiency between trial 3 and 4 (trial 3: 27.30 ± 4.22 %, trial 4: 25.51 ± 0.65 %, $P = .017$). No significant differences were present at either of the relative workloads of 50 % and 60 % W_{max} ($P > .05$) (**Figure 7.6**). Typical error of net efficiency also tended to reduce with increasing workloads, with the 60 % intensity having the smallest typical error across all trials when compared to the 150 W and 50 % intensities.

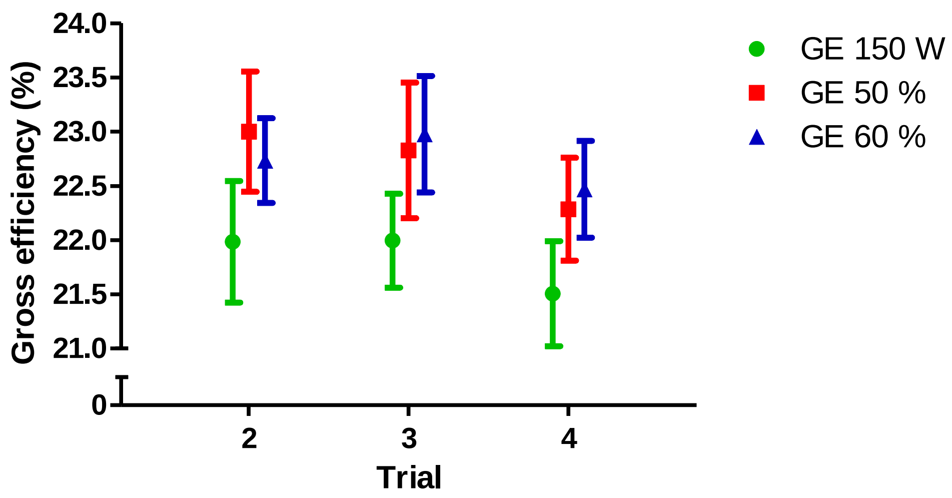


Figure 7.5 Gross efficiency across trials at 150 W, 50 % and 60 % W_{max} (no significant differences).

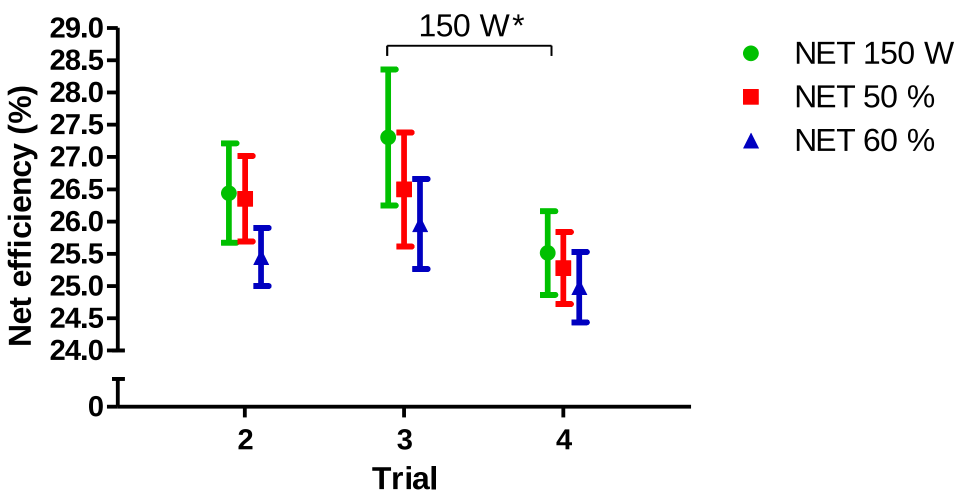


Figure 7.6 Net efficiency across trials at 150 W, 50 % and 60 % W_{max}. Note: * = P < .05.

Time-trial:

There were no significant differences in economy between trials 2-4, in the absolute 150 W workload, relative 50 % and 60 % W_{max} intensities and during the time-trial (P > .05) (**Figure 7.7**). The 60 % intensity most closely tracked performance economy when compared to the 50 % and 150 W intensities. The typical error in economy measurement also reduced as workloads increased when compared to the fixed steady-state intensities. Despite the TT intensity being higher (~ 25 %), economy error was higher than the 60 % typical error when comparing trial 2 and 3 and higher than all steady-state intensities between trial 3 and 4. There was a significant difference between TT power across trials (P = .046) (**Figure 7.8**), with a significant increase between trials 2-3 (P = 0.01) and 2-4 (P = .037). TT power also had low typical error values (CV < 4 %) when compared to gross efficiency, net efficiency and economy.

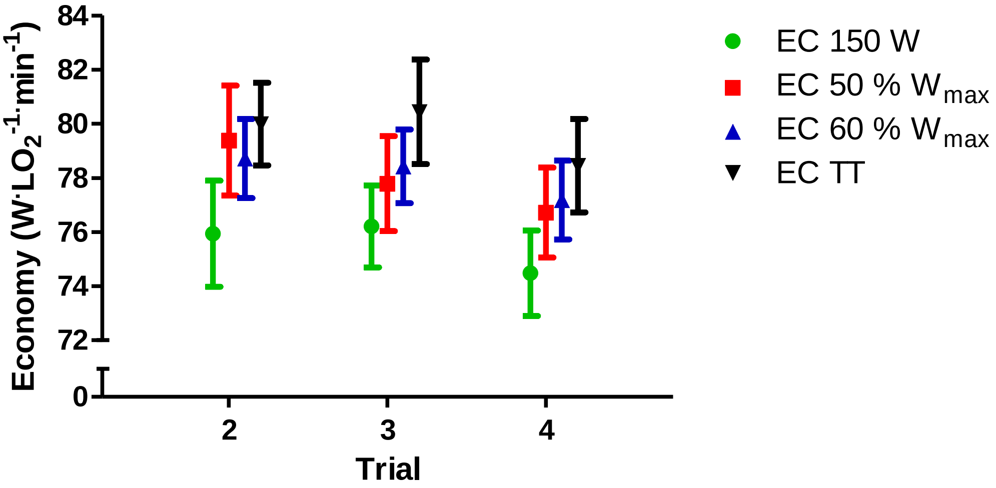


Figure 7.7 Economy across trials at 150 W, 50 % and 60 % W_{max} (no significant differences).

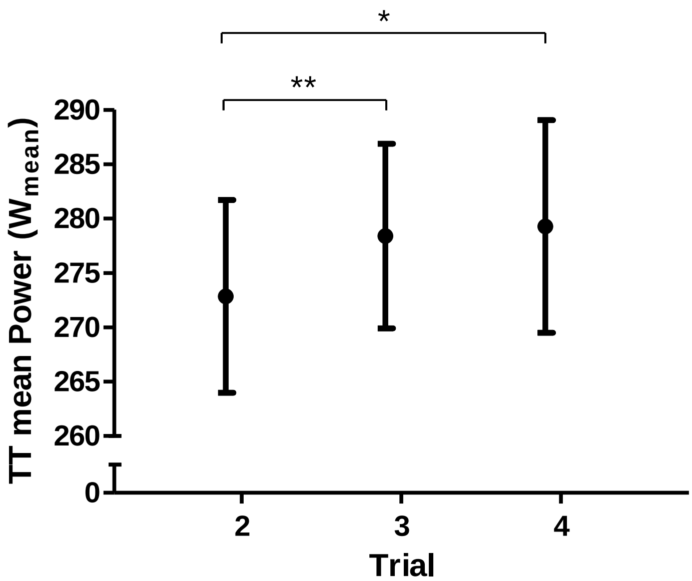


Figure 7.8 16.1 km mean time-trial (TT) power across trials. Note: * = $P < .05$, ** = $P \leq .01$.

Table 7.7 The typical error of energy expenditure and TT power.

	Trial 2-3	**Trial 3-4**
	CV % (CI)	CV % (CI)
GE 150 W	6.17 (4.71-9.14)	4.67 (3.57-6.88)
GE 50 % (W_{max})	6.22 (4.79-9.07)	4.82 (3.72-7.01)
GE 60 % (W_{max})	4.93 (3.80-7.16)	2.89 (2.23-4.18)
NE 150 W	8.83 (6.77-12.90)	6.39 (4.87-9.46)
NE 50 % (W_{max})	8.18 (6.28-11.96)	6.09 (4.65-9.01)
NE 60 % (W_{max})	6.55 (5.04-9.55)	4.30 (3.29-6.33)
EC 150 W	6.22 (4.78-9.06)	5.23 (4.03-7.60)
EC 50 % (W_{max})	6.07 (4.68-8.84)	4.70 (3.62-6.83)
EC 60 % (W_{max})	4.83 (3.72-7.02)	2.82 (2.18-4.08)
TT EC ($W^{.}LO_2$)	5.78 (4.48-8.30)	6.00 (4.61-8.73)
TT Power (W_{mean})	2.28 (1.77-3.24)	3.89 (3.02-5.56)

Note: CV %, coefficient of variation, CI, confidence interval.

Blood parameters:

There were no significant differences in blood variables across all three trials ($P > .05$). When compared to normative data all but one blood parameter was within normal ranges with Cl^- just above the normal range by 2.5 mmol/L (**Table 7.8**). The typical error of the blood parameters stayed relatively consistent when comparing between trials, with no overall reduction in CV between trials 3-4 (**Table 7.9**).

Table 7.8 Mean blood parameter values across trials 2, 3 and 4 with normal range data.

	Mean ± SD	**Normal range***
Na^+ (mmol/L)	140.4 ± 2.6	136-145
K^+ (mmol/L)	5.1 ± 0.7	3.5-5.5
Cl^- (mmol/L)	108.5 ± 3.4	98-106
TCO_2 (mmol/L)	26.0 ± 1.4	22-26
BUN (mg/dL)	16.4 ± 3.9	5-20
Glu (mg/dL)	97.0 ± 8.7	<110
Hct (%PCU)	44.4 ± 2.8	40-54
pH	7.403 ± 0.031	7.31-7.41
PCO_2 (mmHg)	40.0 ± 3.6	35-45
Hb (g/dL)	15.1 ± 0.95	14-18

Note: SD, standard deviation, *, Normal range values cited from Daniels (2010), Na^+, Sodium, K^+, potassium, Cl^-, chloride, TCO_2, total carbon dioxide, BUN, blood urea nitrogen, Glu, glucose, Hct, haematocrit, pH, acidity, PCO_2, partial pressure of carbon dioxide, Hb, Haemoglobin.

Table 7.9 Typical error of blood parameters.

	Trial 2-3 CV % (CI)	**Trial 3-4** CV % (CI)
Na^+ (mmol/L)	1.54 (1.10-2.65)	1.68 (1.25-2.62)
K^+ (mmol/L)	13.68 (9.62-24.54)	13.68 (10.06-22.01)
Cl^- (mmol/L)	2.94 (2.10-5.08)	2.94 (2.19-4.60)
TCO_2 (mmol/L)	3.16 (2.22-5.75)	4.10 (3.01-6.60)
BUN (mg/dL)	15.03 (10.58-27.07)	18.19 (13.31-29.59)
Glu (mg/dL)	6.65 (4.73-11.65)	8.55 (6.33-13.57)
Hct (%PCU)	1.37 (0.98-2.35)	3.58 (2.66-5.60)
pH	0.60 (0.42-1.07)	0.28 (0.21-0.45)
PCO_2 (mmHg)	10.15 (7.06-18.97)	4.13(3.04-6.66)
Hb (g/dL)	1.21 (0.86-2.07)	3.48 (2.59-5.45)

Note: CV %, coefficient of variation, CI, confidence interval, Na^+, Sodium, K^+, potassium, Cl^-, chloride, TCO_2, total carbon dioxide, BUN, blood urea nitrogen, Glu, glucose, Hct, haematocrit, pH, acidity, PCO_2, partial pressure of carbon dioxide, Hb, Haemoglobin.

7.5 Discussion

7.5.1 Within-day trial

The aim of this study was to assess the variability in key parameters under investigation in this thesis. The data presented clearly outlines differences in variability depending upon the techniques used to generate the data. Consecutive skinfold measurement estimating fat % and mass, irrespective of equation had a smaller technical error and variation than when compared to the automated Bod Pod assessment. The TEM of Bod Pod fat % has been previously reported to be lower at 0.45 % compared with the 0.69 % that was found in this study, yet the 0.45 % is still almost double the TEM in the skinfold estimations of body fat % (Collins et al., 1999). This was despite three skinfold measures falling just outside of the skilful threshold defined by Periniet et al. (2005) as a TEM < 5 %, suggesting that a good but not yet completely skilful anthropometrist is still able to outperform the equipment reliability of the Bod Pod in both this study and Collins et al. (1999). The difference in technique reliability of body fat estimation between the Bod Pod and skinfold equations are predicted to be the difference between an upper confidence limit of 0.100 kg (4-site), 0.128 kg (7-site) and 0.312 kg (Bod Pod) (based on; 20 participants with a mean body mass of 70 kg and body fat of 18 %). Although this estimation demonstrates the benefit of utilising a method with the highest technique reliability; it is important to note that these estimations do not account for day-to-day variability. While skinfold measurement was the least variable, discrepancies existed between the different equations used to estimate fat mass by ~2 kg, which would have a direct effect on the calculation of relative fat mass change. Using the mean data from this study; a 1 kg reduction in fat mass would equate to a fat mass reduction of 8.69 % with the 3-site, and a 7.32 % reduction with the 4-site equation, resulting in an absolute 1.37 % discrepancy. This inconsistency is likely due to differences in the number and location of skinfold sites, variations in the underwater weighing reference methods, equipment and participant characteristics. When compared to the Bod Pod estimations of fat %, the 4-site skinfold equation provided the closest mean estimated fat mass. Based on a review of previous studies that have compared the Bod Pod to hydro-densitometry; six out of eight studies reported that the Bod Pod estimated a lower body fat %, ranging from -3.3 % to -0.1 % with only two reporting higher estimations (1.2 % and 0.2 %) (Field, Goran and McCrory, 2002). Assuming that the Bod Pod has a slight tendency to underestimate body fat %, the 4-site equation provided the most likely valid measure of fat % with only a slight over estimation (+0.21 %), with the 3-site (-3.02 %) and 7-site (-2.94 %) underestimating fat %. Consequently the 4-site equation had the highest technique reliability and was considered the most likely valid measure of body composition when compared to the Bod Pod.

7.5.2 Between-day trial

Body mass was the most reliable anthropometric measure based on CV % values in **Table 7.5** determining that changes in body mass >0.82 % are likely to be above natural fluctuations, and changes >1.17 % being almost certainly above natural fluctuations with 95 % confidence. This equates to a change in mass of 0.67 kg and 0.95 kg for the average participant in the between-day study. The low variation in skinfold measurement resulted in the ability to detect small and significant changes in fat % equivalent to a change in fat mass between trial 1-2, 0.46 kg, trial 1-3, also 0.46 kg and trial 1-4: 1.21 kg. Although the mean differences were small the majority of the differences involved the first skinfold measure in trial 1 which could be omitted by not utilising the first skinfold measurement when determining change in estimated body fat. The Bod Pod displayed a similar change in fat % (0.91 %) when compared to skinfold, but potentially due to the higher variability the difference was not detected by repeated measures statistics. This suggests that the Bod Pod is not as sensitive to small changes in fat % than skinfold assessment. There was also indication that the Bod Pod was susceptible to random error, evident during trial 3 where there was a depression in fat % which was not supported with the other paralleled measures of body composition. Importantly a random absolute fat estimation error of 1.6 % (trial 3) would be in addition to equipment error and natural fluctuation.

Resting metabolic rate:

Overall RMR remained consistent regardless of the sampling location and duration. Previous research has suggested numerous measurement times ranging from 10 to 30 minutes or even indeterminate times until $\dot{V}O_2$, $\dot{V}CO_2$ and RER are considered stable; accordingly sampling periods are also quite variant ranging from 5 to 10 minutes or 3 x 5 minutes (Segal 1987; Nieman et al., 2006; Potteiger et al., 2008; Ramires et al., 2012). Considering all of the sampling periods in this study, sampling between 10-20 minutes provided the highest reliability overall, and although a difference was found over the three trials, it was likely due to the increased sensitivity and higher probability of making a type I error. Sampling for 10-20 minutes instead of 30 minutes would also allow for a reduction in the time to collect RMR. This sampling period was in agreement with Isbell, Klesges, Meyers and Klesges (1991) who determined that a 20 minute measurement period provided a stable and reliable measurement of RMR.

Energy expenditure:

Gross efficiency, net efficiency and economy at the 60 % intensity had the lowest CV % resulting in the 60 % intensity being deemed the most reliable and sensitive to change. The average gross efficiency typical error at 60 % (3.91%) was better than the 4.2 % reported by Moseley and Jeukendrup (2001) and the same as the mean CV reported by Noordhof et al. (2010). Net efficiency had a higher overall typical error (~ 2 %) when compared to gross efficiency measured across all workloads. The most likely reason for higher overall net efficiency variation is due to two separate measurements needed to calculate net efficiency; resulting in two times the technical error and two times the typical error of RMR and exercising energy expenditure. There was also a tendency for the variation in efficiency and economy to reduce as workload increased and is theorised to be as a result of more stable and consistent energy production and regulation at higher workloads, however this pattern was not present when measured with Douglas bags (Hopker et al., 2012). Gross efficiency measured with the Douglas bag method has been shown to have a smaller variability with a mean CV % of 1.5 % across workloads compared with the mean CV of 3.91 % during the 60 % intensity (Hopker et al., 2012). Although the collection of gases with Douglas bags, with the lower variability would reduce the number of participants needed in an intervention study, an online breath-by-breath system provides more flexibility to collect continuously over long periods and allows for the possibility of field testing.

TT power:

TT power differences of 6 W between the first (trial 2) and the second (trial 3) TT with only a 1 W mean deviation between the second and third TT's highlight the potential benefits of a habituation trial. Typical error however, was higher between trials 3-4 by 1.61 % when compared to trial 2-3. This is contrary to the findings of Smith et al., (2001) who reported that the CV % in 40 km TT power reduced from 2.1 % to 1.9 % between the second and third repetition. It is possible that the increased distance or the experience of the participants played a role in the variability between the studies. The low variability in the performance measure is vital to detect small changes in performance. This has been explicitly noted in the assessment of elite athletes where differences between winning and losing are very small (Jeukendrup & Martin, 2001), however in the context of this thesis if changes in efficiency and economy are induced the likely associated changes in performance are probably also going to be quite small.

Blood parameters:

A number of blood data points (n = 10) were lost due to corruption (blood clotting or air within the cartridge), which would have had an effect on the statistical power. Due to the inherent nature of the PCA being primarily based in a clinical setting, there are several studies that have compared the PCA to standard laboratory equipment and found acceptable clinical agreement across all parameters (Schneider et al., 1997; Dascombe et al., 2007; Baier et al., 2003). However, no variability data could be found to compare the typical error reported in this study. The blood data was collected and assessed in terms of reliability analysis to allow for a more substantial interpretation of data later in this thesis. Indeed for all data presented in this chapter the reliability coefficients will allow the interpretation of any changes noted in a more coherent manner in the context of statistical power, normal variability and potential insight for future studies.

7.6 Sample size calculations

The below equations were used to estimate sample sizes based on raw typical CV collected in the between-day trials and predicted change values.

$$n = \frac{16(CV)^2}{(\Delta)^2}$$

Equation 22. Sample size equation for crossover design studies. Adapted from van Belle (2011). Where: CV is the coefficient of variation and Δ represents the raw predicted change value when equal group sizes are assumed.

$$n = \frac{64(CV)^2}{(\Delta)^2}$$

Equation 22. Sample size equation for control group studies. Adapted from van Belle (2011). Where: CV is the coefficient of variation and Δ represents the raw predicted change value when equal group sizes are assumed.

Sample sizes have been calculated using mean characteristics presented in this study: body mass 82 kg and body fat 21.9 %. Predicted reductions in mass and fat % were initially based on the average changes in the calorie restricted only group, presented in Amati et al. (2008) equating to -0.52 $kg{\cdot}week^{-1}$. Conservative reductions are presented to account for the participants having a lower starting fat %.

Repeated measures with crossover design:

It is predicted that a short-term intervention with moderate calorie restriction (~ 500 $kcal{\cdot}day^{-1}$) could result in a 1 kg reduction in body mass and a 1% reduction in body fat estimation with skinfold. Using the raw typical error of body mass (0.42 kg) and body fat % (0.67 %) the calculations determined N = 3 and N = 8 would be required to detect the respective predicted changes. If the change in body mass and fat % was half of what was predicted and reduced to 0.5 kg and 0.5 %, a total of N = 12 and N

= 29 would be required to detect these smaller changes. Based on the predicted sample sizes from body composition, a conservative sample size of N = 20 would be able to predict a 9 watt change in performance power and 0.79 of a gross efficiency unit change at 60 % W_{max}.

Field and laboratory comparison:

Based on a change of 2.5 gross efficiency units reported by Bertucci et al. (2012) comparing laboratory and field gross efficiency and using the highest typical error (1.12 units between trial 3-4) in the 60 % intensity, a very small sample size of 4 participants would be required to determine if this degree of change is statically significant. A more conservative estimate of a change of 1 gross efficiency unit, 20 participants would be required, with 30 able to detect a change of 0.82 gross efficiency unit.

7.7 Conclusion

Four-site skinfold assessment of body composition and not air-displacement was used in future chapters, due to lower within- and between-trial TEM and CV % resulting in greater accuracy and sensitivity to detect small changes in fat mass. RMR measured from 10-20 min had the highest reliability overall and therefore will be the preferred sampling time. All absolute and relative intensities of efficiency were within acceptable limits and were used in future chapters; with the understanding that efficiency at the 60 % W_{max} intensity provided the least variable and most reliable results. Laboratory TT performance power and blood analysis also provided acceptable reliability. The typical error from all of the above variables and techniques continued in this thesis were used to discuss changes in forthcoming chapters.

CHAPTER 8 - THE EFFECT OF SHORT-TERM CALORIE RESTRICTION ON CYCLING EFFICIENCY AND PERFORMANCE ECONOMY

Aspects of the following chapter have been presented externally: Saunders, S.C., Coleman, D.A. and Brown, M.B. (2013) The effect of short-term calorie restriction on exercise performance and efficiency in cyclists. In: European College of Sports Science, 26th-29th June 2013, Barcelona.

8.1 Introduction

Reducing fat mass is a key strategy employed by many cyclists prior to a race in an attempt to improve performance (Knechtle, Knechtle and Rosemann, 2009). This is principally achieved with a negative energy balance by either consuming fewer calories with a hypocaloric diet and or expending more calories through physical activity (Volek, VanHeest and Forsythe 2005). Calorie restriction provides the most practical intervention solution in an already exercising population where there is limited scope for increasing energy expenditure through exercise (Garth, Raastad and Sundgot-Borgen 2011). Calorie restriction has also been shown to be the most effective intervention method to reduce body mass, when compared with varying exercise types and combinations of both diet and exercise (Clark, 2015). Research predominantly from a health and weight management perspective have reported reductions in both absolute RMR and when corrected for body composition (Poole and Henson, 1988; Pourhassan et al., 2014). While others have reported that RMR is stable when corrected for changes in fat free mass (van Aggel-Leijssen, Saris, Hul and van Baak, 2001) and only exercising energy expenditure has reduced with calorie restriction (Weigle, Sande, Iverius, Monsen and Brunzell, 1988). Both reductions in RMR and exercise energy expenditure could have beneficial effects for gross and net efficiency. However, little is known about the short-term effect of calorie restriction in a non-obese exercising population, where it is likely that a reduction in total kcal intake will reduce carbohydrate availability having a negative effect on both efficiency and performance (Bergstrom, Hermansen and Hultman 1967). Furthermore, during the initial stages of consuming a hypocaloric diet the benefits from being lighter are unlikely to be substantial, to outweigh the potential negative effects of being calorie restricted. Few studies have researched the direct effect of a hypocaloric diet on cycling efficiency and those who did reported improvements were among non-exercising populations (Amati et al., 2008). Nonetheless cycling efficiency research which has used participants accustomed to cycling have rarely reported the implications of improvements in efficiency on cycling performance (Jobson et al., 2012). Cycling efficiency is considered a key determinant of cycling performance (Lucia et al., 2002; Olds et al., 1995) and despite debate many studies have shown that efficiency can be improved (Coyle, 2005; Hopker, Coleman, Passfield and Wiles, 2010). Short-term intervention studies classified between 2-14 days (Broom, Hopkins, Stensel, King and Blundell, 2014) that have assessed the effect of training interventions on cycling efficiency and mitochondria function, did not report prescribing a compensatory increase in energy intake, despite an increase in training volume and/or intensity (Clark, Costa, O'Brien, Guglielmo and Paton, 2014; Vincent et al., 2015). Consequently, it is possible that some of the changes reported in efficiency could have been confounded by a short-term negative energy balance and small reductions in body mass. Previous research exploring the acute effect of calorie restriction prescribed a high level of calorie deficit (total energy intake ~800 kcal·day^{-1}) and used obese participants unaccustomed to cycling, thus limiting the measurement of efficiency to work rates < 120 W and the application of the findings. Therefore, it was the main aim of this research to investigate the effect of short-term calorie restriction on RMR, gross and net efficiency, cycling economy and TT performance in club level cyclists.

8.2 Methods

Seventeen male participants who had been cycling for a minimum of two years gave their written informed consent and satisfactorily completed a health questionnaire, following approval from Canterbury Christ Church University ethics committee. The physical characteristics of the participants were as follows: age 42 ± 9 yrs, height 1.79 ± 0.07 m, body mass 81.7 ± 9.5 kg, body fat 22.3 ± 5 %, $\dot{V}O_{2max}$ 51.4 ± 8.4 ml·kgmin^{-1}, W_{max} 371.0 ± 42 W·min^{-1}, relative W_{max} 4.57 ± 0.65 W·kg^{-1}·min^{-1}, classifying the cyclists as club level according to W_{max} (Ansley and Cangley, 2009).

Anthropometry:

Anthropometric measures were conducted on every visit; height (m), body mass (kg), body density using 10 site skinfold (mm); Bicep, Tricep, Subscapular, Suprailiac, Supraspinale, mid-Axillary, Chest, Abdominal, Thigh, medial Calf by an ISAK accredited Anthropometrist. Body density was determined using the Durnin and Womersley (1974) four-site equation as it was shown to be the least variable measure and had the greatest validity when compared with the Bod Pod in **Chapter 7**. Body density was converted to a body fat % using the Siri (1956) equation.

Experimental protocol:

Participants visited the laboratory on four occasions, completing a preliminary incremental maximal test visit and three subsequent laboratory visits which included steady-state efficiency measurement and a 16.1 km TT. The conditions within the laboratory were maintained and recorded at; temperature, 17.87 ± 1 °C, humidity, 62.4 ± 8.9 % and barometric pressure, 753 ± 8 mmHg. The intervention consisted of a randomised crossover design where participants either maintained their usual calorie intake (control) or consumed a hypocaloric balanced-deficit diet (intervention), which used the principles of portion control to reduce calorie intake by ~500 $kcal \cdot day^{-1}$ compared to their usual intake, without altering macronutrient ratios. A 500 $kcal \cdot day^{-1}$ deficit is considered moderate and at the lower range of the 500-1000 $kcal \cdot day^{-1}$ deficit that is recommended to induce body mass and fat reduction (Hill, Cateracci and Wyatt, 2006). Both the dietary intervention and control periods were conducted for a total of 14 days each. Participants completed three steady-state efficiency/TT trials (trial 2-4) separated by each of the two week periods. During the control, participants were asked to maintain the same diet pattern noted in their food diary completed prior to the start of the study (**Appendix 5**). All exercise testing was conducted on an electromagnetically braked cycle ergometer (SRM, Jülich, Germany) which was calibrated according to manufactures instructions prior to testing. The ergometer was adjusted to the participant's road bicycle geometry and fitted with compatible pedals. Oxygen uptake ($\dot{V}O_2$, $L \cdot min^{-1}$), carbon dioxide production ($\dot{V}CO_2$, $L \cdot min^{-1}$) and respiratory exchange ratio (RER) were calculated using a metabolic cart breath-by-breath indirect calorimetry system

(Oxycon Pro, Jäeger, Carefusion, Hoechberg, Germany). Participants were instructed to refrain from consuming caffeine for 24 hours, undertaking strenuous exercise for 48 hours and arrive fully hydrated before each test (Pringle and Jones, 2002; Jenkins et al., 2008).

$\dot{V}O_{2max}$ visit:

An incremental exercise test to exhaustion was performed at the beginning to determine the highest minute power (W_{max}) and maximal oxygen uptake ($\dot{V}O_{2max}$, $L \cdot min^{-1}$) over one minute. The protocol began at 150 W for 5 min and increased by 5 W/15 s until a cadence > 60 revolutions per minute (rpm) could no longer be maintained despite standardised verbal encouragement. Participants were allowed to select their preferred cadence and instructed to remain seated. This test informed the sub-maximal starting intensity for the steady-state 50 % and 60 % W_{max} efficiency measurement. A familiarisation 16.1 km TT was also conducted on trial one.

Efficiency and TT visit:

Resting metabolic rate ($j \cdot sec^{-1}$) was assessed with the participants in the supine position, wearing a heart rate monitor (Polar Wearlink, Polar Electro Oy, Kempele, Finland) and facemask for 20 minutes for the purpose of RMR, resting heart rate (HR_R, $beats \cdot min^{-1}$) and net efficiency calculation. Resting metabolic rate and HR_R were determined by the average 10 second data and 1 second data respectively between minutes 10-20 as it was shown to be the least variable in **Chapter 7**. Anthropometric data collection separated RMR and efficiency measurement. Participants cycled at three steady-state intensities for eight minutes each; 150 W, 50 % and 60 % W_{max} (Hopker et al., 2013). If the 50 % intensity was less than 150 W, the order was altered to ensure a progressive increase in power output (this was the case for only one participant). During a standardised five minute recovery period after steady-state cycling but prior to the commencement of the TT, a finger prick blood sample was analysed with a portable clinical analyser (PCA) (i-STAT, Portable 200, Abbott, IL, USA). The PCA provided a basic blood panel which included; sodium (Na^+), potassium (K^+), chloride (Cl^-), total bicarbonate (TCO_2), blood urea nitrogen (BUN), glucose (Glu), haematocrit (Hct), acidity (pH) and partial pressure of carbon dioxide (PCO_2). The 16.1 km self-paced time-trial detailed; a rolling start, data-restricted to distance covered (m) and for participants to remain seated. $\dot{V}O_2$, $\dot{V}CO_2$ and power were averaged during the last two minutes of each stage and for the duration of the TT. Gross, net efficiency and economy were calculated as outlined in **Chapter 6**.

8.3 Data analysis

Gross and net efficiency RER values were all ≤ 1.0, therefore no efficiency values were excluded from the efficiency calculations. Descriptive and analytical statistics were calculated using Excel, SPSS and Graph Pad Prism. The Shapiro-Wilk test was used to assess normality. Independent samples t-tests were used to compare between the randomised groups and environmental conditions. Paired samples t-tests determined significant differences between pre and post intervention body composition and energy expenditure calculations. Generalised estimating equations adjusted for the variance in logged TT economy due to the natural increase in economy as power increases (Nevill, 1997). The economy data were logged to reduce the variability of the data and align with previous recommendations

(Atkinson and Batterham, 2012). An alpha level of significance for all tests was set at 95 % ($P \leq 0.05$).

8.4 Results

Sixteen male cyclists completed the study with one withdrawing due to injury. The cyclists habitual macronutrient ratios were as follows: CHO = 55.53 ± 7.42 %, FAT = 27.97 ± 7.15 % and PRO = 16.50 ± 3.72 % and did not change when comparing three days prior to pre, post and control testing ($P > .05$). There were no significant physiological grouping differences when comparing the cyclists that completed the intervention in the first 14 days and second 14 day period ($P > .05$) **(Table 7.1).**

Table 8.1 An overall comparison of the participants that completed the intervention in the first verses the second intervention period.

	Intervention 1st Mean ± SD	Intervention 2nd Mean ± SD
N	7	9
Age (yrs)	42 ± 9	42 ± 10
Body mass (kg)	80.29 ± 10.88	83.22 ± 9.14
SF Body fat (%)	21.82 ± 4.90	22.68 ± 5.92
Bod Pod Body fat (%)	22.33 ± 6.45	23.27 ± 6.51
$\dot{V}O_{2max}$ ($ml \cdot min^{-1}$)	4188.76 ± 474.49	4153.35 ± 614.42
$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	53.14 ± 10.19	50.13 ± 7.17
W_{max} ($W \cdot min^{-1}$)	377.08 ± 27.58	366.16 ± 51.27
W_{max} ($W \cdot kg^{-1} \cdot min^{-1}$)	4.77 ± 0.74	4.42 ± 0.56

No significant differences were present between groups. Note: SD, standard deviation, N, number of participants, SF, skinfold, $\dot{V}O_{2max}$, maximal oxygen uptake, W_{max}, maximum minute power.

Fourteen participants reduced their body mass when comparing pre to post dietary intervention, one did not change and one gained body mass with an overall significant reduction in body mass (-1.24 ± 0.98 kg; $P < .001$) (**Table 8.2**). There was also a significant reduction in body fat % (-0.64 ± 1.24 %, $P < .05$) and estimated fat mass (-0.81 ± 1.20 kg, $P < .05$), but no significant reductions in lean mass (-0.43 ± 1.06 kg, $P > .05$). The technical error of the measurement was < 5 % for all skinfold sites. When utilising a median split of the data, dividing participants into high and low responders based on body mass change, a reduction in gross efficiency at 60 % (-0.23 GE units) was found in the participants with the greater body mass reduction (-2.48kg), compared to the lower weightloss group (-0.9 kg +0.46 GE units). These differences in gross efficiency were not significantly different ($P = 0.12$). Similar patterns were seen at 150 W, with a reduction of -0.54 gross efficiency units in the -2.48 kg group, verses a gain of 0.65 gross efficiency units in the -0.9 kg group ($P = 0.2$). TT performance was lower -4.25 W in the -2.48 kg group compared to -1.16 W in the -0.9 kg group, but was not significant ($P = 0.66$).

Table 8.2 Individual changes in body mass (kg) pre and post short-term calorie restriction.

	Body mass (kg)		
Participant	Pre intervention	Post intervention	Change
1	93.0	93.5	0.5
2	90.9	90.9	0.0
3	76.9	Withdrew	…
4	91.8	90.5	-1.3
5	79.0	78.3	-0.7
6	72.0	71.9	-0.1
7	78.0	76.5	-1.5
8	89.6	87.9	-1.7
9	88.0	85.8	-2.2
10	70.8	68.8	-2.0
11	72.3	70.4	-1.9
12	69.5	67.2	-2.3
13	88.1	86.3	-1.8
14	102.1	100.0	-2.1
15	71.1	69.2	-1.9
16	72.2	70.5	-1.7
17	83.2	79.9	-3.3

There were no significant differences in RMR, gross efficiency and net efficiency across all intensities (**Table 8.3**). Five blood samples out of thirty-two were lost due to blood clotting or air within the cartridge resulting in an invalid measurement. No significant differences were found between blood parameters when comparing pre to post-intervention with Hb showing a trend to increase (Pre: 15.1 ± 0.9 g/dL, Post: 15.5 ± 0.9 g/dL, $P = .058$) as well as Hct values, but were not significant (Pre: 44.5 ± 2.8 %, Post: 46 ± 2.9 %, $P > .05$). No significant differences in exercising heart rate were found across all intensities. There was no significant difference in TT power (Pre: 282 ± 36 %, Post: 281 ± 32 %) or TT power expressed relative to body mass (Pre: 3.45 ± 0.57 $W \cdot kg^{-1} \cdot min^{-1}$, Post: 3.51 ± 0.60 $W \cdot kg^{-1} \cdot min^{-1}$) ($P > .05$) but, there was a significant improvement in time-trial economy ($P < .05$).

Table 8.3 The effect of short-term calorie restriction on resting metabolic rate, gross, net efficiency and economy.

	Intensity	Pre intervention	Post intervention	Change
RMR ($j \cdot sec^{-1}$)	N/A	111.39 ± 23.01	109.78 ± 23.55	-1.61
GE (%)	150 W (%)	21.50 ± 1.88	21.65 ± 2.02	0.15
	50 % W_{max}	22.28 ± 1.72	21.82 ± 1.33	-0.46
	60 % W_{max}	22.15 ± 1.15	22.16 ± 1.51	0.01
NE (%)	150W (%)	25.48 ± 2.65	25.46 ± 1.95	-0.02
	50 % W_{max}	25.71 ± 2.12	25.02 ± 1.39	-0.69
	60 % W_{max}	24.94 ± 1.46	24.89 ± 1.62	-0.05
EC ($W \cdot LO_2$)	TT	76.26 ± 14.93	78.80 ± 15.46	2.54*

Note: RMR, resting metabolic rate, GE, gross efficiency, NE, net efficiency, EC, economy (* = $P < .05$).

Out of the nine participants that had the control phase first; four were able to maintain their mass within 0.1 kg, one reduced mass (-0.8 kg) and four gained mass (0.5, 1.0, 1.0 and 3 kg). Out of the seven participants that conducted the dietary intervention in the first phase; three participants reduced their body mass further during the control period (-0.3, -0.6 and -0.6 kg), four participants gained mass (0.7, 1.1, 1.7 and 2.2 kg) and with one participant gaining all of the body mass reduced during the dietary intervention. None of the participants finished the control period at a greater mass when compared to pre intervention. Combining the eight participants which gained mass (average increase 1.4 kg) in either the pre- or post-control period, gross and net efficiency across intensities did not show significant differences ($P > .05$). However, there was a tendency for gross efficiency to reduce when measured at 150 W (Pre: 22.27 ± 1.49, Post: 21.49 ± 1.39, $P = .08$) and the 60 % intensity (Pre: 22.72 ± 0.80 %, Post: 22.20 ± 0.81, $P = .06$). Time-trial economy did not show any differences during the control period where participants gained mass (Pre: 76.37 ± 12.98, Post: 76.71 ± 13.07 $W \cdot LO_2^{-1} \cdot min^{-1}$, $P > .05$).

8.5 Discussion

Despite significant changes in body mass and fat mass, two weeks of moderate calorie restriction did not significantly affect RMR, gross and net efficiency or laboratory TT power. This finding could provide a level of reassurance that if a participant reduced body mass by 2.14 % over a two week period between repeated laboratory testing using the methods outlined, that it would have little effect on efficiency measurement at sub-maximal intensities. Consequently previous cycling efficiency research which may have seen small changes in body mass between repeated testing are unlikely to be adversely affected by short-term body mass change. Discounting the participants that either gained mass or changed within the typical error (0.66 kg), there was a mean reduction of -1.88 kg; this was substantially greater than the level that was initially predicted in **Chapter 7** (-0.52 $kg \cdot week^{-1}$). The reason for the conservative estimation was due to the long-term study in which the calculations were based (Amati et al., 2008), not reporting interim mass reduction and therefore a linear relationship assumed. Research has however shown that mass reduces at a faster rate during the initial period of calorie restriction and that the rate tends to slow as the duration of the calorie restriction continues (Heymsfield et al., 2007).

There was a large distribution of body mass reduction, ranging from -0.1 to -3.3 kg during the intervention period. This is a frequent occurrence in dietary interventions and has led to the categorisation of participants as low and high responders in order to better understand the reasons behind the variability (Piccolo et al., 2015). Irrespective of the variation the mean estimated body fat indicated a 0.61 % reduction equivalent to 0.87 kg reduction in fat mass. This suggested that a considerable portion of the mass reduced was indeed caused through a reduction in fat and that the intervention was implemented successfully. However, this also meant that 1 kg of mass was unaccounted, with reductions in visceral fat (Chaston and Dixon, 2008), varying hydration (Fairburn and Cooper, 2014) and reduced carbohydrate levels (Kreitzman, Coxon and Szaz, 1992) considered to be the most likely explanation for the shortfall. Haematocrit levels can provide an indication of hydration status and as blood Hct showed a tendency to increase from 44.5 % to 46 % (albeit not statistically significantly) slight dehydration may have been present in the post-trials. Based on mean height and mass data in this study an absolute 1.55 % reduction in plasma volume (hypovolemia) equates to a 0.231 L (8 %) reduction in plasma water content, based on the prediction equation of total blood volume from Nadler (1962) and on the principle that plasma volume consists of 92 % water (Feher, 2012).

$$Total\ blood\ volume\ (L) = (0.3669 \times m^3) + (0.03219 \times kg) + 0.604$$

Equation 23. Total blood volume estimation equation (Nadler, 1962 cited in Gibon, Courpied and Hamadouche, 2013).

This reduced the amount of unexplained body mass to 0.77 kg with a proportion of this likely explained with intracellular fluid reduction and to a lesser extent interstitial fluid reduction (Minson & Halliwill 2000). It is possible that calorie restriction increases the reliance of stored glycogen during the intervention phase, which can result in lower CHO availability and oxidation during steady-state and TT performance testing, however there was no indication of a reduction in RER levels signifying that carbohydrate utilisation during the trial was not affected. Blood glucose was slightly higher in the post-trial by 6.5 ml/dL (7 %) suggesting that if there was a reduction in carbohydrate storage that it did not affect carbohydrate availability in the bloodstream, or performance power during the 16.1 km TT. It is also important to note that variations in mass reduced could also be influenced by varying degrees of the participants to adopt the dieatary restriction instructions.

The combined duration of steady-state cycling and TT was quite short with an average total time spent cycling ~ 41 minutes. It is quite possible that if carbohydrate stores were depleted it would have a larger influence over a longer duration (Pitsiladis and Maughan, 1999). Furthermore it is also logical to consider that lean mass did not change and therefore power would also unlikely improve based on the strong relationship between lean thigh volume (r = 0.93) and lower limb volume (r = 0.92) to predict maximal power in cycling (Martin, Davidson and Pardyjak, 2007). It is interesting that half of the participants that conducted the control phase first, were able to maintain their mass within a very tight range of just 0.1 kg, but that the other half of participants had large increases in mass above the typical error reported in **Chapter 7**. The changes in body mass over the control phase are symptomatic that body mass in some participants is stable and in others fluctuates considerably, despite a seemingly weight stable population. This is indicative that weight stability is an individualistic phenomenon with varying degrees of tolerances for energy imbalance. This individualistic concept of weight stability is commonly reported and has been attributed to both genetic factors (Matsuo et al., 2009**)** and body composition differences (Hall, 2007). By reassessing the participants after the intervention and again after the control period it provided an insight as to the direction and speed of mass change after dietary restrictions are removed. The majority of participants re-gained a proportion of the mass that was reduced, which could provide evidence of the homeostatic feedback mechanism ensuring mass maintenance (Hammid, 2009), alternatively the mass gain could also be explained by rehydration and replenished carbohydrate stores. Three participants who completed the intervention first reduced their mass even further, with two recording a body mass change approximately one CV % (-0.6 kg relative to lowest CV % = 0.54 kg) and the other well within the noise of the measurement (-0.3 kg). Considering all were supposed to be in the control phase and following guidelines, it is possible that not all adhered strictly to those guidelines, despite written and verbal communication. It is likely that there will be this type of variability in response to future intervention studies which need to be considered within the analysis of data. This point is further highlighted by not all of the participants able to follow the dietary intervention, apparent with 19 % of the 16 participants that completed the study unable to reduce body mass greater than the typical error; these are key factors to consider when designing and recruiting for longitudinal studies with dietary manipulation.

Resting metabolic rate was not affected by two weeks of calorie restriction, with a nonsignificant 1.45 % reduction well within the typical error of the measurement

(11.03 %). Reductions in RMR have been reported during more severe calorie restriction and over longer periods (Dulloo & Jacquet, 1998) with research suggesting that a reduction in fat free mass is a key contributing factor (Zurlo, Larson, Bogardus and Ravussin, 1990). As there was no significant reduction in lean mass, combined with a consistent RMR the results suggest that the mass was indeed reduced in accordance with the moderate restriction that has been shown to have little initial effect on RMR (Foster et al., 1990).

Gross and net efficiency also appeared to be unaffected by the intervention with results from all steady-state intensities within the typical error of the measurement (**Chapter 7**). This is contrary to long-term studies which have reported large changes in efficiency with calorie restriction and body mass reduction in participants unaccustomed to cycling (Amati et al., 2008). It is probable that the combination of the short duration of the intervention and the use of participants accustomed to cycling could be reasons for these results. This finding of unchanged submaximal cycling efficiency in combination with stable performance power would suggest that training intensity (up to 76 % W_{max}) would not be affected by short-term moderate calorie restriction.

An unexpected finding as a result of some of the participants gaining mass during the control period, was that gross efficiency reduced by 5.5 % at the 150 W intensity and reduced by 2.3 % at the 60 % intensity. Due to the lack of statistical power significant differences were not found, but the change in gross efficiency at 150 W was above the typical error of 4.67 % reported in **Chapter 7**. This suggests that mass increase could not only have a negative effect on efficiency, but could also have greater potency due to the mass increase being smaller yet having a larger effect on efficiency.

TT economy was the only energy expenditure calculation to improve and therefore provided the only indication that energy expenditure has the potential to reduce following calorie restriction in participants accustomed to cycling. It must be acknowledged that the exercise intensity during the TT was 76% of W_{max} and although remained relatively constant, it violated the assumption of steady-state and would have resulted in an increased anaerobic energy contribution. Nevertheless economy measurement currently provides the best indicator at performance intensities and is argued to provide a valid insight into the rate of energy production (Faria, Parker and Faria 2005). Despite the improvement in economy the participants were not able to utilise the energy saving to increase exercise capacity during the TT by increasing power output. This provides an interesting insight that might suggest exercising energy expenditure may not be such a key marker of laboratory performance as has been eluded to previously (Joyner and Coyle 2008).

8.6 Conclusion

These results suggest that body mass can be reduced acutely with moderate calorie restriction, without hindering steady-state efficiency or 16.1 km TT performance in participants accustomed to cycling. This study was explicitly conducted in a controlled laboratory environment, however due to the nature of body mass having a more likely profound influence in real world TT cycling (Jobson et al., 2007), it remains to be seen if accurate efficiency and performance measurement can be conducted in the field environment. The 50 % intensity provided similar efficiency results to the 60 % Wmax intensity and had greater variability; therefore the 50 %

intensity provided little additional information and was not included in the steady-state protocol for **Chapters 9** and **10**.

CHAPTER 9: A FIELD AND LABORATORY COMPARISON OF GROSS EFFICIENCY AND PERFORMANCE

Aspects of the following chapter have been presented externally: Saunders, S. C., Brown, M. B and Coleman, D. A. (2014). A laboratory and field comparison of gross efficiency at an absolute, relative and performance intensity. Presented at: American College of Sports Medicine (ACSM), 27-30th May 2014, Orlando, USA.

9.1 Introduction

Cycling efficiency and economy are frequently measured in a laboratory environment on a fixed cycle ergometer with an artificially stable and controlled environment. Road races however, are conducted in the outdoor environment with changeable intensities, gradients and enviromental conditions (Atkinson, Davison, Jeukendrup and Passfield, 2003; Swain, 1998). Although the laboratory provides greater control of the environmental conditions (Akkermans, Sillen, Wouters and Spruit, 2012) resulting in greater methodological consistency; exploring the effects of the more varied field environment on energy expenditure with road-bicycles may improve the understanding of the factors that influence efficiency, the relevance of efficiency measurement and its place within road cycling performance modelling (Joyner and Coyle, 2008; Jobson et al., 2012). With the advancement of reliable portable and wireless technology in both oxygen uptake (Rosdahl et al., 2010) and power measurement (Bertucci et al., 2005), field testing is a more practical and realistic alternative for sport scientists which were previously limited to a laboratory environment (González-Haro et al., 2007). Currently field research has focussed on comparing performance power during time-trials (Smith, Davison, Balmer and Bird, 2001), seated and standing positions (Harnish, King and Swensen, 2007) and comparing up-hill and level cycling (Millet, Tronche and Candau, 2002). Oxygen uptake kinetics but more specifically, cycling efficiency and economy are amongst the latest physiological variables to be tested in the field environment (Millet, Tronche, Fuster and Candau, 2002; Bertucci, Betik, Duc and Grappe, 2012; Nimmerichter, Haselsberger and Prinz, 2014). It has been reported that gross efficiency and cycling economy are higher in the field (GE: 12 % and CE: 11 %) than when using a bicycle on a fixed Axiom ergometer in the laboratory (Bertucci et al., 2012). However, these comparisons may be ergometer specific as previous research has suggested that discrepancies exist when comparing different laboratory ergometers due to differences in crank inertial load and gearing which limits the application of the findings of Bertucci, Betik, Duc and Grappe (2012) to the Axiom ergometer (Guiraud et al., 2008). Consequently, there is a need to explore the differences with a stationary cycle ergometer (SRM) which is more frequently used and considered the new gold standard (Hopker, Myers, Jobson, Bruce and Passfield, 2010) to validate laboratory measures of efficiency and economy. Standardising conditions for repeat measurements is relatively straightforward in the laboratory setting however this is more complex in the field. A previous wind cut off threshold < 3.0 $m \cdot s^{-1}$ has been previously applied when comparing efficiency in the field, despite little justification (Bertucci, Betik, Duc and Grappe, 2012). Therefore, it was considered advantageous to assess the validity of this threshold and compare the effect of wind speed on efficiency and economy measurement in the field. It was the aim of this study to investigate gross efficiency at an absolute, relative intensity and economy during a performance TT in both a field and laboratory environment. It was hypothesised that there would be differences in gross efficiency and economy between field and laboratory measurement but, that the two conditions would be closely correlated.

9.2 Methods

Twenty-eight male participants were recruited from local cycling clubs (see **Table 9.1**) and gave written informed consent following approval from Canterbury Christ Church University ethics committee. The participants were classified as club level cyclists based on their W_{max} from the $\dot{V}O_{2max}$ test (Ansley and Cangley, 2009).

Table 9.1 Participant characteristics.

N = 27*	Mean ± SD
Age (years)	41 ± 11
Stature (m)	1.79 ± 0.06
Mass (kg)	79.9 ± 12.1
Body fat (%)	19.2 ± 5.6
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	3.50 ± 0.65
W_{max} ($W \cdot min^{-1}$)	368 ± 47

Note: N, number, * = One participant was excluded due to power file corruptions, $\dot{V}O_{2max}$, Maximal oxygen uptake, W_{max}, maximum minute power.

The testing occurred over three separate testing days with participants firstly completing a laboratory based incremental test to exhaustion ($\dot{V}O_{2max}$) with the field and laboratory efficiency/economy testing completed in a randomised order 7 ± 2 days apart. Participants were required to refrain from caffeine for 24 hours and strenuous exercise in the 48 hours prior to testing. Participants were also required to complete a 72 hour food and exercise diary preceding the first visit and to keep nutrition and activity similar for the same period prior to testing. Stature (m), body mass (kg) and 4-site skinfold (Durnin and Wormesley, 1974) were measured on the first visit. Temperature, humidity and barometric pressure were measured immediately prior to testing.

$\dot{V}O_{2\,max}$:

Laboratory tests were conducted on a cycle ergometer (SRM, Schoberer Rad Messtechnik, Welldorf, Germany) that was fitted with the participant's clipless pedals and adjusted to match their road bicycle. The protocol started at 150 W for 5 minutes as a warm-up and immediately increased by 5 W/15 seconds until volitional fatigue or a cadence of > 60 $rev \cdot min^{-1}$ could no longer be maintained. The maximal minute power was determined by the highest average power over one minute and used to calculate the relative 60 % steady-state intensity. Breath-by-breath gases (Oxycon Mobile, Jäeger, Würzburg, Germany) were collected during the $\dot{V}O_{2max}$ test as a habituation for the proceeding trials and to classify the participants maximal oxygen uptake.

Laboratory steady-state efficiency and time-trial:

The efficiency steady-state consisted of an absolute intensity at 150 W and a relative intensity at 60 % W_{max} for 8 minutes each, totalling 16 minutes prior to the completion of the TT. Participants were instructed to maintain the same cadence throughout the steady-state cycling while the SRM ergometer maintained the pre-defined power which adjusted for small variances in cadence. Following a five minute rest period and a rolling start, the participants conducted a 16.1 km TT with the SRM in free cycle mode. Participants had free use of the gears to control power, were instructed to complete the TT as fast as possible and remain seated throughout (Grappe, Candau, Belli and Rouillon, 1997). Gases were collected throughout steady-state and TT cycling, with the average of the last two minutes of each stage used to calculate efficiency, and gases averaged over the duration of the TT for economy calculation (See **Chapter 6**).

Field steady-state and time-trial:

Field tests were conducted on a closed-road circuit (distance: 1.359 km/lap), ridden in a clockwise direction. The participant's road bicycle was fitted with a rear wheel power device (PowerTap Pro, CycleOps, Madison USA) and display computer (Joule GPS Promotion, CycleOps PowerTap, Madison, USA). Both tyre pressures were standardised (120 psi) (Grappe et al., 1999) and power offsets zeroed. Following a 30 minute equipment warm-up period the Oxycon Mobile was calibrated in the same manner as the laboratory tests immediately prior to testing, the facemask was secured to the participant and analyser placed in a harness with both modules resting on the back of the participant with a total mass of 0.95 kg (**Appendix 9**). Participants were previously familiarised with the circuit and completed three laps self-regulating power at 150 Watts and three laps at 60 % W_{max}. Following a five minute rest period the participants began the TT with a rolling start and completed 16.1 km (11.85 laps) as fast as they could with time, power and speed data obscured. Participants were instructed to remain seated throughout the TT. Wind, temperature and humidity data were also recorded from the local weather station. Efficiency and economy sampling were conducted with the same criteria as the laboratory tests.

9.3 Data analysis

Descriptive and analytical statistics were calculated with Excel, SPSS and Graph pad prism. Outdoor power was adjusted by +2.7 % based on the study by Bertucci et al. (2005) and in accordance with validity testing conducted in the laboratory (see **Appendix 8**). The data was assessed for normality with the Shaprio-wilk test. The field variables that were considered not normally distributed were: 150 W energy expenditure, TT energy expenditure and TT $\dot{V}O_2$ ($P < .05$). The laboratory measures that were considered not normally distributed were; 150 W, 60 % power and humidity ($P < .05$). Consequently, non-parametric tests were conducted when performing singular comparisons (related samples Wilcoxon Signed Rank) or correlations (Spearman rank tests) for the above variables and paired samples t-tests and Pearsons product moment correlations for parametric data. Pearsons product-moment correlation analysis and linear regression were used to compare TT powers in the laboratory and field environment (Hopkins, 2004). To determine the differences/bias between laboratory and field conditions, limits of agreement were determined with logged power at all three intensities (Nevill and Atkinson, 1997; Bland and Altman, 1986). Generalised estimating equations (GEE) were used to correct for the differences in power across all workloads by adjusting for energy expenditure, for gross efficiency and $\dot{V}O_2$ for economy (Nevill, 1997); they were also performed with cadence, temperature and humidity as additional covariates. Generalised estimating equations are robust against violations of normality and independence of variables, e.g repeated measures, or several measures taken from the same participant (Ziegler, Kastnre and Blettner, 1998). To assess the validity of disregarding field data, if the average wind was > 3 $m \cdot s^{-1}$, all data was analysed regardless of wind speed and then divided into two groups, ≤ 3 $m \cdot s^{-1}$ and > 3 $m \cdot s^{-1}$

average wind speed. For the purpose of correlation analysis of gross efficiency, power and raw energy expenditure at 150 W and 60 % intensities were log transformed with a natural log (LN). Time-trial $\dot{V}O_2$ and power were also log transformed (LN) for economy analysis. Covariate corrected data was also used to establish relationships with repeated measures analysis (Bland and Altman, 1995).

9.4 Results

Missing and excluded data files included; one TT gas file due to an occlusion of the sampling line, two TT power files due to corruption and one field 150 W power file was excluded on the basis that it was 87 W above target power.

Environmental conditions:

The environmental conditions for both the laboratory and field tests can be seen in **Table 9.2**. Temperature, humidity and barometric pressure were significantly different in the field compared to the laboratory (P < .001).

Table 9.2 Descriptive environmental conditions.

Environmental parameters	Laboratory	Field	Difference
Temperature (°C)	22.3 ± 2.1	16.9 ± 6.0	-5.4**
Relative humidity (%)	53.1 ± 8.4	79.8 ± 7.0	26.7**
Atmospheric pressure (mmHg)	867 ± 7	1016 ± 8	149**
Air speed ($m{\cdot}s^{-1}$)	…	5.1 ± 2.9	…

Gust ($m{\cdot}s^{-1}$)	…	6.7 ± 4.4	…

Note: ** = P < .001.

Power:

The participants were able to maintain a similar absolute 150 W (Lab: 147 ± 5 W, Field: 154 ± 15 W) and relative 60 % power (Lab: 218.1 ± 25.7 W, Field: 209.4 ± 26.9 W) in the laboratory compared to the field environment (P > .05) (**Figure 9.1**). The limits of agreement for 150 W were 1.025 x/÷ 1.113 and 60 % power were 0.999 x/÷ 1.071, both were found to not be significant with an equivalent bias of ~4 W at 150 W and ~ -2 W at 60 % in the field condition (P > .05). The limits of agreement for TT power were 0.962 x/÷ 1.096. The bias was equivalent to ~ -10 W in the field condition compared to the laboratory (P < .001) (**Figure 9.2**). There was also a significantly larger within trial power variation (SD) during the field TT compared to the laboratory (Field: 49 W, Lab: 31 W, P ≤ .001). There was also a significant, high positive correlation between TT power in the laboratory and the field (r = 0.80, r^2 = 0.64, P < .001) (see **Figure 9.3**).

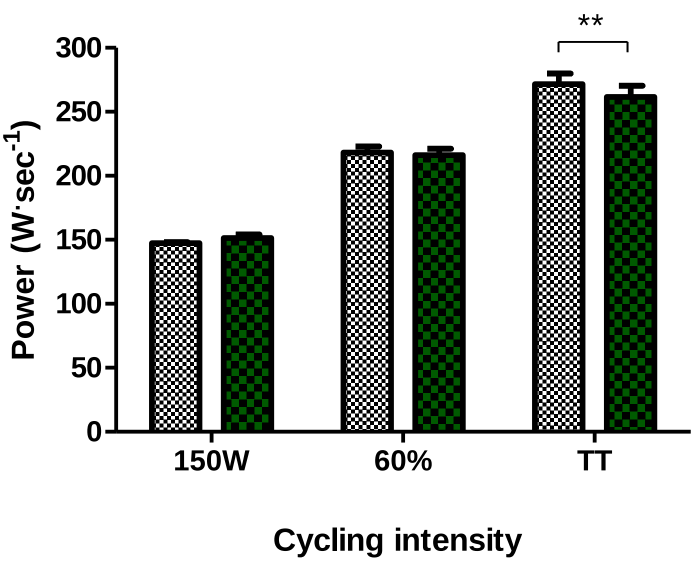


Figure 9.1 A comparison of laboratory absolute power at 150 W, 60 % maximum minute power (W_{max}), during TT performance and field power determined with limits of agreement bias. Note: ▩ = Laboratory, ▩ = Predicted field, ** = P ≤ .001.

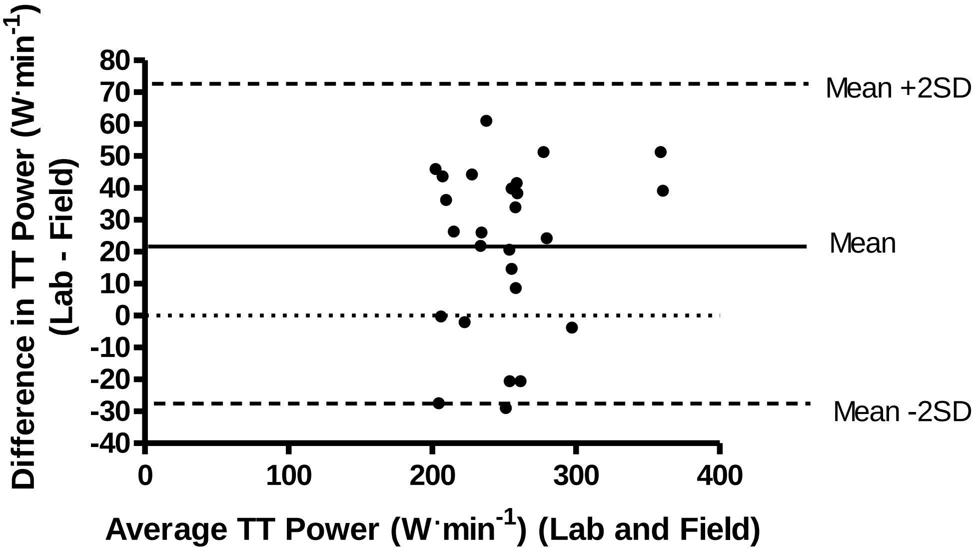


Figure 9.2 The limits of agreement between laboratory and field TT power (Watts·min^{-1}).

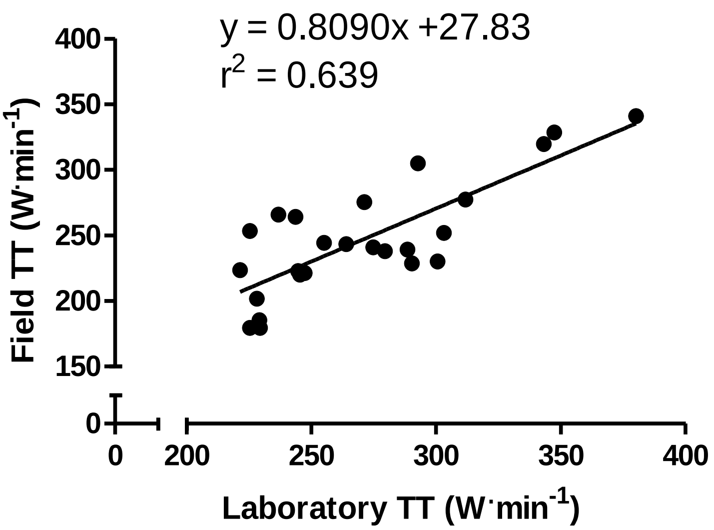


Figure 9.3 The relationship between time-trial (TT) power in the field and laboratory (P < .001).

Cadence:

Cadence was significantly lower in the field compared with laboratory across all intensities (150 W Lab: 91 ± 9, Field: 82 ± 10, 60 % Lab: 93 ± 9, Field: 85 ± 10, TT Lab: 97 ± 8, Field: 88 ± 9, $rev \cdot min^{-1}$, $P < .001$ in all cases, see **Figure 9.4**).

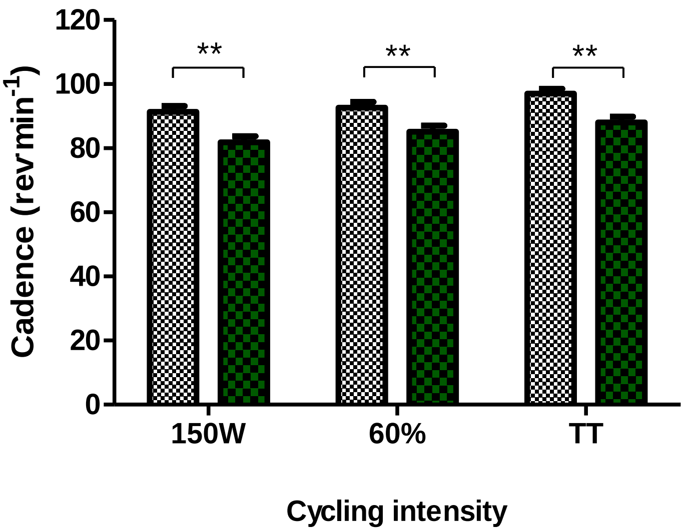


Figure 9.4 A comparison of field and laboratory cadence at 150 W, 60 % maximal minute power (W_{max}) and during the time-trial. Note: [laboratory pattern] = Laboratory, [field pattern] = Field and ** = $P < .001$.

Efficiency and Economy:

Gross efficiency in the field was not significantly different ($P > .05$) compared to laboratory testing at 150 W. Field gross efficiency was significantly lower compared to the laboratory at 60 % W_{max} ($P = .003$). Cycling economy during the time-trial was not significantly different between the two conditions ($P = .09$). Correcting for cadence as well as energy expenditure had no effect on efficiency and economy significance classification (150 W: $P = 0.849$, 60 %: $P = .036$, TT: $P = 0.272$).

Correcting for energy expenditure, cadence, temperature and humidity resulted in no significant differences across all workloads (150 W: P = 0.934, 60 %: P = 0.561, TT: P = .065, see **Table 9.3**).

Table 9.3 The results from the efficiency and economy generalised estimating equations (GEE).

Covariate	Intensity	Laboratory Mean ± SD	Field Mean ± SD	Difference Mean ± SD
EE	150 W (GE %)	18.68 ± 4.37	18.7 ± 3.88	0.02
	60 % (GE %)	20.41 ± 2.16	19.02 ± 1.87	-1.39**
	TT (EC W·$\dot{V}O_2$)	76.62 ± 2.10	73.52 ± 1.47	-3.1
EE & CAD	150 W (GE %)	18.62 ± 4.36	18.76 ± 3.88	0.14
	60 % (GE %)	20.31 ± 2.15	19.11 ± 1.96	-1.2*
	TT (EC W·$\dot{V}O_2$)	76.18 ± 5.62	73.95 ± 4.54	-2.23
EE, CAD, TMP & HUM	150 W (GE %)	18.73 ± 4.75	18.66 ± 4.11	-0.07
	60 % (GE %)	19.98 ± 3.29	19.43 ± 3.82	-0.55
	TT (EC W·LO_2)	78.19 ± 11.96	71.99 ± 10.45	-6.2

Abbreviations: SD, standard deviation, EE, energy expenditure, CAD, cadence, TMP, temperature, HUM, humidity, GE, gross efficiency, EC, economy. Note: * = P < .05, ** = P < .001.

Ventilation (V_E) was significantly lower in the laboratory compared with the field across all conditions when correcting for power and including all trials (see **Figure 9.5**). There were no differences in RER across all intensities when correcting for power (P > .05).

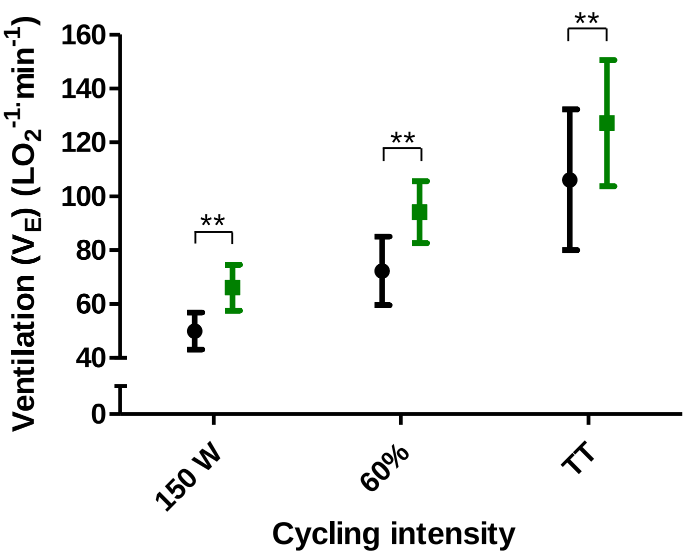


Figure 9.5 A comparison of field and laboratory ventilation at 150 W, 60 % W_{max} and during the TT. Where; ● = Laboratory, ■ = Field. Note: ** = $P < .001$.

Thirteen field and laboratory comparisons were conducted with an average wind speed ≤ 3.0 $m \cdot s^{-1}$ with fourteen > 3.0 $m \cdot s^{-1}$ (see **Table 9.4** for details on environmental conditions). Combining the 150 W and 60 % intensities repeated observation correlation analysis determined a significant positive correlation in gross efficiency between the two conditions ($r = 0.406$, $P = 0.035$). This relationship was improved when trials with wind speeds > 3 $m \cdot s^{-1}$ were excluded ($r = 0.651$, $P = .016$). When economy values across intensities were combined there was a significant positive correlation of very low strength between laboratory and field economy regardless of wind speed ($r = 0.27$, $P = .049$). This relationship was improved when trials with wind speeds > 3 $m \cdot s^{-1}$ were excluded ($r = 0.35$, $P = .039$). Excluding trials with wind speeds > 3.0 m.s^{-1} had little effect to the differences in V_E and RER between the conditions.

Table 9.4 Descriptive environmental conditions separated by a 3.0 m·s^{-1} wind speed threshold.

Environmental parameters	Field ≤ 3.0 m·s^{-1}	Field > 3.0 m·s^{-1}
Number	13	14
Temperature (°C)	16 ± 6	17 ± 6
Humidity (%)	80 ± 7	79 ± 9
Barometric pressure (mmHg)	1019 ± 7	1012 ± 5
Air speed (m·s^{-1})	1.4 ± 0.4	4.3 ± 1.5
Gusts (m·s^{-1})	1.8 ± 0.7	5.7 ± 2.8

9.5 Discussion

The main aim of this study was to assess the differences between field and laboratory measures of efficiency and economy in cyclists. Gross efficiency at 150 W did not show any differences between the two conditions which is consistent with previous findings associated with measuring efficiency at low work rates (Poole & Henson, 1988). This could also be due to the higher variation and therefore lower sensitivity at 150 W in comparison to the higher relative powers, demonstrated in both **Chapter** and **8**. Only the relative 60 % W_{max} intensity was considered significantly different (P = .003), with field gross efficiency being 6.8 % lower than laboratory and equivalent to an extra 15 W of power generation in the laboratory for a comparable energy expenditure in the field. However, the cyclists' cadence was significantly ~ 9 % lower in the field compared to the laboratory across all workloads. Preferred cadence in the laboratory has been previously reported by Jobson et al., (2012) to be within 90-100 rpm, the cyclists fall within this typical range during laboratory but not field cycling across all intensities. This difference in cadence combined with absolute metabolic differences, have been attributed to flywheel cycle ergometers having greater inertia at faster flywheel and pedal speeds (Voigt and von Kiparski, 1989; Hansen, Jorgensen, Jensen, Fregly and Sjogaard, 2002) Interventions exploring the physiological cost of a reduction in cadence in laboratory studies (80 vs. 100 rev·min^{-1}) have reported a 7 % higher efficiency with the reduction in movement speed (Stebbins, Morre and Casazza, 2014). Although this has not been demonstrated with field based studies to date, it was considered important to account for this by adding cadence as a covariate in the analysis because of the laboratory-based data. This inclusion reduced the difference in efficiency between laboratory and field measures although differences still remained statistically significant (5.9 %, P = .036). Reporting a lower efficiency in the laboratory is contrary to the study by Bertucci, et al. (2012) who reported a 12 % higher gross efficiency in the field. It was proposed that the ergometer used in their study did not have a flywheel mechanism and therefore had a lower crank inertial load was the main reason for the reduced efficiency on their ergometer. Crank inertial load was described as having a positive relationship with gross efficiency (Bertucci et al., 2012) and as the SRM ergometer in this study had a flywheel it is postulated that the crank inertial load was higher and therefore could possibly account for the differences noted in this current study. Crank inertial load is one of a number of biomechanical factors that could potentially account for the lower field efficiency in this study, the others include; gearing (Guiraud et al., 2008), body position (Fintelman, Sterling, Hemida and Li, 2015) and stabilisation during road cycling.

Biomechanical factors such as body position and aerodynamic resistance can be affected by both wind speed and yaw angle (Fintelman, Sterling, Hemida and Li, 2014), which are just two of the many environmental conditions which are notoriously difficult to predict and standardise with significantly different conditions being reported in this study ($P < .001$) and by González-Haro, Galilea, Drobnic and Escanero (2007). By adding temperature and humidity as additional covariates, it resulted in none of the intensities being considered significantly different and brought the mean difference to just 2.7 % for the 60 % W_{max} intensity. Adding temperature and humidity as covariates resulted in ~50 % reduction of the differences in gross efficiency compared to only correcting for energy expenditure and cadence. Changes in environmental conditions have been shown to influence gross efficiency with Hettinga et al., 2007) reporting a reduction of a 0.9 gross efficiency unit (equivalent to a 4.4 % reduction), suggesting that efficiency should have been lower in the warmer laboratory conditions. The negative effects of a higher temperature have been theorised to be caused by an increased priority to dissipate heat with increased periphery blood flow (Bertucci, Arfaoui, Janson and Polidori, 2013). The difference in efficiency reported by Hettinga et al. (2007) was however, with a large 20°C increase in temperature, and it is possible that the much smaller increase in temperature seen in this study was not sufficient to outweigh other physiological and biomechanical factors.

Bertucci et al. (2012) described a wind speed cut off threshold during field testing of $< 3\ m \cdot s^{-1}$, while other field comparisons have failed to state any such criterion (Nimmerichter, Haselsberger and Prinz, 2014; Mooses, Tippi, Mooses, Durussel and Mäestu, 2015). Despite the field tests being separated by the wind speed threshold the average temperature, humidity and atmospheric pressure of each group were very similar (**Table 9.3**) resulting in an equivalent comparison of the environmental conditions. The relationship between gross efficiency and economy in the laboratory and field was improved by introducing this wind threshold and this appears to be a realistic and justifiable cut off for field data collection.

TT mean power was 9 % lower in the field condition compared to the laboratory ($P < .001$). This contradicts a study by Smith et al. (2001) in which a 3 % higher mean power in field based 40 km TT compared to the laboratory was reported. Smith et al. (2001) also reported that field performance time was 5% slower in the field despite the higher power. This discrepancy has been linked to body size, air resistance and gradient (Jobson et al., 2007; Peterman, Lim, Ignatz, Edwards and Byrnes, 2015). TT mean power was highly and positively correlated between the laboratory and the field ($r = 0.80$, $P < .001$). Although 64 % of the variance in field power was explained by the laboratory assessment this still resulted in 36 % unexplained variance in this analysis. Utilising participant's own road bicycle could have resulted in energy transfer inconsistencies between the site of force application at the pedal and power measurement in the rear wheel hub. This phenomenon is referred to as 'drive chain efficiency' where bicycles have differing levels of frictional losses most notably effected by gear ratio and chain tension (Spicer, Richardson, Ehrlich and Bernstein, 2000). Although it is theorised that frictional losses and energy transference could cause small but likely consistent differences in the field power measurement; the benefits of measuring energy expenditure on the participant's habitual road bike, unlike Nimmerichter, Haselsberger and Prinz (2014) who used a single mountain bike, and the ease of fitting the power tap wheel in the field far outweighed the minor inaccuracies. In addition, the aim was to intentionally compare the differences between a fixed ergometer and free wheeled bicycle as cycling efficiency is far more frequently measured on a fixed ergometer in the laboratory. It was believed that comparing the two arguably opposing cycling modes, would provide the most applicable comparison to cycling efficiency research conducted on a fixed cycle ergometer. Furthermore, due to potential differences in bottom bracket configurations hindering SRM crank attachment, and the potential for multiple habituation trials required to acclimatise participants to cycling on a treadmill, the likelihood of a higher level of error was outweighed for the design of the initial research into the comparison between field and laboratory efficiency measurement. That being said a more likely explanation for the unexplained portion are varying air speed conditions, as only the average air speed was recorded during assessment, and the small but relevant changes in gradient, which are both likely contributed to significantly higher within trial variations in field power (18 W). Greater undulations in power have been attributed to decreased mean power during time-trials, with the optimal pacing strategy for a theoretical 0 % gradient TT > 10 minutes, is to maintain the highest constant power output (Atkinson, Peacock, St Clair Gibson and Tucker, 2007). Fluctuations of within trial power are rarely reported but this study determined an 18 W ($P < .001$) higher variation in field power compared with laboratory, which could explain why there was an increased ventilatory drive present in the field condition. Higher ventilatory drive increases the total energy cost of breathing and has been calculated to account for between 0.2 and 0.3 gross efficiency units based on an energy cost of breathing between 2.14 - 2.74 ml·L (Hopker et al., 2013). Using the same range, the difference in ventilation at 150 W accounted for between 0.43-0.54 of a gross efficiency unit and 0.41-0.52 of a gross efficiency unit at 60 % W_{max} intensity. Using the mean 60 % energy cost of breathing, it would reduce the differences in efficiency by 0.4-0.5 gross efficiency units. Thus for the 60 % intensity with energy expenditure correction the differences would reduce from -1.39 to -0.93 %; with cadence added as a covariate the reduction would be from -1.2

to 0.74 %; and the difference was almost completely attenuated with the environmental conditions added, reducing the difference from -0.55 to -0.09 %. With the calculation of the additional ventilation cost the difference in TT economy would also be reduced by between 1.09-1.39 $W{\cdot}LO_2^{-1}{\cdot}min^{-1}$. This would reduce the difference between the 150 W and 60 % economy differences by more than 40 % from -3.1 to -1.86 and -2.23 to -0.99 $W{\cdot}LO_2^{-1}{\cdot}min^{-1}$ respectively. The increased energy cost of breathing made only a small reduction to the difference in economy at the TT intensity from -6.2 to -4.96 $W{\cdot}LO_2^{-1}{\cdot}min^{-1}$. Overall this suggests that the difference in energy expenditure could be accounted by the increase in ventilation and the associated additional energy costs. Consequently the differences previously reported in field efficiency could be as a result of confounding factors that have not been accounted for in past research. This study validates laboratory measurement of gross efficiency and time-trial economy when power, cadence and environmental factors are either stable or included as confounding variables, and these variables need to be considered if the scientist is trying to estimate field based energy expenditure. Also of note, based on the different findings reported here compared to previous work (Bertucci et al., 2012), the exercise scientist will also need to consider available data on their chosen ergometer if making these estimations; as the assumption of congruence between Axiom and SRM ergometers field estimates from laboratory assessments would have been invalid.

9.6 Conclusion

This study successfully compared efficiency and performance TT's both in a field and laboratory environment. Due to the variability of the field environmental conditions and the notion that efficiency is very sensitive to changes in both temperature, intensity and cadence (Hettinga et al., 2007; Cámara, Maldonado-Martín, Artetxe-Gezuraga and Vanicek, 2012), it is believed that it will be very difficult to assess the small changes in efficiency that are predicted in **Chapter 7** and reported in **Chapter 8**. Therefore field assessment of efficiency changes were not pursued in **Chapter 10**, but field performance TT testing was conducted on the basis that TT's are often conducted in all environmental conditionss and have a smaller CV % (**Chapter 7**). Hence changes in field performance TT's were thought to be a more realistic and robust endeavour to determine small changes. Furthermore, a longer period of calorie restriction is likely to induce a greater magnitude of body mass change, which is theorised to have a larger effect on field TT performance **(**Jobson et al., 2007**)**.

CHAPTER 10 - THE EFFECT OF MEDIUM-TERM BODY MASS CHANGE ON CYCLING EFFICIENCY AND PERFORMANCE.

10.1 Introduction

Competitive cyclists are considered a particularly weight conscious population, with a large proportion of competitive cyclists indicating that a lower body mass has beneficial effects on performance (Haakonssen, Martin, Jenkins and Burke, 2015). Body mass reduction is primarily advocated by cyclists due to improvements in power to weight ratio, which results in the greatest advantage when climbing uphill (Swain, 1994). However, efficiency which is regarded as a key determinant of performance, (Olds et al., 1995; Lucia et al., 2002) has also been reported to improve with reductions in body mass within the health and weight loss field (Rosenbaum et al., 2003; Amati et al., 2008; Goldsmith et al., 2009). Due to exact changes in body mass being rarly reported in elite cyclists it is difficult to ascertain and speculate the exact physiological efficiency effects with mass reduction, therefore this Chapter is reliant at least initially on research from sedentary populations with over-weight and obese participants (Rosenbaum et al., 2003; Amati et al., 2008; Goldsmith et al., 2009). Consequently, in the vast majority of studies where calorie restriction has been achieved, efficiency has either not been calculated, or calorie restriction alone (without an additional exercise intervention) has failed to significantly improve efficiency (Poole and Henson, 1988, Amati et al., 2008). Low power outputs, grouping bias and high variation in efficiency due to a lack of habituation to cycling, may explain why differences have not been found with medium-term calorie restriction (Amati et al., 2008). Although calorie restriction has been reported to be one of the most popular means for reducing body mass (Haakonssen et al., 2015) it has the potential to hinder cycling performance over longer periods by also causing a reduction in fat-free mass (Clark, 2015). The ratio of fat mass to fat-free mass reduction varies between studies with a tendency to range from ~3:1 to ~2:1 (fat:FFM) (Rosenbaum et al., 2003; Larson-Meyer et al., 2006; Amati et al., 2008), with the difference in ratio likely due to the severity of calorie restriction and duration of intervention. Conversely, a moderate calorie deficit with athletes has resulted in significant changes in fat mass between 23-31 % with no reported reductions in lean mass (combined mass of organs, bones, muscle, water and connective tissue) (Garthe, Raastad and Sundgot-Borgen, 2011). The maintenance of lean mass was attributed to four strength and conditioning sessions per week implemented during the intervention (Garthe, Raastad and Sundgot-Borgen, 2011); although a previous study by Connolly, Romano and Patruno, (1999) also reported lean mass maintenance without the addition of exercise. Reductions in fat-free mass but more specifically lean mass would be considered detrimental to performance by reducing maximal power output and TT performance (Martin, Davidson and Pardyjak, 2007). Therefore, there is a need to investigate the effect of calorie restriction in a non-obese regularly exercising population to determine the impact upon power output and TT performance.

Fluctuations in body mass have been described in longitudinal studies to change by as much as 7 kg in a competitive cyclist (Coyle, 2005) and with endurance training to reduce by 12.5 kg equivalent to 0.63 $kg{\cdot}week^{-1}$ (Lee, Kumar & Leong, 1994). Body mass variations are therefore, also likely to occur with medium-term studies, albeit to a lesser extent but, particularly when energy expenditure is manipulated through training. Despite the potentially confounding effect of body mass and composition changes over the course of a study, variations are rarely reported. The majority of studies exploring efficiency are classified as medium-term, defined as ranging from 2 to 12 weeks (Broom, Hopkins, Stensel, King and Blundell, 2014); (3 weeks: Louis, Hausswirth, Easthope and Brisswalter, 2012, 7 weeks: Nalcakan, 2014, 12 weeks: Kristoffersen, Gundersen, Leirdal, Iversen, 2014), with 6 weeks being one of the most popular intervention durations (Luttrell and Potteiger, 2003; Hintzy, Mourot, Perrey and Tordi, 2005, Williams et al., 2009, 6 & 12 weeks: Hopker et al., 2010). Subsequently, it is yet to be quantified how changes in body mass over the most frequently used intervention duration (6 weeks) can influence changes in efficiency in a non-obese cycling population, which may have previously confounded or exaggerated results from medium-term repeated measures design studies. It was therefore, the aim of this study to build on the previous study in **Chapter 8** to see the effect of a longer period of calorie restriction, but with testing under isocaloric dietary conditions (neutral energy balance) representing a more ecologically valid scenario of pre-race season preparation.

10.2 Methods

Twenty-nine male participants who had been cycling for a minimum of two years gave their written informed consent to participate in the investigation and satisfactorily completed a health questionnaire. The physical characteristics of the participants were as follows; age 40 ± 11 yrs, height 1.79 ± 0.07 m, body mass 77.5 ± 7.2 kg, body fat 18 ± 5 %, $\dot{V}O_{2max}$ 47.19 ± 8.62 ml·kgmin^{-1}, W_{max} 373.0 ± 42.9 W·min^{-1}, relative W_{max} 4.84 ± 0.60 W·kg^{-1}·min^{-1} (mean ± SD).

Experimental protocol:

Participants visited the laboratory on six separate occasions with a $\dot{V}O_{2max}$ and an efficiency/TT visit repeated in a consecutive three phase format (two pre, two post and two follow-up visits). The conditions within the laboratory were; temperature, 21.4 ± 2.2 °C; humidity, 51.6 ± 8.0 %, barometric pressure, 755 ± 9 mmHg. Anthropometric measures were conducted on every visit; height (m), body mass (kg), six-site skinfold (mm) (Bicep, Tricep, Subscapular, Iliac crest, Thigh and Calf) by an ISAK accredited Anthropometrist. Body density was determined using the Durnin and Womersley (1974) equation. Body density was converted to a body fat % using the Siri equation (1956) (see **Chapter 6**). All exercise testing was conducted on an electromagnetically braked cycle ergometer (SRM, Jülich, Germany) which was calibrated according to manufacturer's instructions prior to testing. The ergometer was adjusted to the participant's road bicycle geometry and fitted with compatible pedals. Oxygen uptake ($\dot{V}O_2$, L·min^{-1}), carbon dioxide production ($\dot{V}CO_2$, L·min^{-1}) and RER were calculated via a portable breath-by-breath indirect calorimetry system (Oxycon Mobile, Jäeger, Carefusion, Hoechberg, Germany). Participants were randomised to either a body mass reduction intervention or were provided with no dietary instruction in the six week period between the pre and post visits. The follow-up phase was conducted six weeks after the post intervention tests where no dietary instructions were provided for either group. Testing was performed at a similar time of day to control for circadian variance. The participants were asked to refrain from consuming caffeine for 24 hours, undertaking strenuous exercise for 48 hours and arrive fully hydrated before each test (Pringle and Jones, 2002; Jenkins et al., 2008).

$\dot{V}O_{2max}$ visit:

An incremental exercise test to exhaustion was performed at the beginning of each phase to determine W_{max} (W·min^{-1}) and $\dot{V}O_{2max}$ (L·min^{-1}) using the same protocol that has been previously described in **Chapter 6**. This informed the sub-maximal starting intensity for the steady-state 60 % W_{max} efficiency test. A familiarisation 16.1 km TT was conducted on the first pre visit.

Efficiency and TT visit:

Resting metabolic rate (joules·sec^{-1}) was assessed with the participants in the supine position, wearing a heart rate monitor (Polar Wearlink, Polar Electro Oy, Kempele, Finland) and facemask for 20 minutes for the purpose of RMR and net efficiency calculation. Resting metabolic rate and HR_R, (beats·min^{-1}) were determined by the average 10 second data and 1 second data respectively between 10-20 min. Anthropometric data collection separated RMR and efficiency measurement. Participants cycled at two steady-state intensities for eight minutes each at an absolute 150 W intensity and a relative 60 % W_{max} intensity (Hopker et al., 2013). During a standardised five minute recovery period a finger prick blood sample was collected in a capillary tube, syringed into a disposable cartridge (EC8+, Abbott, IL, USA) and placed in a PCA (i-STAT, Portable 200, Abbott, IL, USA). This provided a measure of the participants; blood urea nitrogen (BUN). The 16.1 km self-paced TT detailed; a rolling start, data-restricted to distance covered (m) and for participants to remain seated, with gas collection throughout.

Efficiency and Economy:

Oxygen uptake and $\dot{V}CO_2$ were averaged from 10 second breath-by-breath data between minutes 6:00-8:00 and 14:00-16:00 during steady-state cycling and averaged across the whole 16.1 km TT. Power was averaged at the same equivalent time-intervals. Gross, net efficiency and economy were calculated as outlined in **Chapter 6**.

Field TT power:

Thirteen participants also conducted an additional 16.1 km TT test both pre- and post-intervention in the field environment on a closed-road circuit to assess the effect of the intervention on performance power and time. This testing was opportunist in nature and considered secondary to the original proposal which resulted in only a selection of participants being able to conduct field testing. This was based on the flexibility of the participants and the compatibility of their road bicycle. The participant's road bicycle was fitted with a rear wheel power device (PowerTap Pro, CycleOps, Madison, USA) and display computer (Joule GPS Promotion, CycleOps PowerTap, Madison, USA). Both tyre pressures were standardised (120 psi) (Grappe, Candau, Barbier, Hoffman, Belli and Rouillon, 1999) and power offsets zeroed. Participants were previously familiarised with the circuit and completed three laps self-regulating power at 150 W and three laps at 60 % W_{max}. Following a five minute rest period the participants began the TT with a rolling start and completed 16.1 km (11.85 laps) as fast as they could with time, power and speed data obscured. Participants were instructed to remain seated throughout the TT. Wind, temperature and humidity data were also recorded from the local weather station.

Dietary instructions and training monitoring:

All participants provided a three day food diary prior to testing. The body mass reduction group were instructed to use portion control to reduce their total calorie intake by ~ 500 kcal·day^{-1} without altering macronutrient ratios. They were also instructed to consume an isocaloric diet in the three days prior to testing. Compliance with the intervention and pre-testing protocol were determined by body mass change and pre-testing food diaries (**Appendix 5**). Particular emphasis was given to ensure participants consumed the same meal two hours prior to testing. Training data was obtained from online recording programs (STRAVA, Garmin Connect+ and Training Peaks). Data was collated in weekly segments to assess differences in distance, time and elevation in the six weeks preceding the participant's commencement of the study and between the three phases of the study.

10.3 Data analysis

The data was analysed based on original group assignment into either intervention group or control group. Descriptive and analytical statistics were calculated using Excel, SPSS and Graph Pad Prism. All data was checked for the presence of outliers and the Shapiro-Wilk test used to assess normality. The following variables were found to violate the assumptions of normality; body mass ($P < .001$), lean mass ($P < .001$), Na^+ ($P <.05$), K^+ ($P < .001$), CL^- ($P < .05$), pH ($P < .001$) and PCO_2 ($P < .001$). Consequently, non-parametric tests were conducted when performing singular comparisons (related samples Wilcoxon Signed Rank) or correlations (Spearman rank tests) for the above variables with paired samples t-tests and Pearsons product moment correlations for parametric data. Two-way repeated measures ANOVA's were used to assess TT power, RMR, training and dietary data between group and across phases. Where data violated assumptions of sphericity, Greenhouse-Geisser results were used. Generalised estimating equations in a two phase format adjusted for the variance in logged (LN) energy expenditure (j·sec^{-1}) for gross and net efficiency at 60 % W_{max} and logged $\dot{V}O_2$ was used to adjusted TT economy. The 150 W intensity was not corrected for energy expenditure due to the limited variation in power (CV = 0.7 %). Pre- and post-intervention V_E and RER were corrected for power with GEE's to explore the specific changes in these parameters.

For the purpose of correlation and regression analysis, power and energy expenditure measured at 60 % W_{max} and TT intensity were log transformed (LN) before allometric scaling was applied to gross, net efficiency and economy (Atkinson & Batterham, 2012). Pearson product-moment and Spearman rank correlations highlighted variables with a significant relationship to efficiency and performance power. An alpha level of significance for all tests was set at 95 % ($P \leq 0.05$).

A secondary analysis assigned groupings based on mass change forming a mass reduction and mass increase group to assess if the results differed based on mass change (three participants were moved in total; two participants into experimental and one into control). The reasoning for a secondary analysis was due to the possibility that there may have been cross contamination between the intervention and non-dietary instruction group.

10.4 Results

Group physical characteristics:

Twenty-nine males completed a pre and post intervention phase with twenty-four completing the follow-up phase. Based on data from the $\dot{V}O_{2max}$ test, the participants were classified as 'club level' based on mean W_{max}, according to Ansley and Cangley (2009). There were no differences in physical characteristics between groups measured at the pre intervention stage (**Table 10.1**). The group that received no dietary instruction between the six week pre and post phase gained body mass and are referred to as the mass increase group.

Table 10.1 Physical characteristics comparing mass reduction and increase group at the pre intervention phase.

	Dietary intervention Mean ± SD	**Mass increase** Mean ± SD
N	13	16
Age (yrs)	42 ± 11	38 ± 12
Body mass (kg)	75.9 ± 4.9	78.8 ± 8.9
SF Body fat (%)	19.2 ± 3.5	17.7 ± 6.7
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	3.49 ± 0.68	3.76 ± 0.62
$\dot{V}O_{2max}$ ($ml \cdot kg min^{-1}$)	46.26 ± 8.64	47.94 ± 8.81
W_{max} ($W \cdot min^{-1}$)	366 ± 31	379 ± 51
W_{max} ($W \cdot kg^{-1} \cdot min^{-1}$)	4.86 ± 0.38	4.83 ± 0.74

Note: SD, standard deviation, N, number, SF, skinfold, $\dot{V}O_{2max}$, maximal oxygen uptake, W_{max}, maximal minute power. No significant differences existed between the two groups ($P > .05$).

Body composition:

Between the pre- and post-phase there was a 3.03 % reduction in body mass in the dietary intervention group and a 2.41 % increase in the group that received no intervention (mass increase) and were statistically significant changes ($P < .001$) (see **Table 10.2**). There was a significant reduction in fat-free mass in the dietary intervention group pre to post ($P < .001$), and there was a significant increase in the mass increase group ($P < .05$). There was a significant decrease in fat mass in the intervention group and a significant increase in fat mass for the increase group pre to post ($P < .05$). Participants were considered mass stable in the follow-up phase as there were no significant differences in either the dietary intervervention group (-0.3 kg) or mass increase group (0.1 kg) ($P > .05$).

Table 10.2 Changes in body composition pre and post intervention.

	Dietary intervention	**Mass increase**
Body mass Δ (kg)	-2.3 ± 1.5**	1.9 ± 1.9**
Fat mass Δ (kg)	-1.0 ± 1.1*	1.2 ± 1.6*
Fat-free mass Δ (kg)	-1.3 ± 0.9**	0.7 ± 1.0*

Note: * = $P < .05$, ** = $P < .001$.

Cadence:

There were no significant differences in cadence during efficiency measurement in the dietary intervention group (150 W: 91 ± 8, 60 %: 92 ± 8, TT: 97 ± 7 $rev \cdot min^{-1}$) or mass increase group (150 W: 91 ± 9, 60 %: 94 ± 9, TT: 96 ± 7 $rev \cdot min^{-1}$) across phases ($P > .05$).

Laboratory TT power:

There was no main effect for group ($P > .05$), but there was a phase effect ($P = .049$) for TT power, there was also a significant group x phase interaction pre to post intervention in TT power ($P = .006$). There was no significant main effect or interaction of time-trial power between post and follow up ($P > .05$) (see **Figure 10.1** and **Table 10.3**).

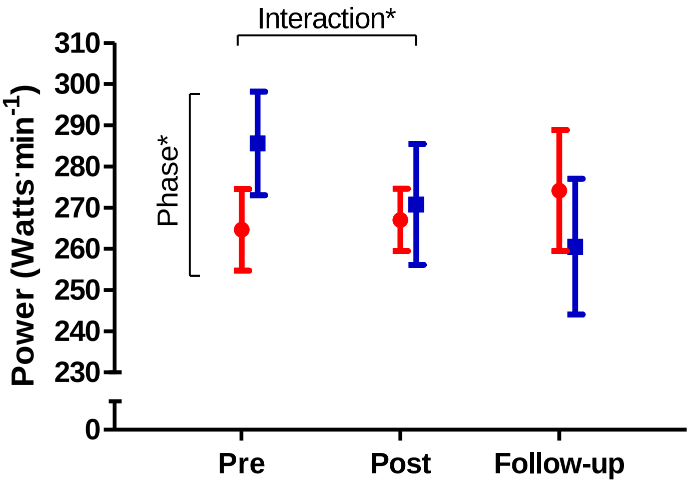


Figure 10.1 Change in TT performance power across all phases and between groups. Note: -■- = Mass increase, -●- = Dietary intervention, Interaction* = Interaction effect (P < .05). Error bars represent standard error of the mean (SEM).

Table 10.3 Change in time-trial power ($W·min^{-1}$) from pre to post and post to follow-up.

Group	Δ Pre to post	95 % CI	Δ Post to follow-up	95 % CI
Dietary intervention	5.0	-12 to 22	7.85	-8.3 to 24.0
Mass increase	-14.2	-23 to -5.6	-10.24	-29.2 to 8.7

Note: Δ, delta (change), CI, confidence interval.

Field TT power:

Six participants from the dietary intervention and seven from the mass increase group conducted field TT's. The environmental conditions are presented in **Table 10.4** and were reasonably stable with only a significant reduction in temperature in the post testing. The mean TT power for both groups was 237 W, although the mass reduction group had a smaller distribution of mean power of 21 W and the mass increase a 55 W standard deviation in TT power. The mass reduction group power increased by 17 W post intervention whereas the mass increase group displayed similar TT power with only a 2 W reduction. Despite the increase in power in the dietary intervention group and stability in power in the mass increase group, TT time was slightly lower post, attributed to variable weather conditions (albeit not significant) (**Figure 10.2**).

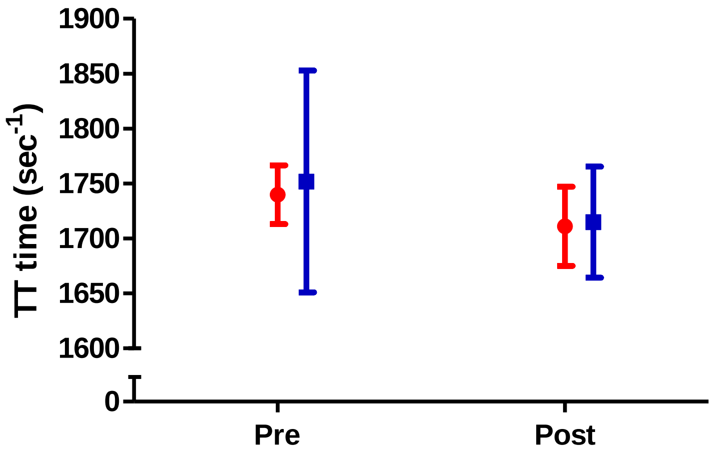


Figure 10.2 Change in field TT time from pre to post intervention. Note: -■- = Mass increase, -●- = Dietary intervention, with no significant difference (P > .05). Error bars represent standard error of the mean (SEM).

Table 10.4 Descriptive field environmental conditions pre and post intervention.

Environmental conditions	**Pre intervention** Mean ± SD	**Post intervention** Mean ± SD	**Difference**
Temperature (°C)	17.7 ± 5.4	13.0 ± 4.2	-4.7*
Humidity (%)	79.6 ± 7.2	80.0 ± 5.1	0.4
Atmospheric pressure (mmHg)	1015 ± 4	1018 ± 12	3
Air speed ($m \cdot s^{-1}$)	5.6 ± 2.7	3.9 ± 2.7	1.7
Air gust ($m \cdot s^{-1}$)	7.5 ± 4.7	4.9 ± 3.6	2.6

Note: * = P < .05.

Resting metabolic rate:

There was no significant main effect or group interaction between pre to post RMR or post to follow-up ($P > .05$) (see **Table 10.5**).

Table 10.5 Change in resting metabolic rate (joules·sec^{-1}) from pre to post and post to follow-up.

Group	Δ Pre to post	95 % CI	Δ Post to follow-up	95 % CI
Dietary intervention	-1.30	-8.8 to 6.2	-1.60	-9.5 to 6.3
Mass increase	2.06	-6.7 to 11	5.17	-5.8 to 16.2

Note: Δ, delta (change), CI, confidence interval.

Economy at TT:

There was no significant main effect in economy for phase or group between pre and post intervention ($P > .05$), there was a significant group x phase interaction ($P = .005$). Pairwise comparisons indicated a significant reduction in the mass increase group economy pre to post intervention (82.99 to 78.89 $W \cdot LO_2^{-1} \cdot min^{-1}$, $P = .004$). There was no significant main effect or interaction between post and follow-up (77.01 to 78.47 $W \cdot LO_2^{-1} \cdot min^{-1}$, $P > .05$) (see **Figure 10.3** and **Table 10.6**).

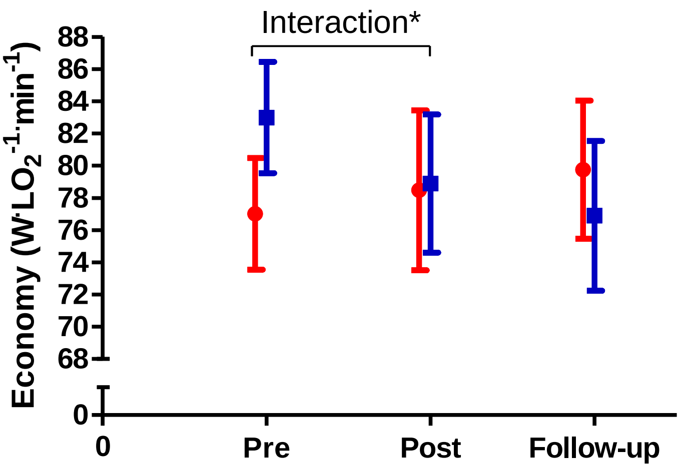


Figure 10.3 Economy during the TT across all phases and between groups. Note: —■— = Mass increase, —●— = Dietary intervention, Interaction* = Interaction effect (P < .05). Error bars represent SEM.

Table 10.6 Change in economy ($W \cdot LO_2^{-1} \cdot min^{-1}$) from pre to post and post to follow-up.

Group	Δ Pre to post	95 % CI	Δ Post to follow-up	95 % CI
Dietary intervention	1.46	-1.3 to 4.2	1.28	-1.7 to 4.3
Mass increase	-4.10	-6.6 to -1.6	-2.0	-3.6 to 4.0

Note: Δ, delta (change), CI, confidence interval.

Gross efficiency at 150 W:

There was no significant effect of phase ($P > .05$) or group ($P > .05$) but there was a significant interaction ($P = .039$) comparing pre to post intervention in gross efficiency at 150 W (**Figure 10.4**). Pairwise comparisons indicated a significant decrease in efficiency pre to post in the mass increase group (21.00 to 19.58 %, $P = .028$). There were no differences in gross efficiency at 150 W in the dietary intervention group between pre and post (20.76 to 20.79 %) ($P > .05$).

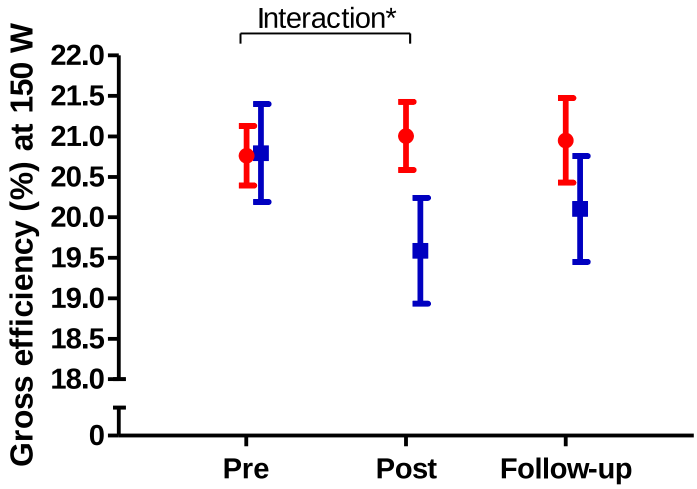


Figure 10.4 The effect of body mass change on gross efficiency (%) at 150 W. Note: -■- = Mass increase, -●- = Dieatary intervention, Interaction* = Interaction effect ($P < .05$), Group* = Group difference ($P < .05$). Error bars represent SEM.

Gross efficiency at 60 % maximal power:

Three efficiency calculations from pre-testing, three from post-testing and one from follow-up at the 60 % W_{max} intensity were excluded on the basis of an RER > 1.0. No significant main effects of group or phase were present in gross efficiency at 60 % W_{max} when controlling for energy expenditure pre to post intervention ($P > .05$). There was a significant phase group interaction in 60 % W_{max} gross efficiency ($P < .01$). Pairwise comparisons indicated no significant change in gross efficiency with the dietary intervention (21.27 % to 21.64 %) ($P > .05$) and a significant reduction in gross efficiency with mass increase (22.11 to 21.36 %) ($P < .01$) when measured at 60 % W_{max} (see **Figure 10.5**).

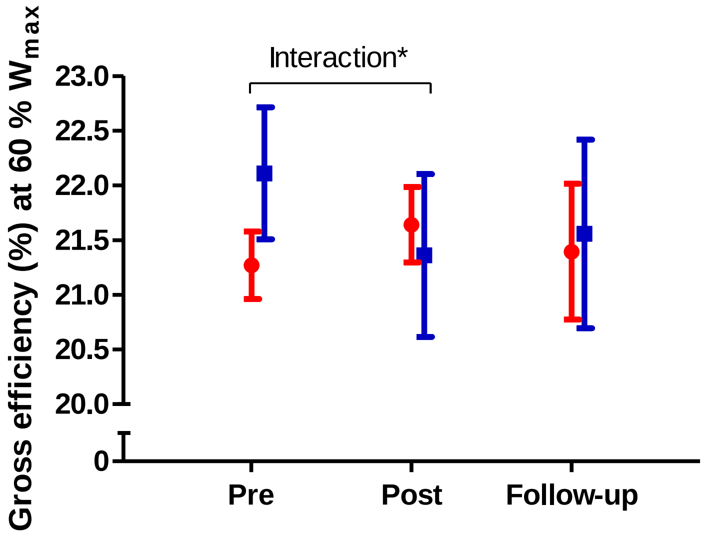


Figure 10.5 The effect of body mass change on gross efficiency (%) at 60 % W_{max}. Note: ■ = Mass increase, ● = Dietary intervention. Interaction* = Interaction effect ($P < 0.01$). Error bars represent SEM.

Net efficiency at 150 W:

There was a significant main effect of phase ($P < .01$), but no main effect for group or interaction in net efficiency measured at 150 W when comparing pre to post intervention ($P > .05$). Pairwise comparisons indicated a significant reduction in the mass increase group (24.14 to 23.10 %) ($P < .01$) (see **Table 10.7**).

Net efficiency at 60 % maximal power:

No significant phase or group differences were found in net efficiency at 60 % W_{max} pre to post intervention ($P > .05$). There was a significant phase and group interaction when controlling for energy expenditure ($P < .05$). The pairwise comparisons indicated that there was a significant reduction in net efficiency at 60 % W_{max} in the mass increase group pre and post ($P < .05$). No differences in net efficiency at 60 % W_{max} in the dietary intervention group between pre and post were present (**Figure 10.6**).

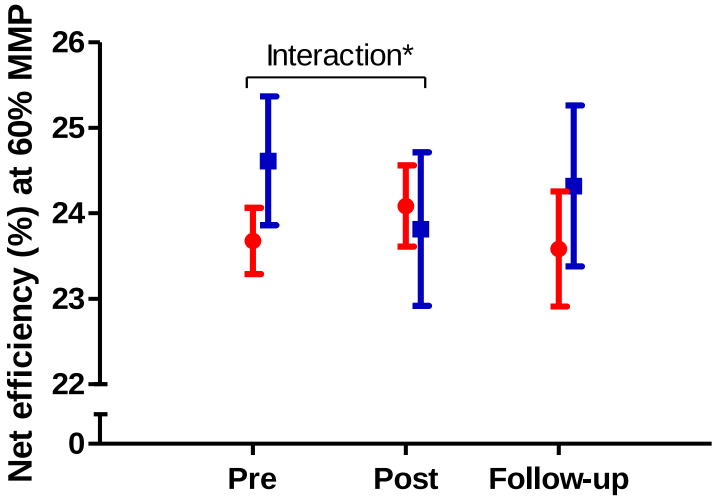


Figure 10.6 The effect of body mass change on net efficiency (%) at 60% W_{max}.
Note: -■- = Mass increase, -●- = Dietary intervention, Interaction** = Interaction effect ($P < 0.001$). Error bars represent SEM.

Table 10.7 Overall changes in cycling efficiency as a result of a medium-term body mass change intervention.

Efficiency	Intensity	Dietary intervention Δ Absolute	Dietary intervention Δ Relative	Mass increase Δ Absolute	Mass increase Δ Relative
GE (%)	150 W	0.03 ± 1.18	0.14 ± 5.65	-1.42 ± 2.27	-7.03 ± 11.24
	60 %	0.85 ± 1.72	3.96 ± 8.02	-0.75 ± 1.64	-3.39 ± 7.54
NE (%)	150 W	-0.31 ± 1.74	-1.30 ± 7.28	-1.05 ± 3.77	-4.35 ± 15.62
	60 %	0.41 ± 1.39	1.73 ± 5.87	-0.80 ± 3.02	-3.24 ± 12.37

Note: Δ, delta (change), GE, gross efficiency, NE, net efficiency and SD, standard deviation.

There was no significant phase, group or interaction effects in 150 W, 60 % gross and net efficiency post to follow-up ($P > .05$) (**Table 10.8**).

Table 10.8 Overall changes in cycling efficiency from post intervention to follow-up.

Efficiency	Intensity	Dietary intervention		Mass increase	
		Δ Absolute	**Δ Relative**	**Δ Absolute**	**Δ Relative**
GE (%)	**150 W**	-0.05 ± 2.14	-0.27 ± 10.53	0.51 ± 3.43	2.61 ± 14.95
	60 %	-0.25 ± 1.19	-1.14 ± 5.49	0.19 ± 2.97	0.90 ± 12.37
NE (%)	**150 W**	-0.01 ± 3.90	-0.03 ± 16.49	0.71 ± 7.72	3.12 ± 33.31
	60 %	-0.50 ± 1.64	-2.10 ± 6.90	0.51 ± 3.60	2.14 ± 15.16

Note: Δ, delta (change), GE, gross efficiency, NE, net efficiency.

Ventilation and respiratory exchange ratio:

No phase, group or interaction effects were identified in V_E at 150 W or at 60 % W_{max} ($P > .05$), however there was a significant phase effect of V_E during the TT ($P < .05$) and no interaction ($P > .05$). Pairwise comparisons identified that only difference was a reduction in V_E in the intervention group (pre: 125.3, post: 115.7 $L \cdot min^{-1}$, $P < .05$). There were no significant differences in phase, group or interaction effects in RER across all of the intensities ($P > .05$).

Predicting changes in performance economy:

Changes in TT economy had the strongest relationship with changes in net efficiency at 60 % ($r = 0.709$), and changes in economy at 60 % W_{max} ($r = 0.722$), ($P < .001$) showing significant high positive correlations (**Figure 10.7**).

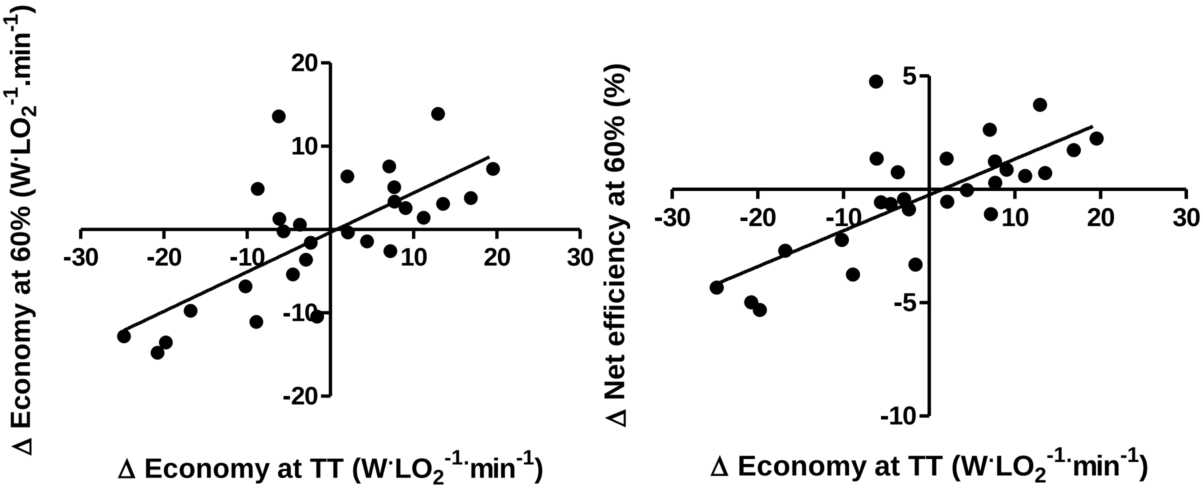


Figure 10.7 The relationship between changes in TT economy verses changes in 60 % economy (left graph) ($y = 0.4739x - 0.3436$, $r^2 = 0.503$) and 60 % net efficiency (right graph) ($y = 0.1581x - 0.2438$, $r^2 = 0.522$). Note: Δ, delta (change), TT, time-trial.

Training data:

There was a significant phase effect of training distance ($P = .039$), and elevation ($P = .03$) but not average time or speed ($P > .05$) when comparing 6 weeks prior to the study and 6 weeks during the intervention period. There were no significant group differences or interactions ($P > .05$) (**Figure 10.8)**.

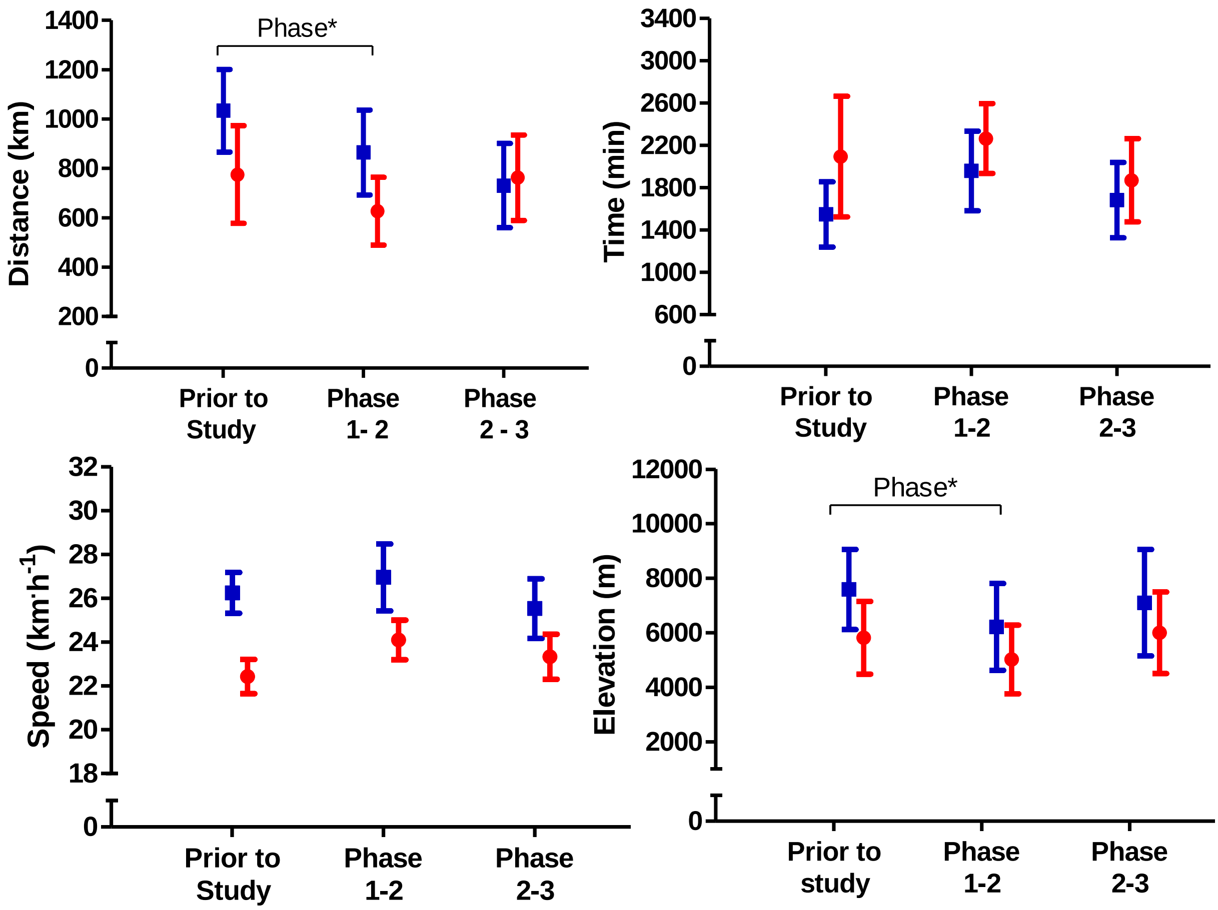


Figure 10.8 Top left - showing average training distance (km). Top right - showing average training time (min). Bottom left - showing average speed ($km{\cdot}h^{-1}$). Bottom right – showing elevation. Note: -■- = Mass increase, -●- = Dietary intervention, Phase* = Phase effect ($P < .05$). Prior to study = six weeks prior to the commencement of the study, Phase 1-2 = during the six week intervention period, Phase 2-3 = during six week follow-up period.

Dietary data:

There were no significant phase, group or interaction effects between CHO: 396.5 ± 120.9 $g{\cdot}day^{-1}$, FAT: 83.0 ± 30.9 $g{\cdot}day^{-1}$, PRO: 111.8 ± 37.8 $g{\cdot}day^{-1}$ (g) and total kilocalories 2681.6 $kcal{\cdot}day^{-1}$, intake across all three phases and between groups ($P > .05$) (**Figure 10.9**). The average macronutrient ratio throughout the study was CHO: 67.1 %, FAT: 14.0 %, PRO: 18.9 %.

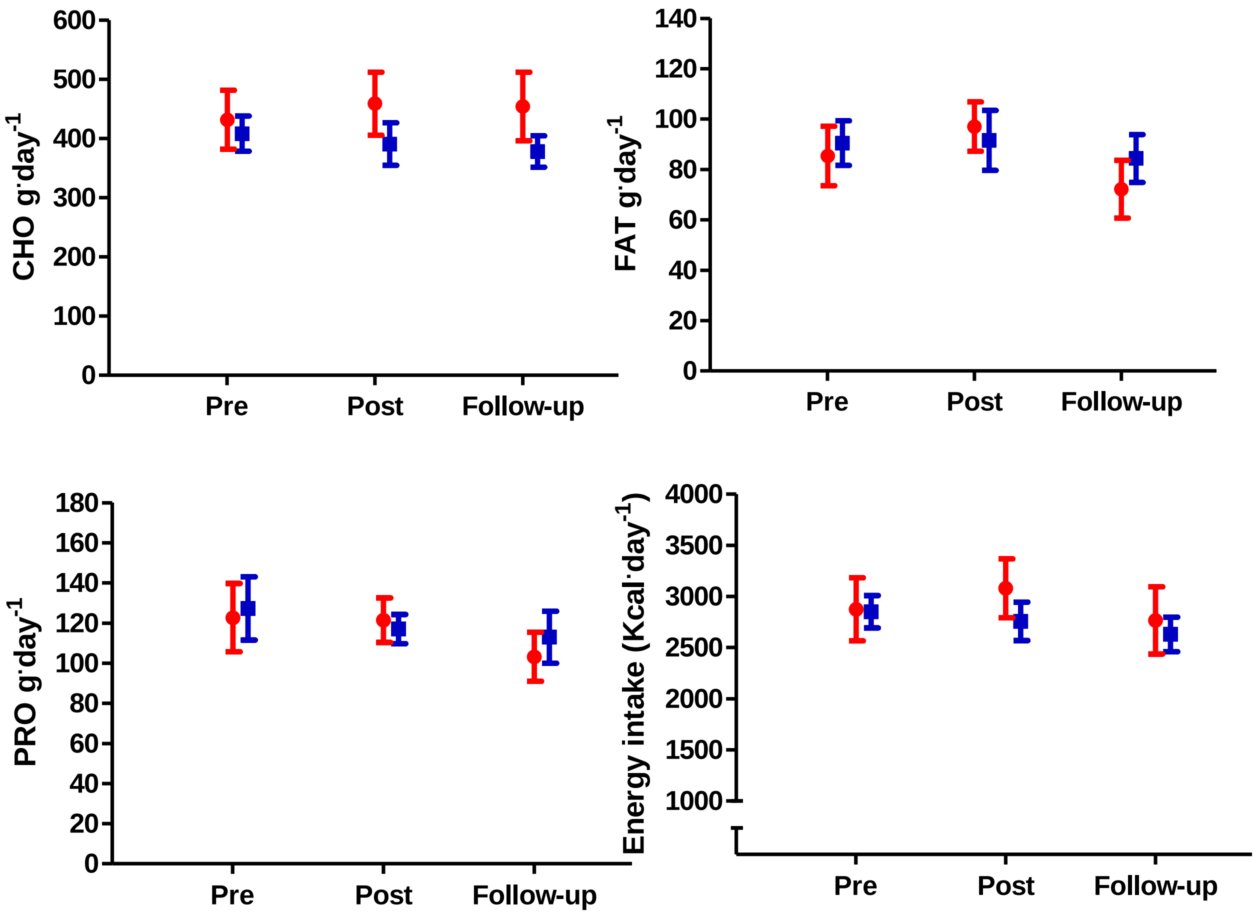


Figure 10.9 Top left - Showing average Carbohydrate (CHO) intake ($g{\cdot}day^{-1}$). Top right - Showing average Fat (FAT) intake ($g{\cdot}day^{-1}$). Bottom left – Showing average Protein (PRO) intake ($g{\cdot}day^{-1}$). Bottom right – Showing average total energy intake ($kcal{\cdot}day^{-1}$). Dietary data averaged across the three days prior to Pre, Post and Follow-Up testing. Note: -■- = Mass increase, -●- = Dietary intervention. No significant differences were present.

10.4.1 Post-hoc group analysis

By allocating participants based on body mass change rather than original group allocations, the results did not change direction but overall the changes became stronger. Physical characteristics did not significantly change ($P > .05$), but the magnitudes of the changes in mass (Δ 0.1-0.3 kg) and body composition (0.1-0.2 kg) increased slightly (**Table 10.9**).

Table 10.9 Changes in body composition pre and post intervention with group allocations determined by body mass change.

	Mass reduction	**Mass increase**
Body mass Δ (kg)	-2.4 ± 1.4**	2.2 ± 1.3**
Fat mass Δ (kg)	-1.1 ± 1.4*	1.3 ± 0.9*
Fat-free mass Δ (kg)	-1.4 ± 0.8**	0.9 ± 0.9

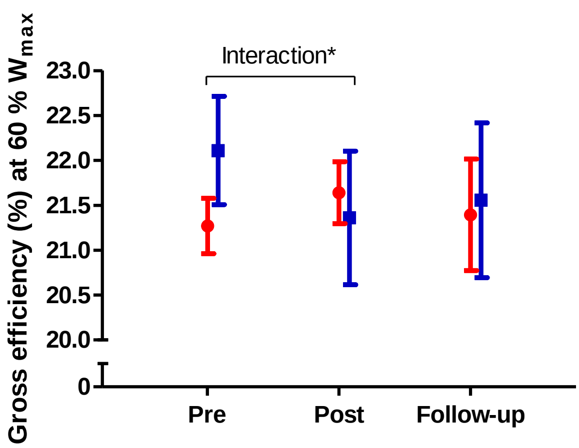
Note: * = P < .01, ** = P < .001.

The secondary analysis had the most notable influence on gross efficiency at the 60 % intensity where a greater magnitude of improvement was present with body mass reduction from ($P < .05$ to $< .01$) (**Table 10.10**). This was also visually apparent when comparing efficiency at the 60 % intensity based on original grouping and post-hoc body mass change (**Figure 10.10**).

Table 10.10 Overall changes in cycling efficiency as a result of a medium-term body mass change using post-hoc group allocations.

		Mass reduction		**Mass increase**	
Efficiency	**Intensit y**	**Δ Absolute**	**Δ Relative**	**Δ Absolute**	**Δ Relative**
GE (%)	150	0.17	0.81	-1.24	-6.04
	60 %	0.66	3.13	-0.99	-4.26
NE (%)	150	0.35	1.42	-0.98	-4.11
	60 %	0.53	2.22	-1.01	-4.11

Note: Δ, delta (change), GE, gross efficiency, NE, net efficiency.



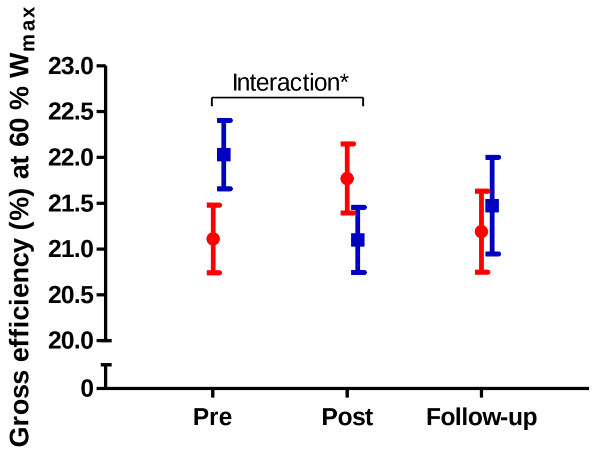


Figure 10.10 The effect of body mass change on gross efficiency (%) with original group allocations compared to post-hoc body mass change at 60 % W_{max}. Note: (blue square marker) = Mass increase, (red circle marker) = Mass reduction. Interaction* = Interaction effect ($P < 0.01$). Left graph is based on original intervention and control groups. Right graph is based on group's determined by post-hoc body mass change. Error bars represent SEM.

10.5 Discussion

It was the aim of this study to determine the effect of a six week moderate calorie restriction intervention on efficiency and TT performance power in participants accustomed to cycling.

Body mass reduction:

Gross and net efficiency were significantly improved at the 60 % W_{max} intensity (GE: 3.96 % and NE: 1.73 %) following a 2.3 kg reduction in body mass (3.02 % body mass). If comparing the body mass effect based on post-hoc group allocations the improvement was equivalent to 3.13 % of a gross efficiency unit and 2.22 % for net efficiency. The reduction in body mass was in-line with the linear predictions from the results presented in Amati et al. (2008). This is the first study to show that improvements in efficiency can be achieved with 'only' calorie restriction with participants accustomed to cycling riding at substantially higher power outputs (~223 W) than have previously been investigated. This finding is in concurrence with the similar efficiency improvements (4 %) reported by Amati et al., (2008), despite a longer duration (16 weeks) and a much larger reduction in body mass (8.3 kg). It could therefore be theorised that the majority of the improvements in efficiency occur during moderate-length calorie restriction, with only a small proportion of the improvement in efficiency attributed to the magnitude of mass reduction. It is important to note that a significant improvement was not found at 150 W and yet there was a tendency for efficiency to improve; suggesting that efficiency differences at lower power outputs are conducive but more difficult to detect, most likely due to the higher variability seen in **Chapter 7**. Cycling TT economy also increased by 1.90 % based on original group allocations or by 5.2 % based on post-hoc body mass change groups, both values were however below the typical error (5.78 %) (**Chapter 7)**. The higher economy change had the potential to equate to a 7 W increase in power for the same energy expenditure. However, in a similar manner and supporting the findings of **Chapter 8**, the participants were unable to utilise the energy saving and produce a noticeably higher power output during the TT. Reductions in RMR have been speculated to potentially contribute to reductions in efficiency and economy, however RMR did not change following the ~500 $kcal \cdot day^{-1}$ deficit, suggesting that this level of moderate calorie restriction is suitable for participants that exercise regularly, and more importantly is a sustainable method of mass reduction due to RMR stability. Previous studies that have reported substantially lower RMR with body mass reduction have been in the more severe calorie restriction studies (Grande, Anderson and Keys, 1958; Dulloo and Jacquet, 1998; Hill, 2004), with moderate deficits showing little change (Foster et al., 1990). RMR stability therefore suggests that the improvement in gross efficiency at 60 % W_{max} intensity was predominantly due to reductions in exercise energy expenditure, confirmed with net efficiency also showing improvement. This phenomenon where RMR remains stable and the majority of the improvements in energy expenditure are when exercising, have been previously reported by Amati et al. (2007). It is theorised that the improvement seen in exercise and not RMR could be attributed to the reductions in fat mass reducing the demand of blood to the periphery for cooling due to a reduction in subcutaneous insulation. Although adipose tissue has a very low metabolic rate accounting for between 3-5 % of RMR in non-obese participants, during exercise the muscles produce 3-4 times more heat than mechanical energy (Dullo, 2010) and so a reduction in the insulation of heat energy could have a large impact upon performance. This is based on the notion that the rate of heat storage, determined by the rate of heat production minus heat dissipation (Webb, 1995), will be slower with a thinner subcutaneous adipose layer and that exercising in cooler environments represents a similar scenario to a reduction in environmental temperature, demonstrated to have a higher gross efficiency than hot environments (Hettinga et al., 2007). Additionally, a reduction in the metabolic cost of the 1.3 kg or 1.7 % of fat-free mass could also account for the energy saving during exercise and why there was little change at rest. This theory could also explain why differences were not found at 150 W due to the lower exercise intensity causing a smaller metabolic demand. Muscle tissue at rest only accounts for between 20-30 % of the total RMR and so a small reduction in muscle mass at rest is unlikely to have a large influence on 24 hour REE (Zurlo, Larson, Bogardus, and Ravussin, 1990). If the change in

FFM mass were assumed to be a pure reduction in lean tissue it is estimated to account for an 16.9 kcal·day^{-1} reduction in REE or 18.2 kcal·day^{-1} with post-hoc analysis (Hill, Cateracci and Wyatt, 2006). Based on the average RMR in this study (2088 kcal·day^{-1}) the reduction in lean mass at rest is estimated to cause only a 0.81 % reduction in RMR. However, the metabolic rate of lean mass during exercise can increase by 50-100 times the energy cost at rest resulting in a multiplication of the change in lean mass energy expenditure, which would have a greater potential and more probable effect while exercising (Bhagavan, 1992). A possible reason for the reduction in fat-free mass, if assumed to be primarily muscle mass, is theorised to be as a result of a lower production of the insulin-like growth factor-1 (IGF-1), reducing the body's ability to synthesise lean tissue (Benardot and Thompson, 1999). IGF-1 has been reported to decrease during short-term calorie restriction (Smith, Underwood and Clemmons 1995) but has been reported to stabilise in long-term (1 year) moderate calorie deficit studies (Fontana, Weiss, Villareal, Klein and Holloszy, 2008). The pattern of IGF-1 following a calorie restriction intervention would therefore coincide with both short- and medium-term calorie restriction, where similar changes in lean mass have been reported (Krotkiewski, Landin, Mellström and Tölli 2000). A reduction in lean mass could also suggest why improvements in TT power were not found as it may have had an opposing effect on the small amount of energy that was saved during the TT. Currently there are no studies that have demonstrated an improvement in efficiency and simultaneously measuring improvements in performance; it is therefore unknown that without the reduction in lean mass if participants are able to utilise the savings in energy expenditure.

Diet has also been a factor that has been shown to influence economy and efficiency values. In this study dietary analysis supported the notion that the participants were not calorie restricted in the three days prior to testing and demonstrated a very small increase in carbohydrate intake and total kcal consumed (pre to post). This increase was likely attributed to natural overcompensation in dietary intake following a period of calorie restriction, which has been previously reported in both animal and human studies when 'alternate day fasting' (Varady and Hellerstein, 2007). To determine if the small changes could have influenced the efficiency improvement, changes in CHO (g) were correlated with changes in efficiency, but a negligible relationship found ($r = .0145$, $P = 0.62$). Interestingly the largest difference in macronutrient ratio was reported between post and follow-up testing where no differences in efficiency were found. Additionally substrate usage was not affected by calorie restriction as no differences were reported in macronutrient usage based on RER values and protein oxidation via BUN readings ($P = .689$). Previous research that has reported changes in efficiency with dietary interventions have demonstrated that much larger macronutrient changes (30 % versus 70 % total kcal from CHO) are necessarily to induce a ~ 0.5 % change (Cole et al., 2013). Consequently dietary changes were ruled out as a confounding factor. A decrease in training volume with a negligible increase in intensity was present between pre and post testing in the mass reduction group. Based on a study by Kriskoffersen et al. (2014) who recruited a similar population type and conducted an intervention over the same duration, reported that efficiency remained stable with the prescription of high intensity training. Therefore, it would seem unlikely that efficiency would be influenced by a much smaller training alteration and if anything, would have had an opposing negative influence upon efficiency and is unlikely to account for the improvement.

Body mass increase:

Fluctuations in control group body mass and body composition are commonly reported with a specific tendency for gains in both body mass (1-1.9 kg) and fat mass (0.8-1.4 kg) while FFM tends to increase (Spence, Galantino, Mossberg and Zimmerman 1990; Treuth et al., 1985; Dove, 2008). Hence the finding in this study that mass and fat mass increased in the control group is not a new concept and is further supported with the gain in body mass during the control phase of **Chapter 8**. Exploring the effect of mass increase was not an original intension of this study, however, the non-dietary intervention group increasing mass provided a more comprehensive perspective of the relationship between efficiency and body mass change. The non-intervention group that gained mass increased by an average of 1.9 kg or 2.2 kg with post-hoc analysis which was in proportion to the decrease in the mass reduction group, providing a comparable change in mass. The increase in mass caused a greater detrimental effect on gross efficiency by reducing it by -7.03 % at 150 W, -3.39 % at the 60 % W_{max} intensity. The results were comparable with post-hoc group allocations with a reduction in efficiency of -6.04 % at 150 W and -4.26 % at the 60 % intensity. Net efficiency reduced by 4.35 % in the mass increase group at 60 % W_{max} and again was similar with post-hoc group allocations at 4.11 %. Body mass changes have been likewise explored by Goldsmith et al. (2009) who increased and decreased body mass both by 10 % of initial mass, but despite the same magnitude of change, efficiency decreased by a higher percentage in the mass increase group (25 %) than it increased with the mass reduction group (15 %). The research by Goldsmith et al. (2009) was conducted at very low power outputs (10-50 W), and would usually be a criticism, however in combination with the findings in this study it suggests that body mass has a greater potential to reduce efficiency than it does to improve, irrespective of the power output in which efficiency is measured.

RMR did not significantly change in the mass increase group and changes were within the 95 % confidence intervals presented in **Table 10.5**. RMR has been reported to change by 10 $j \cdot s^{-1}$ with much greater mass increase (7.6 kg) and over a similar time period (Diaz, Prentice, Goldberg, Murgatroyd and Coward, 1992), but 10 $j \cdot s^{-1}$ would still be considered within the typical error of RMR measurement (11 %) presented in **Chapter 7**. This further suggests that the RMR remains quite stable during medium-term mass increase and that the detrimental effect to efficiency was due to exercising energy expenditure increasing and not RMR. There was no difference in the pre-testing dietary data to provide an indication that the increase was due to increased energy intake, however, this only provided a three day measurement and therefore an increased energy intake during the six week period could not be dismissed. Another possibility for the mass increase was the reduction in energy expended through training, demonstrated with a phase effect in total distance, time and elevation. This reduction in training from pre- to post-intervention occurred in both groups making the conditions paralleled and therefore arguably uninfluential to efficiency measurement if considering the interaction effect. The reduction in training distance is estimated to account for a net increase of 92.67 $kcal \cdot day^{-1}$, based on the reduction in training distance by 28.16 $km \cdot week^{-1}$ and an average energy expenditure of 9.56 $kcal \cdot min^{-1}$ when participants were exercising at 150 W in the laboratory. The 150 W intensity provided the closest estimate based on an average training speed of 24.9 $km \cdot h^{-1}$ equating to 129 W if the training was conducted on the SRM ergometer. Despite the equation being an estimation, it provided an indication that a reduction in energy expenditure through training was unlikely to be responsible for the increases in body mass.

Unlike the mass reduction group where power remained relatively stable, the mass increase group produced 5.2 % less power during the laboratory TT following mass gain, which equated to a 37 second slower simulated TT. Nonetheless the TT time calculation only takes into account the power reduction and does not consider changes in biomechanical factors such as; increased frontal surface area and greater inertia affecting both acceleration/deceleration and incline cycling, due to the multiplication of acceleration due to gravity that would further hinder TT time (McGinnis, 2005; Jobson et al., 2007). These biomechanical principles would suggest that an increase in body mass has the potential to have a much larger detrimental effect on field performance than laboratory. Even so the performance TT's conducted in the field environment pre and post intervention contradicted this notion, with only a 2 W detriment to performance with a negligible 1.64 % improvement in time, likely linked to the variable temperature and moderate but consistent wind speeds. Assessing the potential influence of submaximal efficiency on changes in TT power, the changes in efficiency at 150 W ($r^2 = 0.0554$) and 60 % W_{max} ($r^2 = 0.0105$) did not help explain the reduction in performance TT power in the mass increase group. Body composition analysis indicated a non-significant increase in FFM (0.7 kg) following mass gain, which based on the significant positive association with lean leg mass and peak performance power ($r = 0.614$), would have been predicted to result in a marginal increase in power or at the least maintenance (Winter, Brookes and Hamley 1991). Therefore it would appear that the increase in FFM seen in this study may not have been attributed specifically to lean mass and that the other components of FFM such as; fluid content **(**Fairburn and

Cooper, 2014) and carbohydrate storage (Kreitzman, Coxon and Szaz, 1992) could have accounted for the increase. FFM was not significantly altered while fat mass increased by 1.2 kg. It is theorised that in the same way that a reduction in subcutaneous fat mass could improve efficiency, that an increase could reduce efficiency by increasing the demand on the periphery to dissipate excess heat and thereby reduce the rate and effectiveness of oxygen delivery to the working muscles. Despite limited within group differences that are interpreted with caution, the reduction in body mass and increase in body mass between groups provided a body mass difference of 4.2 kg, a 2.2 kg difference in fat mass and a 2 kg fat-free mass change. This indicated significant interactions between TT power, TT economy, gross efficiency at 150W, 60% W_{max} and net efficiency at 60 %. This suggests that it is possible to manipulate TT power, economy and cycling efficiency with both mass increase and decrease and that they diverge in opposing directions. The presence of the interactions strengthens the level of interpretation and speculation regarding the positive influence of body mass reduction and negative influence of body mass gain on performance, efficiency and economy.

Follow-up:

The follow-up phase failed to show any significant differences to sub-maximal efficiency, with a tendency for gross and net efficiency to return to similar baseline values following the six week follow-up which saw mass maintenance in both groups. Utilising the research by Goldsmith et al. (2009) who found both a significant improvement (15 %) and decrease (25 %) in efficiency following two weeks of weight stability after either a 10 % reduction or a 10 % increase in body mass respectively; it could be inferred that the change in efficiency following mass alteration is attenuated between 2-6 weeks after initial change. The small improvement in TT economy in the mass reduction group also appeared to be attenuated with body mass maintenance but in the mass increase group tended to reduce further with maintenance (although not significantly). None of the submaximal economy or efficiency measurements provided a very strong association between performance TT economy, however, in the interest of being able to predict changes in TT economy from submaximal intervals of economy and efficiency, the highest intensity provided the best indicator of changes in energy expenditure during TT performance. It is therefore suggested that the greater the relative power output the more valid an efficiency measurement, assuming that assumptions of anaerobic respiration and steady-state are adhered.

10.6 Conclusion

Efficiency only slightly increased, with performance remaining consistent during moderate calorie restriction. This was despite inducing a significant level of body mass and fat mass reduction. Conversely, an increase in mass had a greater negative effect on both efficiency and performance measures in the participants that gained mass. These findings also suggest that the changes in the rate of energy production and power output may only be a temporary change that returns to original values within six weeks of maintaining either the increased or decreased mass. Consequently the changes in energy expenditure are unlikely to be as a direct result of mass change, and are more likely linked with the hormonal and metabolic processes during dietary induced positive and negative energy balance.

CHAPTER 11: GENERAL DISCUSSION

This chapter will review the thesis aims and further explore the factors that influence efficiency and performance, by conducting retrospective analysis of the key variables across experimental chapters. Overall implications, limitations and future research directions will also be discussed along with a final thesis conclusion.

11.1 Review of thesis aims

11.1.1 Body mass change and efficiency

The primary aim of this thesis was to assess the effect of body mass change on steady-state cycling efficiency and TT performance (16.1 km). The results indicated that a -2.4 kg reduction in body mass positively influenced gross efficiency by 3.13 %, or 0.66 % of a gross efficiency unit (based on post-hoc body mass change group allocations) (**Chapter 10**). This improvement represented half of the overall improvement in efficiency reported following six weeks of high intensity training (Hopker, Coleman, Passfield and Wiles 2010; 6.5 % relative improvement) and was similar to the 3.57 % change seen across a competitive cycling season (January to September) (Hopker, Coleman and Passfield, 2009). Therefore, six weeks of moderate calorie restriction not only has the ability to improve gross efficiency in a trained population, but to a comparable degree as the improvements seen towards the end of a competitive racing season. Furthermore, the improvement was also akin to the changes reported by Amati et al. (2008), despite a far greater mass change (8.2 kg) and duration (16 weeks), which resulted in ~ 4 % improvement in gross efficiency. While larger proportional improvements in net efficiency (~ 10 %) have been reported with 10 % body mass changes similar to those presented in Amati et al. (2008), these studies tended to be conducted with untrained participants and measured at very low power outputs (10 & 50 W) (Rosenbaum et al., 2003; Goldsmith et al., 2010). It is therefore suggested that the majority of the improvements observed with trained participants following mass reduction are likely achieved between 2-6 weeks of energy imbalance. This concept is based on the consideration that efficiency was stable in the short-term study (**Chapter 8**), and the changes observed in the medium-term study (**Chapter 10**) being comparable to previous studies with substantially greater mass reduction. Declines in exercise rather than resting energy expenditure, were considered primarily responsible for the overall improvement, demonstrated by net efficiency showing a similar trend to improve (2.22 %), coupled with stability in RMR (-0.2 $j{\cdot}sec^{-1}$) (post-hoc group allocations). Stability in RMR has previously been reported by Foster et al. (1990), utilising a moderate calorie restriction, but numerous other studies implementing high calorie deficits have largely opposed this finding concluding that changes in energy expenditure were almost exclusively from RMR (Apfelbaum, Bostsarron and Lacatis, 1971; Poole and Henson, 1988; Hill, 2004). However, this research is in support of the findings of Amati et al. (2008), who reported a preference for changes to occur in exercising energy expenditure rather than RMR. Despite differences in the severity of energy expenditure, it is theorised that small alterations in cellular efficiency, be that in peripheral or central systems, are easier to detect during exercise due to the multiplication of energy expenditure along with any potential energy saving or increment (Bhagavan, 1992). Still, it is difficult to fully address to which degree each component of TDEE alters, due to the complex and often expensive measurement equipment required, combined with strict participant protocols. The adaptations in energy expenditure are also likely to be a rather individualistic process, influenced by genetic factors (Maclean et al., 2011), specific macronutrient ratios (Cole, Coleman, Hopker and Wiles, 2014), training status and type (Hopker, Coleman and Wiles, 2007) and body composition (Kriketos, Sharp, Seagle and Hill, 2000), which further hinders the determination of the dominant changes in TDEE with energy imbalance.

Investigating the effect of a positive energy balance on efficiency was not a main aim of this thesis, but a mass gain of 2.2 kg (post-hoc groupings) appeared to have a stronger negative effect on gross efficiency (-4.26 %), when compared to an equivalent mass reduction. This finding that mass gain resulted in a greater detrimental effect on efficiency relative to mass reduction has been previously reported (Goldsmith et al., 2010). Unfortunately, despite Goldsmith et al. (2010) measuring glycolytic and oxidative enzyme markers they were unable to explain the seemingly negative bias for a reduction in efficiency due to mass gain. Alike to the mass reduction condition, the reductions in efficiency were predominantly attributed to changes in exercise energy expenditure rather than RMR. By combining individual change values from the short-term (**Chapter 8**) and medium-term study (**Chapter 10**), correlation analysis demonstrated a significant low to moderate negative relationship between changes in efficiency and changes in body mass ($r = -0.423$, $P = .011$) (**Figure 11.1**). This analysis was repeated with body fat change, which had a similar but slightly weaker relationship ($r = -0.41$, $P = .014$) (**Figure 11.2**) and with fat-free mass change, which had a negligible negative relationship ($r = -.24$, $P = 0.163$). Remarkably, changes in absolute body mass explained a similar level of variation as estimated fat mass change, despite a simplistic two compartmental body composition model making several assumptions that have the potential to increase error. Conversely, estimated fat-free mass change provided little explanation of the changes in efficiency, likely attributable to fat-free mass not simply representing lean mass, but numerous other variable components of body tissue. This retrospective analysis fortifies the concept that efficiency has a negative relationship with body mass and composition change, and that efficiency can be both positively and negatively influenced by body mass and composition perturbations.

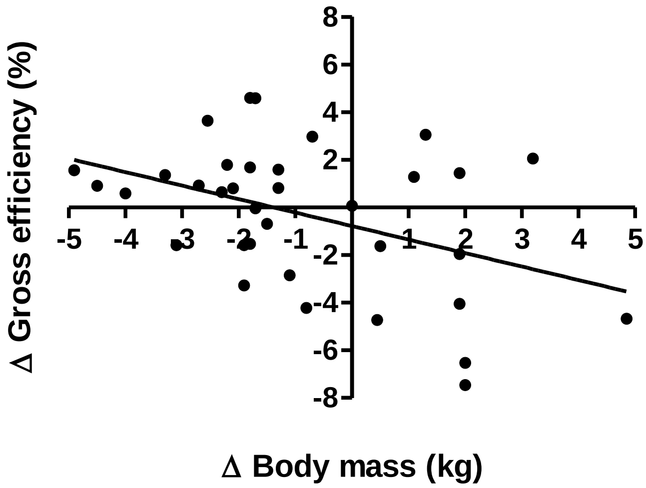


Figure 11.1 The relationship between body mass change and the changes in gross efficiency at 60 % W_{max}, (Number = 35), $r^2 = 0.1792$, $y = -0.5670x + -0.2112$.

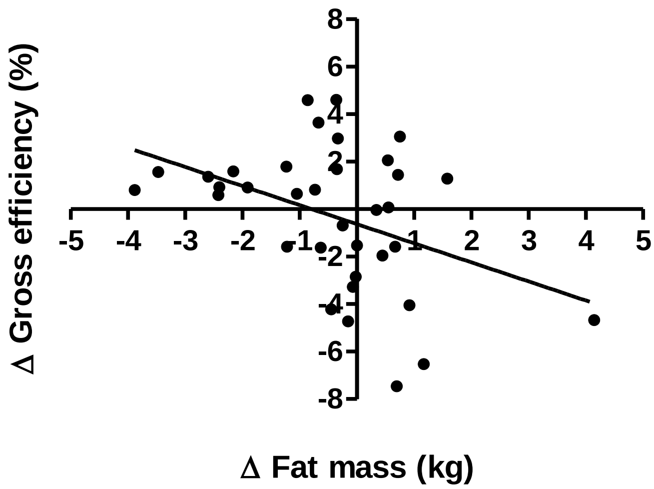


Figure 11.2 The relationship between fat mass change and changes in gross efficiency at 60 % W_{max}, (Number = 35), $r^2 = 0.1679$, $y = -0.8039x + -0.6310$.

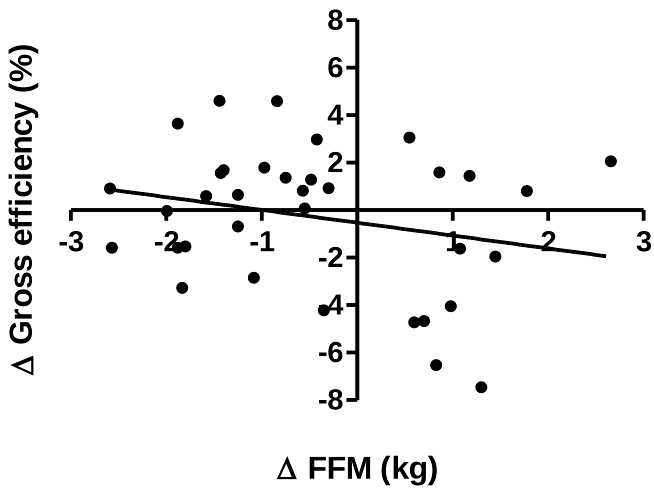


Figure 11.3 The relationship between FFM change and changes in gross efficiency at 60 % W_{max}, (Number = 35), $r^2 = 0.05799$, $y = -0.5399x + -0.5290$.

Currently the mechanisms for the changes in efficiency can only be speculated at this stage, and as cellular alterations are beyond the scope of this research, however both pulmonary and cardiovascular areas can be explored. Based on initial examinations; blood parameters, $\dot{V}O_2$ and RER were largely unable to identify or explain the mechanistic improvement in steady-state efficiency, with an interaction of $\dot{V}O_2$ only present during performance economy measures. Although it is acknowledged that specific assumptions surrounding cycling economy during a performance TT may be violated, the change in economy was similar to gross and net efficiency variables measured during steady-state cycling. Unfortunately further analysis was unable to determine if the reduction in $\dot{V}O_2$ was as a result of changes in O_2 extraction or ventilation. This could be attributable to a heightened sensitivity of the measures to noise at a lower tier of oxygen uptake measurement, and/or, the reduction in $\dot{V}O_2$ was sufficiently distributed between reductions in O_2 extration and ventilation. Nonetheless, it is conceivable that V_E could be influenced more mechanistically, as there is evidence to suggest that a reduction in body mass, but particularly visceral and torso subcutaneous fat, can reduce intra-abdominal pressure which intern reduces air-way resistance (Pelosi et al., 1997; Aaron et al., 2004). Traditionally air-way resistance has been assessed in regard to maximal values, but it is possible that it could result in a lesser contraction of the ventilation muscles during sub-maximal intensities, resulting in less energy being expended. By utilising research from Vella, Marks and Robergs (2006) who reported an average oxygen cost of 2.44 (ml.L) to ventilate between 35-50 % maximum ventilation, it is possible to calculate the change in ventilation cost. Assuming a consistent RER value and using the changes in V_E at the 150 W workload to minimise discrepancies with exercise intensity; reduced V_E in the mass reduction group attributed only 0.03 % of the 0.17 % increase in efficiency, with an increase in V_E in the mass gain group accounting for a similar but opposing -0.04 % of the -1.24 % overall reduction in gross efficiency. Consequently the changes in ventilation are likely to have only a very small role/if any on the alterations in efficiency, as energy expenditure changes in the same direction, but the cost of ventilation is unable to account for the majority of the changes observed.

Cardiovascular adaptations provide an indication of more central mechanistic details and have the potential to partially explain the changes in exercising energy expenditure. Heart rate changes have yet to be fully explored in this thesis, and so further analysis indicated that heart rate and gross efficiency at 150 W had a non-significant negative relationship of low strength when combining data across experimental studies ($N = 43$, $r = -0.30$, $P = .054$), this relationship was only marginally improved when using data solely from the medium-term study ($N = 28$, $r = -0.342$, $P = .075$). Consequently reductions in heart rate have the potential to only partially explain a proportion of the changes in efficiency, and would not be recommended as a reliable marker for efficiency change, as heart rate only accounted for 19 % of the variation.

A specific theoretical reason for utilising body mass to influence efficiency was based on the thermoregulatory response of exercise; founded by the theory that peripheral veins dilate to increase heat dissipation from the epidermis, which may result in lower blood availability and reduced oxygen delivery (Bertucci et al. 2013; Hettinga et al. 2007). By altering the thickness of the subcutaneous adipose tissue, it was theorised to change the insulating capabilities and change the magnitude of the vasodilation mechanism during the same exercise intensity and environmental conditions. Therefore a reduction in subcutaneous fat could improve thermoregulation and improve efficiency, with an increase in body fat likely to reduce the effectiveness of heat dissipation and result in a higher energy cost during exercise. Considering that 75-88 % of the chemical energy obtained from ATP hydrolysis has the potential to be transferred as heat energy (based on efficiency values in this thesis), it is possible that a small improvement in heat dissipation effectiveness could improve oxygen delivery, and therefore whole organism efficiency. Although thermoregulatory responses were not measured during this study, if they made a substantial contribution to efficiency change, it could be argued that a marker for this mechanism would likely be changes in skinfold thickness. To explore this theory, further analysis was conducted assessing the relationship between the changes in the sum of six skinfold sites to changes in gross efficiency. Explicitly, data points from the medium-term study were used due to the limited time for subcutaneous fat to be reduced within the short-term study. Utilising adjusted 60 % W_{max} intensity, the analysis demonstrated a non-significant low association between changes in skinfold and gross efficiency (N = 22, r = -0.36, P = 0.114).

Although the relationship was in the correct direction with the above theory, there was only a small potential influence of the mechanistic parameters in non-obese participants, and that the absolute mass change was likely too low for there to be a substantial thermoregulatory influence.

Fat free mass perturbations during body mass reduction are commonly reported with a negative energy balance, with the majority of studies reporting a loss in fat-free mass, unless specific resistance training is prescribed (Clark, 2015). Conversely increases in body mass often result in an increase in fat-free mass, with a steeper increase during the initial stages of mass gain and a proportional shrinking of fat-free mass gain with greater body mass increments (Mingrone et al., 2001). By combining both short and medium-term studies; body mass reduction induced a reduction in fat mass relative to fat-free mass at a ratio of 1.4:1 (kg) respectively, in addition mass gain altered body composition at a ratio of 1.2:1 (kg) (fat mass:fat-free mass). Although the ratio of fat-free mass change is quite high relative to previous longer-term studies (Rosenbaum et al., 2003; Goldsmith et al., 2010), it is important to note that short- and medium-term studies have a tendency to alter numerous components of fat-free mass such as; hydration, glycogen storage and food stuffs within the gastrointestinal tract (Corvilain, et al., 1995; Heymsfield et al., 2012). Furthermore, reductions in visceral fat have been noted to outweigh subcutaneous fat reductions during the initial stages of an energy imbalance (Chaston and Dixon, 2008; Bakker et al., 2015). As body fat estimations with skinfold measurement are reasonably unaffected by the above variations, FFM as the opposing compartment tends to be particularly affected as all other changes are assumed to be as a result of fat-free mass. Supposing that a proportion of the changes in fat-free mass were as a result of lean mass change, due to lean tissue being 3.25

times more metabolically active than subcutaneous tissue (Hill, Cateracci and Wyatt, 2006). Therefore reductions or increases in lean mass are theoretically more likely to result in changes in absolute energy expenditure. However, the two compartmental body composition measure, make it difficult to determine the precise resultant decrease or increase in lean tissue. Overall gross efficiency seemed to be more sensitive to increases in body mass, with concurrence across all exercise intensities. This would suggest that there is a type of negative bias within physiology whereby it would appear easier to reduce efficiency than it is to improve.

Interestingly the follow-up phase demonstrated that the process of energy imbalance rather than the absolute mass change, was most likely responsible for the changes in efficiency, as during the follow-up phase where body mass remained stable and participants were assumed to be in a neutral energy balance, efficiency appeared to return to pre-testing values. Therefore the follow-up results suggest that the mechanism for efficiency change is more likely linked with a physiological process that is present only during energy imbalance, rather than a mechanical advantage/disadvantage due to changes in total mass, fat-mass, lean mass or thermoregulation. This mechanism has been specifically noted with energy intake deficit (Rosenbaum et al., 2003), with body mass reductions as a result of exercise failing to reduce energy expenditure (Fontana and Klein, 2007). In addition, once energy balance is achieved, the majority of the benefits are not present following six weeks of mass maintenance. This implies that efficiency may only be temporarily affected following the cessation of an energy restriction/increase period, and could call into question the longevity of the improvements reported in previous training studies (Hintzy, Mourot, Perrey and Tordi, 2005; Hopker, Coleman, Passfield and Wiles 2010). This also suggests that a reasonably reactive energy imbalance mechanism is responsible for the efficiency change. Resting metabolic rate showed the largest (albeit very slight) changes, during the follow-up trial when the participants had been mass stable. This could either suggest a possible delay in the reaction of RMR as a compensatory homeostatic mechanism, or that the energy imbalance and total mass change was insufficient to induce a change in RMR as a homeostatic mechanism. If employing the set-point theory the mass stability observed following six weeks of free-living conditions would suggest that either the mass reduction was not severe enough or of an adequate duration to induce a body mass return, or that body mass return takes longer than initial mass change. With the studies in combination, these findings suggest the presence of a homeostatic control process during exercise, but that it is delayed, based on stability in the short-term study and reductions in exercising energy expenditure detectable after six weeks. Therefore it seems logical to consider that the change in energy expenditure following 2-6 weeks of mass change, is predominantly process orientated, rather than linked to physical changes of body mass (based on the follow-up phase), at least during the early stages of mass perturbation. It is not inconceivable that greater mass changes would likely have a larger effect on the biomechanical and thermoregulatory factors influencing efficiency and energy expenditure; as although dependent on starting body fat %, have a greater potential for change.

11.1.2 Performance and efficiency

The notion that efficiency has been described as a key determinant of performance (Horowitz et al. 1994; Olds et al., 1995; Lucia et al., 2002), provided the early justification for assessing efficiency in combination with performance, and making the link with performance an important secondary aim for this thesis. Utilising unique participants across studies, **Figure 11.4** demonstrates that initial gross efficiency has a positive, low strength association with TT performance power ($r = 0.135$, $P = .364$). This indicated that gross efficiency explains less than 2 % of the variation in performance power and is unable to differentiate between participants performance. To provide a comparison, absolute W_{max} (**Figure 11.5**) and $\dot{V}O_{2max}$ (**Figure 11.6**) were also assessed in the same manor, as they are considered to have a robust predictive ability regarding performance power. Both W_{max} ($r = 0.907$, $P < .001$) and $\dot{V}O_{2max}$ ($r = 0.642$, $P < .001$) variables presented significant, much stronger and positive correlations with TT power. Therefore it is disputed that efficiency may not be a key performance determinant in an absolute sense and there may be merit to downgrade the efficiency performance relationship. While it is clear that gross efficiency if compared to $\dot{V}O_{2max}$ and W_{max} is not analogous in regard to being able to predict or differentiate between participants starting performance, it is argued that if all other variables stayed the same that an improvement in efficiency would likely result in an improvement in performance.

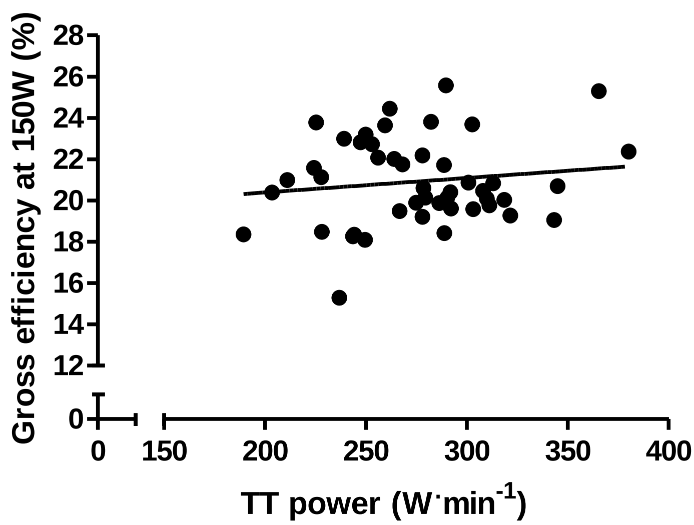


Figure 11.4 The relationship between time-trial power and gross efficiency at 150 W by combining data from Study 2 (**Chapter 8**) and Study 4 (**Chapter 10**). ($N = 47$), $r^2 = 0.01834$, $y = 0.007005x + 18.99$

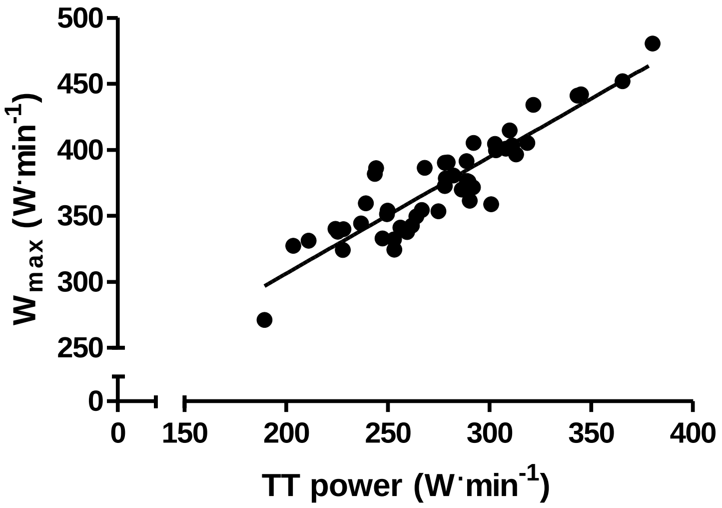


Figure 11.5 The relationship between time-trial power and W_{max} by combining data from Study 2 (**Chapter 8**) and Study 4 (**Chapter 10**). (Number = 47), r^2 = 0.8218, y= 0.8830x + 129.7

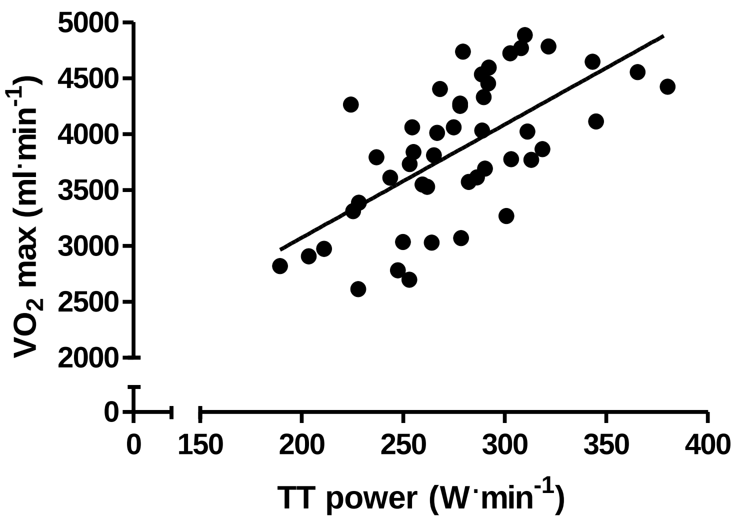


Figure 11.6 The relationship between TT power and absolute $\dot{V}O_{2max}$ by combining data from Study 2 (**Chapter 8**) and Study 4 (**Chapter 10**). (Number = 47), r^2 = 0.4124, y= 10.13x + 1047.

The results from the medium-term study (**Chapter 10)** suggest that an efficiency improvement or reduction does indeed result in a similar mirrored effect on TT performance power, with a greater reduction in efficiency in the mass increase group having a greater negative influence (mass reduction: 1.9 W increase, Mass increase: -15.1 W reduction). The results from the short-term study (**Chapter 8)** also support the concept that efficiency is linked with performance as both efficiency and performance power remained seemingly unaffected by short-term calorie restriction (relative change in GE at 60 % W_{max}: .04 % & TT performance power: -1 W). This is a novel finding as performance improvements are rarely empirically tested and are often assumed based on performance models (Joyner and Coyle, 2008) or predicted based on purely efficiency improvements. When predicting performance changes with efficiency fluctuations it is often assumed that the saving in efficiency is able to equate to a direct and equivalent change in power output. However Cole (2015) showed this not to be the case, with efficiency improvements only accounting for ~33 % of the total 5 % (88 s improvement over a 16.1 km laboratory TT) performance improvement following a combined pre, during and post dietary intervention. These differences are highlighted in **Table 11.1** where actual performance changes are compared to predicted. Gross efficiency showed no change in the short-term study and so performance was similarly predicted to remain stable. Due to changes in the medium-term study, the analysis suggested that not only can the direction of performance change be correctly predicted, but also to a large extent the magnitude, with the mass increase group prediction differing by only 3 W and 7 W in the mass increase group. These prediction differences are within the natural variation of performance power outlined in **Chapter 7** (CV: 2.28-3.89 %).

Table 11.1 Predicted verses actual changes in laboratory performance based on gross efficiency changes measured during the 60 % W_{max}.

Intervention	**Δ Gross efficiency (% GE unit)**	**Δ Predicted performance (W·min^{-1})**	**Δ Laboratory performance (W·min^{-1})**
Short-term			
Calorie restriction (N = 17)	+0.01	+0.13	-1
Medium-term			
Mass reduction (N = 14)	+0.66	+8.62	+1.9
Mass increase (N = 15)	-0.93	-12.14	-15.1

Note: Performance change based on an average TT power of 280 W and an average gross efficiency of 21.45 %, Δ, delta (change), N, number, GE, gross efficiency.

While it is acknowledged that performance changed only marginally with mass reduction, the results nonetheless suggest that mass reduction can at the least maintain absolute power. This is despite mass reduction often being associated with a negative influence on absolute power, due to a proportion of the reduced mass consisting of fat-free mass, which often predisposes reductions in hydration status, CHO storage (Heymsfield et al., 2012) and lean mass (Stein et al., 1991); all factors that can reduce performance (Heigenhauser, Sutton and Jones, 1983). Considering that energy intake manipulation does not have a direct mechanistic pathway to improve performance power, the results suggest that efficiency may have been the crucial reason for the significant interaction. This notion is strengthened by the understanding that there were no significant differences in both W_{max} and $\dot{V}O_{2max}$

variables in either groups (P > .05). It is however noteworthy that real world performance is determined by a multifaceted interaction of a number of variables and that it is too simplistic to consider that improvements in efficiency will always result in an improved performance. Conversely it must also be acknowledged that reductions in mass while maintaining absolute power will inevitable result in an improvement in power to weight ratio, which both the simulated laboratory TT and flat field TT will not reflect. Had a separate measure of time to climb an incline been measured, it would seem likely that the performance differences would have been more pronounced. Subsequently both the changes in laboratory performance and predicted performance do not take into account the additional potential for mass change to influence field performance as a result biomechanical variables. These include the potential for small physical changes in; leg mass and inertia, total rider mass, and rider position inducing changes in both frontal surface area and drag coefficient (particularly if aerodynamic body position is restricted by excess fat mass) (Kyle, 2003; Hopker et al., 2010). Thus changes in biomechanical variables can be both positively and negatively influenced by body mass change, and theoretically would cause an additive effect in the same direction of performance change observed in this research. Consequently the results suggest that mass reduction can at the least maintain absolute power, providing support for the current elite practice to reduce mass prior to a cycling race (Coyle, 2005; Moore, 2015). In summary the above performance findings suggest that mass reduction tended to either maintain or slightly improve TT power, whereas mass increase had a tendency to reduce performance power.

11.1.3 $\dot{V}O_{2max}$ and efficiency

Previous studies have reported that gross efficiency has an inverse relationship with $\dot{V}O_{2max}$ in world class professional road cyclists (N = 11, r = -0.63, P = 0.04) (Lucia et al., 2002). As $\dot{V}O_{2max}$ and efficiency calculations are inherently dependent on absolute $\dot{V}O_2$ values, a common criticism is that an inverse relationship could be partly due to gas analysis calibration error, with tests conducted on the same day, utilising the periodic calibration of equipment. However, by conducting testing on separate days it is likely to alleviate some of these issues, albeit increasing the potential for inter-day variation. Therefore a tertiary aim of this thesis was to explore if a similar relationship existed in trained club level cyclists by measuring the two variables on different days. To assess the relationship, data was pooled from all studies, which indicated a significant moderate to high inverse relationship (r = -0.671, P < .001). This finding was very similar to the relationship reported by Lucia et al. (2002) and indeed suggests that the same relationship is present in club level cyclists. Considering that efficiency and $\dot{V}O_{2max}$ values are intrinsically linked with absolute $\dot{V}O_2$, it is proposed that cyclists with a higher absolute $\dot{V}O_{2max}$ utilise a similarly higher $\dot{V}O_2$ at a relative exercise intensity, which results in a lower efficiency. Thus to improve efficiency, a lower $\dot{V}O_2$ for the same sub-maximal intensity would be required. Conversely the relationship may also explain why cyclists often appear similar despite differences in absolute $\dot{V}O_{2max}$ values, suggesting that a cyclist with a lower $\dot{V}O_{2max}$ may be able to compensate by having a higher efficiency. Currently the most plausible reason for the inverse relationship is still speculated to be linked to either genetic factors and or the dominance of type

I muscle fibres in the participants with the highest efficiency values (Horowitz, Sidosis and Coyle, 1994; Lucia et al., 2002).

11.1.4 Lung volume and function

Lung capacity (VC) and function (FEV_1 & FEV_1 %) were speculated earlier in this thesis to provide a potential physiological marker to explain absolute efficiency. However, following further analysis by combining data across studies (N = 45), neither of the lung parameters had a significant relationship with gross efficiency at 150 W ($r \leq 0.2$, $P < .05$). Consequently despite a reasonably substantial cohort of participants, lung capacity and functioning appeared to explain very little of the variation in gross efficiency at a fixed absolute work load.

11.2 Implications of the findings

11.2.1 Performance

Changes in efficiency have been demonstrated in this thesis to have implications for both laboratory and field performance power (**Chapter 10**). On average the reduction in mass in the medium-term study resulted in a 5.4 second quicker laboratory TT, with an increase in mass resulting in a 37.4 second slower laboratory TT. Utilising changes in field performance power, TT performance was calculated to be 74.5 seconds quicker with mass reduction and 9.3 seconds slower with mass gain. Raw power was used for the calculation of time to further minimise the potential confounding influence of environmental conditions to control for trials not being conducted on the same day (see **Appendix 10** for power to time conversions). Had all trials been completed on the same day, time would have been equivalent to absolute power with all factors being equal. It is important to note that field performance based on recorded time improved equally in both groups (~ 30 sec) with environmental conditions attributed for the discrepancy. It would be anticipated that if all trials were conducted at the same time/within a short period of times (in line with TT races) the changes in power would have reflected differences between the groups, for time changes post intervention. The above calculations based on a simple power to time relationship, do not take into account the biomechanical changes as a result of body mass change, which are likely to have an additive effect. To provide context for the changes in calculated performance, the top five results from the last three 16.1 km National TT Championships were obtained and presented in **Table 11.2**. On average only 7 seconds separated the top five TT places, with just 13 seconds differentiating between 1st, 2nd and 3rd place. Assuming a bell shaped curve, the time separating TT placing is likely to be even closer towards the average cyclist time, resulting in a greater potential to influence placing for a similar time difference. For this reason, a small overall increase or decrease in performance power over the duration of a TT can have very real positioning consequences despite seemingly small changes in absolute power.

Table 11.2 The mean top five placed 16.1 km National TT Championship results from 2013-2015.

Intervention	Time (min:sec)	Difference with previous (sec)
1st place	18:52	5
2nd place	18:57	8
3rd place	19:05	10
4th place	19:15	6
5th place	19:22	N/A

Note: Data obtained from: Cycling Weekly (2013), Snowdon Sports (2014) and Jones and Wynn (2015), (Events, N = 3).

Equally, if improvements in efficiency were either not able to translate to an increase in absolute power, or that an increase in power was not considered beneficial, for instance during consecutive road race cycling with energy conservation being considered a key tactic (Baker, 2013). Using efficiency change, it is also possible to calculate the potential energy saving cost/additional cost of cycling. As this research did not find any considerable changes in RMR, energy expenditure calculations were determined solely on changes in gross cycling efficiency. Based on an overall 0.66 % improvement in efficiency achieved in the mass reduction group, 7.4 $kcal{\cdot}hr^{-1}$ would be conserved while cycling at 60 % W_{max}. Conversely by gaining mass the reduction in efficiency would equate to a 10.4 $kcal{\cdot}hr^{-1}$ greater energy expenditure.

Although these values are reasonably minor, amateur and professional cyclists frequently undertake several hours of cycling per week, often conducting multiple consecutive days of training and racing, which would result in an accumulation of these values. It is also noteworthy that these changes were achieved with only a small ± 3 % change in body mass, enabling the potential for either greater mass change or a combination of intervention strategies to further alter efficiency. Additionally, reductions in absolute energy expenditure following a fixed work load intensity may allow a cyclist to maintain a higher power while remaining sub-threshold. As both lactate and onset of blood lactate accumulation thresholds are considered to influence performance (Ghosh, 2004), maintaining a higher power while remaining sub-threshold could have added implications for both physiological exercise demands and performance.

11.2.2 Short-term calorie restriction

Two weeks of moderate calorie restriction did not demonstrate that it influenced efficiency or performance, and suggested that homeostatic control adaptations following moderate calorie restriction are either not present or currently undetectable. Therefore it could be inferred that efficiency is a reasonably robust measure and that it may not be completely necessary to ensure an isocaloric diet is consumed in the days leading up to laboratory testing, if the deficit is only mild (< 500 $kcal \cdot day^{-1}$) and conducted for a short period (< 2 weeks). Hence the results provide some support for the practice of weight-cycling during a competitive season.

11.2.3 Field and laboratory comparison

This thesis also sort to explore the logistics of measuring gross efficiency in an outdoor field environment (**Chapter 9**). The findings indicated that there was a higher power variation in the field condition but that the vast majority of participants were able to maintain the desired steady-state powers for efficiency assessment. When comparing between a stationary cycle ergometer in a controlled environment and a power measurement device on a road bicycle, the results specified that it was essential to control for differences in power output and cadence, with temperature and humidity variables also having an influence on efficiency. Specifically this research validated the use of a wind cut-off threshold of $\leq 3\ m{\cdot}s^{-1}$ to reduce testing variability that was previously proposed by Bertucci et al. (2012). Accordingly it was demonstrated that it is possible to measure efficiency in the field, with the most consistent field measure of gross efficiency being recorded at the 60 % W_{max} intensity, matching laboratory measurement. While the analysis demonstrated an ability to account for confounding variables, the study indicated the importance of strict environmental criteria.

11.3 Limitations

Both the severity of the hypocaloric intervention and the magnitude of body mass reduction were limited in regard to the desire of this research to recruit club level cyclists that train frequently. Recruiting club level cyclists opposed to sedentary participants was projected to limit the possibility of a training effect and overcome a large criticism of previous weight loss research (Amati et al., 2008; Rosenbaum et al., 2003). However to ensure sufficient and safe mass reduction, the calorie restriction was set at a moderate -500 kcal.day-1 for health, well-being and to minimise lean mass reduction. Cyclists recruited for the intervention group had to have a minimum of 18 % body fat to satisfy ethical approval, which is at the upper end of what is considered a typical body fat % for a cyclist (7-18 %) (Knechtle, Knechtle and Rosemann, 2009). Despite the recruitment criteria, all cyclists were classified according to W_{max} as club level (Ansley and Cangley, 2009). As a result of intervention constraints, the implications for this thesis are somewhat limited to changes in body mass of 2.4 ± 1.4 kg, with mass changes greater than this currently only speculated to induce additional effects on efficiency and performance.

Few studies have assessed the effect of cycling efficiency on measured changes in performance (Jobson et al., 2012), and although this investigation did measure pre- and post-performance, it only utilised a 16.1 km TT that is considered a reasonably short cycling distance. This distance was used for several reasons; to minimise closed road circuit resources, ensuring portable equipment battery time limits were not exceeded and to ensure participant testing time was manageable considering multiple variables and test visits. In addition 16.1 km time-trials are considered a normal and popular race distance (Jones and Wynn, 2015). Theoretically it is feasible that a longer TT distance could have induced a performance detriment in the mass reduction group. This concept is based on the relationship between energy restriction and lower muscle glycogen stores, which are unlikely to be stressed to the point of limiting performance during ~26 minutes of cycling (Ivy, 1991). A longer TT distance may also result in more consistent power output over the course of the performance trial, which could add greater accuracy when detecting changes. Thus a longer TT may induce a better 'steady-state' performance measure and in combination with an overall decrease in RER values, would also increase the legitimacy of calculating gross efficiency during such performance.

Regarding research design, the non-dietary intervention group in the medium-term study increased mass to an almost identical but opposing degree as the mass reduction group. Although this improved the understanding of the influence of energy imbalance on efficiency resulting in significant interactions, the lack of a control group was an initial criticism of a key study by Amati et al. (2008). Based on data from both the short- and medium-term studies, the research is the first to evidence that club level cyclists may find it difficult to maintain a set body mass when requested, and that by providing only basic mass stability guidelines during a control period, mass tends to increase. Furthermore, not all participants that were prescribed a hypocaloric diet were able to demonstrate mass reduction, with some participants either remaining mass stable or increasing mass. The initial short-term intervention demonstrated a high degree of compliance, with 87.5 % of the participants reducing mass, with only 12.5 % either gaining or maintaining mass. However, despite similar compliance strategies, six weeks of calorie restriction resulted in a greater level of non-compliance with 23.5 % either gaining or maintaining mass (based on initial intervention group allocations). It is postulated that the increase in duration coupled with the seasonal time of year were two of the most probable causes for the reduction in compliance. Inter-individual differences with energy balance however cannot be completely ruled out as having an influence on the rate and magnitude of total body mass and fat mass change. Therefore an important finding is that a greater level of monitoring may be needed with longer-term studies to minimise mass gain during control periods, and that calorie restriction studies may require over recruitment at a greater proportion linked to the duration of the intervention.

Substantial efforts were made to standardise the food intake and training of participants in the three days prior to testing in particular, however recording food intake is often reported to result in an observation effect (~ 5 % reduction in energy intake) and an under reporting of food intake (5-20 % reduction in energy intake) (Wrieden, Peace, Armstrong and Barton, 2003). This continues to be a limitation of research in this field and could only be addressed with an invasive clinical setting where food is provided and intake monitored 24 hours a day for the intervention period. This clinical approach is expensive, disruptive to participants and removes a level of applicability. Technical error with training recording equipment at times limited the detail that could be obtained, but again is something that is common with training monitoring.

Gross efficiency provides a measure of whole organism efficiency and as such only provides an indication of the dominant resultant direction of efficiency change. While additional variables were measured alongside efficiency and performance such as; blood parameters, HR and the component parts of oxygen uptake, little mechanistic evidence was apparent to explain why efficiency changes occurred. Consequently this thesis may only really speculate as to the causes of efficiency change with further investigation required.

11.4 Future directions

It is theorised that gross efficiency could be manipulated further by either combining efficiency interventions or increasing the severity and or the duration of the energy imbalance. The simplicity of energy intake manipulation leaves a multitude of interventions that could be conducted alongside. It is theorised that by either increasing the severity of the restriction and or the duration of the intervention, it could potentially further influence efficiency, via a greater opposing influence of the homeostatic control mechanisms. This may lead to substantial change in RMR which would be combined with changes in exercise energy expenditure. Based on previous research utilising magnitude of change as the main criteria, further mass reduction combined with high intensity exercise is speculated to be a likely candidate for inducing efficiency changes (Hopker et al., 2010). Research by Amati et al. (2008) demonstrated an impressive additive efficiency effect when severe calorie restriction was combined with a substantial increase in exercise volume. However it is unknown if an additive effect could be observed with participants already accustomed to cycling, even if a novel form of high intensity training was implemented. Furthermore, based on the compliance from the final study of this thesis, the more aggressive calorie restriction/longer-term diet might be better explored initially in a number of well controlled case studies to assess outcomes before significant resources are invested for a large scale intervention.

Changes to macronutrient ratios could not only induce further changes in efficiency be could also be used to manipulate the rate of mass reduction, due to differences between macronutrient storage efficiency (Donato and Hegsted, 1985). It is theorised that a high protein, low glycaemic index (GI) diet has the most potential to induce a higher level of mass reduction, in comparison to the same kcal intake but with a dominance of CHO (Gallego et al., 2016). High protein low GI diets have been shown to cause a lower blood sugar spike, resulting in a lower tendency to store energy that has also been shown to increase satiety levels (Paddon-Jones et al., 2008).

The follow-up phase in the medium-term study highlighted the possibility that efficiency may only be temporarily altered following changes in energy balance; therefore an area that may be worth investigating is to track the efficiency return to pre intervention values. This would potentially enable a more precise use of calorie restriction to manipulate efficiency prior to a cycling race, while ensuring a sufficient period of time to consume an isocaloric diet, limiting the negative effects.

Unfortunately this research was unable to reveal the mechanistic causes for the changes in efficiency and so future research could incorporate additional variables such as; skin and core temperature measurement, and hormone and enzyme response tracking, in an attempt to determine the causes of efficiency change in club level cyclists. Of particular interest would be insulin, leptin and ghrelin as they are closely linked with metabolism and have previously been investigated in calorie restriction studies using sedentary participants (Maclean et al., 2011; Hardie, Ross and Hawley, 2012). The enzyme AMPK as a key metabolic regulator, would also interesting to explore in regard to mass change, but, could also provide a novel avenue to further explore the relationship with efficiency, $\dot{V}O_{2max}$ and performance power.

Little is currently known about muscular changes in trained cyclists as a result of energy imbalance, with gross efficiency values only providing an overall change in energy expenditure. By measuring changes in muscle glycogen stores, oxidative enzymes and muscular activation, it could help explain where the physiological efficiency changes take place. Another possibility is the use of a dual-energy X-ray absorptiometry scanner which can be used as a 3-compartmental model, or a multi-compartmental model approach, which can utilise up to a 4-compartmental model (Andreoli et al., 2004). Utilising a variety of techniques to further separate key components of body composition, would more accurately calculate the changes. This would allow for a more precise analysis to determine the proportion of efficiency change that could be attributed specifically to lean mass change.

The field and laboratory comparison study was successful in measuring efficiency in the field environment, however variation differences were present with environmental conditions and power. While environmental conditions are accepted to be difficult to control in a field environment, testing in a velodrome would provide an alternative to alleviate the differences. Also, although the TT course was reasonably level, due to participants having to manually adjust power output in the field compared to a computer controlled electronic brake on the laboratory ergometer, power variation was higher in the field. The disparity between the variations could be improved by requiring participants to manually control power in the laboratory condition, or allow several sessions of power meter training prior to field efficiency measurement. Another potential endeavour regarding ergometer comparison, would be to determine the differences between efficiency measured with a free-wheeled bicycle on a treadmill, rollers and with a turbo trainer to further understand the mechanical influences on cycling efficiency.

11.5 Conclusion

Over the course of this thesis body mass change has been explored in regard to changes in efficiency and performance. The investigations within this thesis were able to achieve notable body mass change with results indicating that efficiency can be both positively and negatively influenced in participants accustomed to cycling. Importantly, only exercising energy expenditure and not RMR was observed to be influenced by energy imbalance, with both efficiency and performance power appearing unaffected by short-term moderate calorie restriction. The research provides further evidence that during energy imbalance that energy expenditure and in turn efficiency is adjusted accordingly in the opposing direction of mass change in an attempt to maintain a stable body mass. This energy saving could therefore in part explain the commonly described weight loss plateau. Based on the results from investigations throughout this thesis and combined with retrospective analysis conducted in this chapter, the statement that efficiency is considered a key determinant of performance has been called into question. On the previso that further research substantiated the findings in this thesis, the statement could be rephrased with efficiency being considered an important variable to induce changes in performance, rather than a key determinant. Comparisons between field and laboratory efficiency measurement indicated that it was indeed possible to measure efficiency in the field environment and that efficiency measured in the field may appear lower than the laboratory unless changes in power, cadence and environmental conditions are considered. Mechanistic reasons for the changes in efficiency remained allusive and further research is required to highlight the most likely physiological and or biomechanical process which results from energy imbalance and body mass change.

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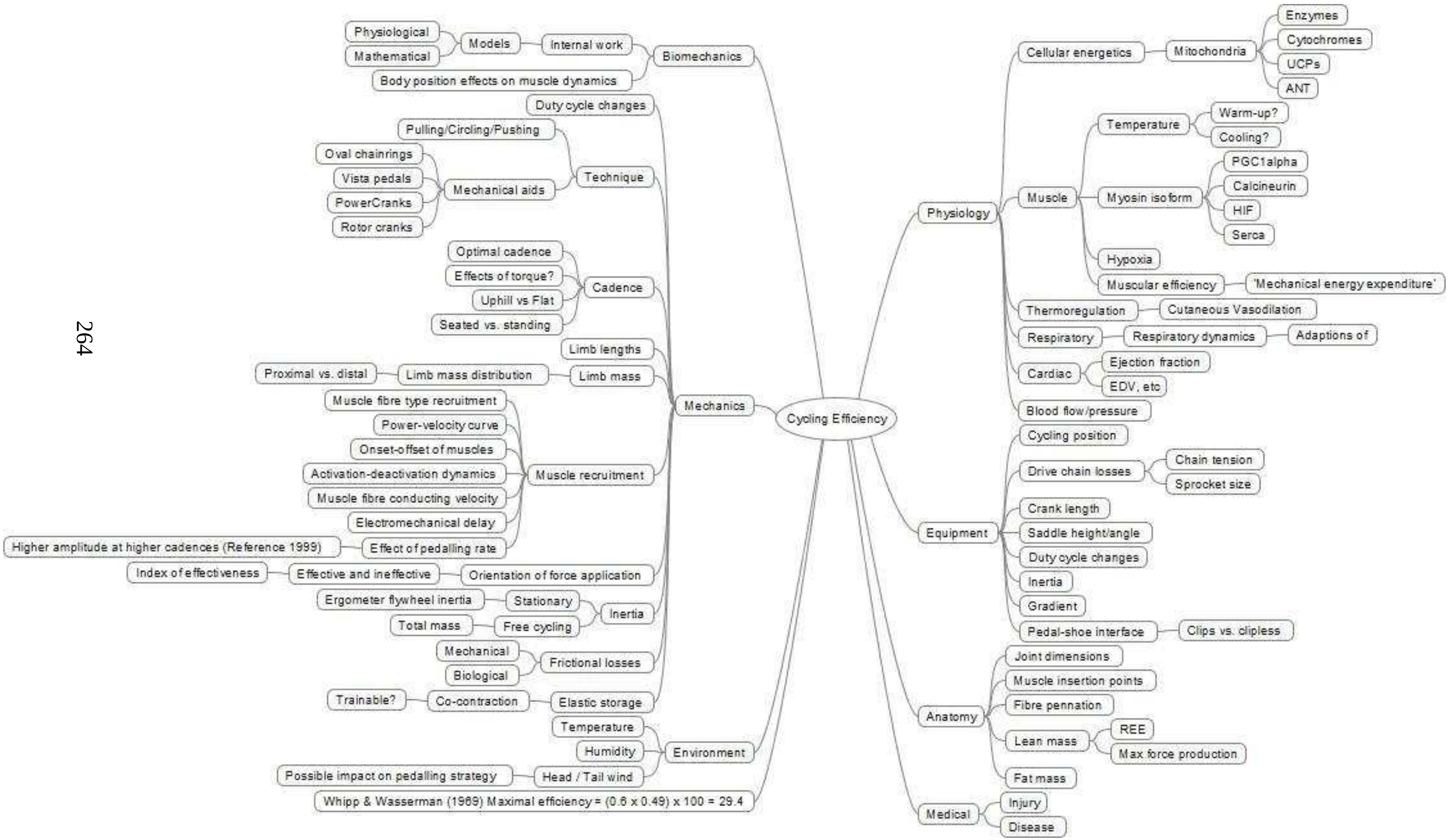
APPENDICIES

Appendix 1: Illustration of the factors influencing cycling efficiency



Appendix 2: Participant information

Research Title: The effect of a six week dietary intervention on indoor and outdoor cycling efficiency and performance.

Researcher: Samantha Saunders **Tel:** 01227 767700 ext (3145)
Research Tel: 07840 254143
e-mail: s.saunders311@canterbury.ac.uk

Superviser: Dr. Damian Coleman **Tel :** 01227 782639
e-mail : damian.coleman@canterbury.ac.uk

Superviser: Dr. Mathew Brown **Tel:** 01227 767700 ext (3168)
e-mail: mathew.brown@canterbury.ac.uk

Invitation to take part

You are invited as a volunteer to take part in a research investigation. Before you decide to take part it is important for you to understand why the research is being conducted and what will be required of you should you agree to be involved. Please take time to read the following information carefully and discuss it with the researcher. If there is anything that is not clear or if you would like more information please do not hesitate to ask.

Background

Recently, a great amount of research has been conducted on cycling efficiency due to the publication of a controversial case study on Lance Armstrong, suggesting that efficiency improvements were the reason for his domination in the sport. So far, some of the largest reported improvements in cycling efficiency have been reported in a long term weight-loss and exercise study, however it is unknown if these improvements occur in habitual cyclists. This study therefore aims to assess the effect of 6 weeks of moderate calorie restriction on cycling efficiency and 10 mile time-trial performance compared to a control group.

Efficiency explained

Efficiency provides an indication of your ability to convert stored energy (e.g. fat and carbohydrate) into power at the pedals. We measure the amount of total energy you use by monitoring inspired and expired oxygen and carbon dioxide and we can measure the power you produce from cranks with strain gauges. Your efficiency is then calculated by dividing the energy you produce (power) by the total amount of energy that you use and is presented as a percentage.

Location

Canterbury Christ Church University, North Holmes Road, Canterbury, Kent, CT1 1QU (Sports Science Laboratory: Ag 59) and Fowlmead Country Park, Deal, Kent, CT14 0BF. The majority of testing will take place at the University with a maximum of three visits to Fowlmead (dependant on equipment compatibility).

What will be expected of you?

If you decide to take part in this study you will be asked to attend the sport science laboratory on six occasions with an additional three visits to Fowlmead's closed road circuit over a 17 week period. All participants will be asked to record and keep similar their diet three days before testing. Participants in the dietary intervention group will be asked to maintain a usual diet (same types of foods) except reduce their calorie intake by 500 kcal per day for 6 weeks. For example if your usual calorie intake is 3000 kcal you will be asked to consume 2500 kcal per day. Participants in the control group will be asked to maintain their usual diet and training.

Study schedule

<table>
<tr><th>Group</th><th>Weeks 1, 2 & 3</th><th>Weeks 3-8</th><th>Weeks 8, 9 & 10</th><th>Weeks 10-15</th><th>Weeks 15, 16 & 17</th></tr>
<tr><td>Control</td><td rowspan="2">Visit 1: Induction, maximal test and time-trial familiarisation
Visit 2/3: TT in lab
Visit 2/3: TT at Fowlmead</td><td>Control</td><td rowspan="2">Visit 4: Maximal test
Visit 5/6: TT in lab
Visit 5/6: TT at Fowlmead</td><td>Control</td><td rowspan="2">Visit 7: Maximal test
Visit 8/9: TT in lab
Visit 8/9: TT at Fowlmead</td></tr>
<tr><td>Dietary intervention</td><td>Dietary intervention</td><td>Control</td></tr>
</table>

Visit 1, 4 and 7: Induction and Maximal test (VO_2max)

You will be shown around the lab; the study protocols will be discussed with the opportunity to ask questions and then asked to fill out an informed consent and health questionnaire. Some simple measurements will then be recorded.

- Height and mass
- Estimated body fat % using a 6-site skinfold caliper technique
- Lung capacity
- Finger prick blood sample

You will complete a 5 minute warm-up and then a maximal aerobic ($\dot{V}O_2$max) test starting at 150 W increasing by 5 W every 15 seconds until volitional exhaustion or you can no longer maintain your pedal rate (**Figure 1**). Afterwards you will complete a familiarisation 16.1 km time-trial.

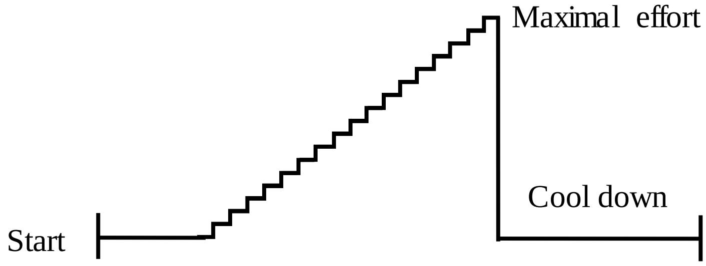


Figure 1. $\dot{V}O_2$max test.

Visit 2, 5 and 8: Self-paced laboratory 16.1 km (10 mile) Time-Trial

Pre measurements - Body mass and resting energy expenditure (lying down for 20 minutes while your O_2 and CO_2 are analysed). You will then complete a standard warm-up at 150 W and 60 % of the maximum intensity achieved during the VO_2max test for 8 minutes each. The 16.1 km self-paced time-trial (**Figure 2**) will then commence after a finger-prick blood sample. You will then complete a cool down.

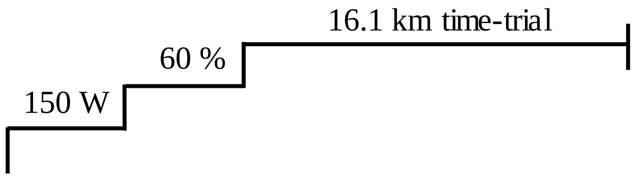


Figure 2. Ramped start to the 16.1 km time-trial protocol.

Visit 3, 6 and 9: Self-paced outdoor 16.1 km Time-trial

An outdoor 16.1 km time-trial will be performed on a closed road circuit at Fowlmead Country Park. A specialized power tap wheel or SRM cranks will be fitted to your road bike and you will wear a portable gas analysis system that weighs 950g. Outdoor TT's are dependent on equipment compatibility with your bike and not all cyclists will be required to perform outdoor testing.

To participate in this study you must:

- Be a male aged between 18-65 years
- Have been cycling regularly for at least 1 year.
- Have an estimated body fat of 13% or above (dietary intervention group only).
- Have been weight stable for the last 2 months.
- Be a non-smoker
- Not be taking any medications (for high cholesterol, high blood pressure, etc.)
- Have no known heart conditions or diabetes.
- Be without injury or illness.
- Not be taking any performance enhancing substances (excluding caffeine).

Prior to all visits you will be expected to:

- Avoid participation in any strenuous exercise for 48 hours (above regular training intensities).
- Avoid drinking alcohol and caffeinated drinks (i.e. coffee, tea, and cola) for 24 hours.
- Consume the same food 3 days prior to testing.
- In the 2 hours before the testing session consume no food or energy drinks and drink only **plain** water (aim to consume around 1 litre of water prior to testing).
- Bring appropriate cycling shorts, T-shirt/jersey, cycling shoes, pedals and if possible your bicycle on the first visit.

Advantages of taking part

A benefit of taking part in this study is that you will receive feedback, with explanations, on your body composition (e.g. % body fat), cardio-respiratory fitness (e.g. maximal heart rate, maximal oxygen uptake and efficiency) and time-trial performance (e.g. average power output, cadence and time).

Disadvantages of taking part

The main disadvantage of taking part in this study is probably the time commitment. To complete all aspects of the study you will be required to attend the lab on six occasions, and complete three outdoor time-trials which equates to 10-15 hours of your time: 2 hours for the first visit and 1.5 hours per visit thereafter. Although every effort will be made to keep lab time as succinct as possible, equipment malfunctions can happen and you may be asked to re-attend sessions. There is the possibility of muscle soreness after testing; however, this should be no different to the feeling after an intense training session. You will be asked to complete a 3 day food diary and exercise log at the beginning of the study which will require a few moments to complete. You will also be asked to keep your diet and exercise similar 3 days prior to testing with particular consistency to the meal prior to testing while noting down any changes.

Additional information

You may at any time withdraw from the Study. You do not have to give any reason, and no one can attempt to dissuade you. If you ever require any further explanation, please do not hesitate to ask. If you refuse to give consent to participation in this study, or withdraw from it at a later time, it shall not prejudice you in any way.

In addition, the following withdrawal criteria also apply:

- If you have any known injuries.
- At the request of the researcher – Miss Samantha Saunders, supervisor Dr Damian Coleman or Dr. Mathew Brown.
- Failure of the equipment to record.

Any information obtained during this study will remain confidential as to your identity: if it can be specifically identified with you, your permission will be sought in writing before it is published. Other material, which cannot be identified with you, will be published or presented at meetings with the aim of benefiting others. The results of this study will be published as part fulfilment of a PhD thesis with intent to submit the research at conference and as a journal article. You have a right to obtain copies of all papers, reports, transcripts, summaries, and other material published or presented, on request to the researcher or their supervisor, if appropriate.

All information will be subject to the conditions of the Data Protection Act 1989 and subsequent statutory instruments. Experimental records, including paper records and computer files, will be held for a minimum of 5 years, in conditions appropriate for the storage of personal information. You have right of access to your records at any time.

A full scientific protocol for this Study has been approved by Canterbury Christ Church University Research Ethics Committee. This protocol complies with all current legislation, including the Draft Additional Protocol to the Council of Europe Convention on Human Rights and Biomedicine on Biomedical Research (CDBI/INF (2001) 5 dated 18 July 2001). Further details of the approval will be provided to you if you wish and you have a right to have a copy of the full protocol to retain, if you so request of the researcher.

Appendix 3: Health questionnaire

Department of Sport Science, Tourism and Leisure

Sport Science Health and Fitness Questionnaire

Name: ……………………………………………………….

Date of Birth: ……………… Age: ……… Sex: ……..

Please answer the following questions by **circling** the appropriate response and if necessary providing extra information in the spaces provided.

ANY INFORMATION CONTAINED HEREIN WILL BE TREATED AS CONFIDENTIAL

1. How would you describe your present level of fitness?

Untrained / Moderately trained / Trained / Highly trained

2. Average number of hours spent exercising **……………………….per wk**

3. How would you describe your present bodyweight?

Underweight / Ideal / Slightly overweight / Very overweight

4. How would you describe your smoking habits?

Non smoker / Previous smoker / Currently smoking

5. How would you describe your alcohol intake?

Never Drink / An occasional drink / A drink every day / More than one drink a day

(Note 1 drink = 1 unit)

6. Have you had to consult your doctor within the last six months? **Yes / No**

If you have answered **yes**, please give details:**……………………………………….**

7. Are you presently taking any form of medication? **Yes / No**

If you have answered **yes**, please give details:**………………………………………**

8. Do you suffer or have you ever suffered from any of the following?

a. Diabetes **Yes / No** b. Asthma **Yes / No**

c. Epilepsy **Yes / No** d. Bronchitis **Yes / No**

e. Any form of heart complaint **Yes / No** f. Serious Back or Neck Injury **Yes / No**

g. High blood pressure **Yes / No** h. Aneurysm [1] or Embolism[2] **Yes / No**

1: Arterial wall weakness causing dilation. 2: Obstruction in the Artery.

9. Is there a history of heart complaint in your family? **Yes / No**

If you have answered **yes**, please give details:**………………………………………**

10. Do you have any allergies? **Yes / No**

If you have answered **yes**, please give details:**………………………………………**

11. Do you currently have any form of muscle or joint injury? **Yes / No**

If you have answered **yes**, please give details:**………………………………………**

12. Have you had to suspend your normal training/physical activity in the last two weeks? **Yes / No**

If you have answered **yes**, please give details:**……………………………………………**

Appendix 4: Informed consent form

Canterbury Christ Church University

CONSENT FORM

Title of Project: The short term effects of calorie restriction on cycling efficiency and time-trial performance.

Name of Researcher: Samantha Saunders, Dr. Damian Coleman and Dr. Mathew Brown

Contact details:

Address:

Tel:

Email:

Please initial box

1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time, without giving any reason. ☐
3. I understand that any personal information that I provide to the researchers will be kept strictly confidential ☐
4. I agree to take part in the above study. ☐

______________________	______________	__________________
Name of Participant	Date	Signature

________________________	______________	__________________
Researcher	Date	Signature

Copies: 1 for participant 1 for researcher

Appendix 5: Food record sheet

		Day Month Year					
Day…………day		Date: / /		Day Order:			
Please use a separate line for each item eaten; write in weight of plate; leave a line between different 'plate' entries.							
A	B		C	D	E	F	Office Use
Time	Food eaten		Brand name of each item (except fresh food)	Full description of each item including: -whether fresh, frozen, dried, canned. cooked: boiled, grilled, fried, roasted.	Weight Served	Weight of Leftovers	Actual Weight
am/pm	home	away			(gms)	(gms)	(gms)

Appendix 6: Exercise activity diary

EXERCISE LOG

Name:

Date: Sleep (hrs): ________ Day:

Exercise	Type of training	Duration	Distance	Intensity*	Heart rate	Difficulty**	Notes
Example 1: Cycling	Continuous	3 hrs	40 miles	13 mph	160 bpm	Medium	Hilly course

*Intensity: Mph/Kph or Light/Moderate/Vigorous **Difficulty: Easy/Medium/Hard

Date: Sleep (hrs): ____________ Day: M Tu W Th Fr Sa Su

Exercise	Type of training	Duration	Distance	Speed	Heart rate	Difficulty*	Notes

Appendix 7: Laboratory set-up

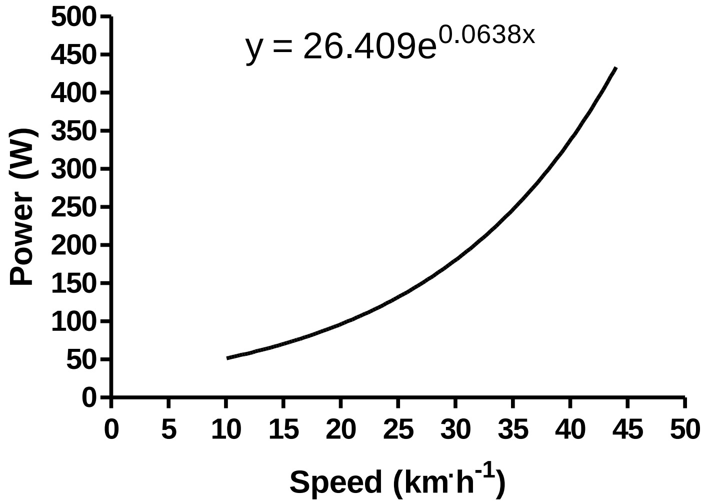
Appendix 8: Simultaneous SRM and PowerTap measurement

Simultaneous power measurement with SRM cranks and a Powertap wheel fitted to a road bicycle while cycling on a treadmill in the laboratory.

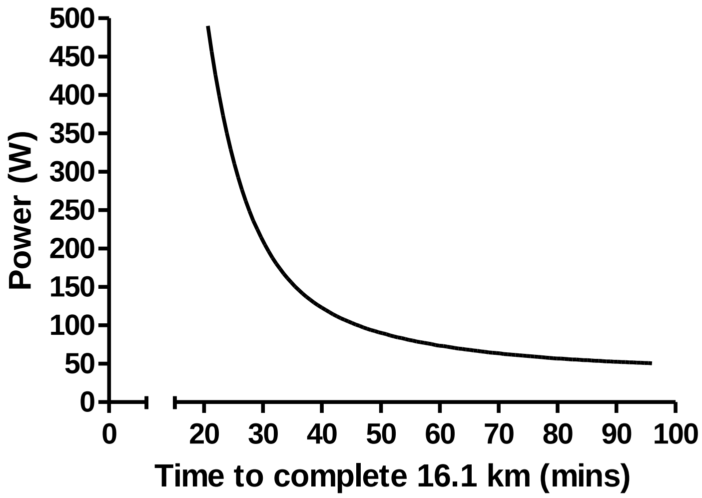
Minute average	SRM (W)	Powertap (W)	Difference (W)	Difference (%)
1	94.17	91.23	-2.93	-3.22
2	93.97	91.30	-2.67	-2.92
3	110.22	105.47	-4.75	-4.50
4	115.32	112.37	-2.95	-2.63
5	138.79	135.92	-2.88	-2.12
6	158.75	153.77	-4.98	-3.24
7	169.38	163.98	-5.39	-3.29
8	176.70	171.63	-5.07	-2.95
9	192.91	187.88	-5.03	-2.67
10	203.93	198.62	-5.31	-2.67
11	214.98	209.97	-5.01	-2.39
12	223.26	217.35	-5.91	-2.72
13	226.53	220.10	-6.43	-2.92
14	230.83	225.78	-5.04	-2.23
15	232.92	229.23	-3.68	-1.61
16	253.29	248.55	-4.74	-1.91
17	260.18	252.42	-7.76	-3.07
18	269.43	263.82	-5.61	-2.13
19	281.17	275.48	-5.68	-2.06
20	290.82	285.73	-5.08	-1.78
21	302.99	296.15	-6.84	-2.31
22	312.12	305.43	-6.68	-2.19
23	315.06	310.67	-4.39	-1.41
24	323.77	318.60	-5.17	-1.62
25	325.06	319.48	-5.57	-1.75
26	335.53	328.12	-7.42	-2.26
27	346.98	341.50	-5.48	-1.61
28	355.13	350.50	-4.63	-1.32
29	365.79	359.73	-6.06	-1.68
30	375.78	372.53	-3.25	-0.87
31	384.16	379.87	-4.29	-1.13
32	391.93	386.97	-4.97	-1.28
33	400.78	395.91	-4.87	-1.23
Average	256.74	251.70	-5.05	-2.23

<u>Appendix 9: The arrangement of the Oxycon Mobile and PowerTap wheel in the field.</u>

Appendix 10: SRM power and time, and power and speed curve



The exponential power and speed curve from the SRM ergometer. $R^2 = 0.9985$.



The relationship between power and time to complete a 16.1 km TT using a non-liner regression line with a two-phase association. Y = 8512 + [(43.92-8512)*96.19*.01] * [1-exp(-0.1593*x)] + [(43.92-8512)*(100-96.19)*.01] * [1-exp(-0.04006*x)], R^2 = 0.9992. (GraphPad Software Inc. 2007).