The Physiology and Bioenergetics of Ultraendurance Mountain Bike Racing

by
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ABSTRACT

Ultraendurance mountain bike racing is a relatively new sport and has received scant research attention. The practical difficulty of field-testing during competition has played a role in this dearth of knowledge. The purpose of this thesis was to investigate the physiology and bioenergetics of cross-country marathon (XCM) and 24 hour team relay (24XCT) mountain bike racing.

Study One analysed the physiological characteristics of XCM competitors and compared them to data from studies in the literature for Olympic-distance cross-country (XCO) mountain bike competitors. The XCM participants had lower mean peak aerobic capacity (58.4 ± 6.3 $mL \cdot kg^{-1} \cdot min^{-1}$), greater body mass (72.8 ± 6.7 kg) and estimated percentage body fat (10.4 ± 2.4%) compared to values reported for XCO competitors in the literature. Stature (1.77 ± 6.0 m) and normalised peak power output (5.5 ± 0.7 $W \cdot kg^{-1}$) were comparable. These data suggest that specific physiological characteristics of XCM competitors differ from those of XCO competitors.

Study Two quantified and described the exercise intensity during a XCM race by monitoring heart rate responses. The mean heart rate (150 ± 10 $beats \cdot min^{-1}$) for the duration of the race equated to 82 percent of maximum heart rate and did not differ significantly throughout the race ($p = 0.33$). The data indicated that the XCM race was of a high aerobic intensity. Prior to the competition the relationship between heart rate and $\dot{V}O_{2peak}$ for each participant was established during an incremental laboratory test. Energy expenditure was estimated by assigning 20.2 kJ to each litre of oxygen consumed. The mean rate of energy expenditure during the race was estimated to be 59.9 $kJ \cdot min^{-1}$. Furthermore, no anthropometric or physiological measures were correlated to race speed, indicating that other factors contribute to race performance.

The third study was a laboratory-based investigation to determine whether physiological factors relevant to 24XCT racing change with time of day. On separate days participants cycled on an ergometer for 20 min at 82 percent of maximum heart rate at 06:00, 12:00, 18:00, and 00:00 h. Significant differences ($p < 0.05$) were observed for several physiological responses (heart rate, oxygen uptake, salivary cortisol concentrations and intra-aural temperature) but not for performance variables (power output and self-selected cadence). It was concluded that the laboratory protocol lacked ecological validity and that it was necessary to test within a race using authentic 24XCT competitors.

In order to measure in-race performance, Study Four examined the agreement between a bottom-bracket ambulatory ergometer (Ergomo®Pro) and the criterion SRM power meter in a field-based setting. Analysis of absolute limits of agreement found that the Ergomo®Pro had a systematic bias (± random error) of 4.9 W (± 6.12). Based on tolerances recommended in the literature the unit was considered fit for purpose for measuring power output during 24XCT racing.

Study Five was a multiple case-study design that examined the physiological and performance parameters of a team during a 24XCT race. It was reported that mean work-shift speed (18.3 ± 2.6 $km \cdot h^{-1}$), power output (219 ± 50.9 W) and cadence (64.1 ± 9.3 rpm) were variable between participants and between work-shifts. A commonality amongst the participants was an increase in speed during the final work-shift compared to the penultimate one. A decline in work-shift heart rate was observed throughout the race. For the majority of participants an increase in gross efficiency (1.7 ± 1.4 %) was reported from the penultimate to the final work-shift. It was concluded that pacing strategies were employed and that the improved efficiency was caused, in part, by an increased familiarity with the course during the race.

Study Six examined the nutritional practices and energy expenditure of the same team during the same 24XCT race. Energy expenditure during the work-shifts was estimated in accordance with Study Two. Resting energy expenditure during the recovery periods was estimated using the Harris and Benedict formula (1919). Food and fluid consumption were determined via food diaries and hydration status was assessed by measuring the refractive index of urine. Energy consumption (17.3 ± 2.2 MJ) was considerably less than energy expenditure (30.4 ± 6.1 MJ) with the former accounting for only 57 percent of the latter. The energy cost during the work-shifts was estimated to be 74.5 $kJ \cdot min^{-1}$. Mean fluid intake (6.3 ± 0.9 L) for the 24 h was sufficient to maintain hydration status.

Based on these studies an integrated model of the factors that influence ultraendurance mountain bike performance was developed. The domains that influence race speed are physiological factors, technical and tactical factors, and nutritional strategies. The sub domain that influences these is environmental factors. Collectively this information is of practical importance to sport scientists, coaches and athletes involved with designing nutritional and tactical preparation strategies and training programmes for this sport.

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INDEX OF ABBREVIATIONS

♀	Female
♂	Male
ACSM	American College of Sports Medicine
ACTH	Adrenocorticotropic hormone
ANOVA	Analysis of Variance
AT	Anaerobic threshold
ATP	Adenosine triphosphate
BASES	British Association of Sports and Exercise Sciences
beats·min^{-1}	Beats per minute
BM	Body mass
BMI	Body mass index
BSA	Body surface area
BTPS	Body temperature and pressure with saturated water vapour
CHO	Carbohydrate
CV	Cardiovascular
CoV	Coefficient of Variance
DH	Downhill
DHIU	Discontinuous high-intensity ultraendurance
ECG	Electrocardiogram
EICF	Exercise induced cardiac fatigue
EE	Energy expenditure
EI	Exercise intensity
EMG	Electromyogram
FFM	Fat free mass
FVC	Forced vital capacity
GE	Gastric emptying
GI	Gastro-intestinal
GPS	Global positioning system
h	Hour
HIU	High-intensity ultraendurance
HR	Heart rate
HR_{ave}	Average heart rate

HR_{flex}	Heart rate flex point
HRM	Heart rate monitor
HR_{max}	Maximum heart rate
HR_{mean}	Mean heart rate
HR_{min}	Minimum heart rate
kcal	Kilogram calorie
kJ	Kilojoule
km	Kilometre
$km \cdot h^{-1}$	Kilometres per hour
L	Litre
LSD	Least significant difference
LT	Lactate threshold
m	Metre
Mbar	Millibar
min	Minute
MJ	Megajoule
$mL \cdot kg^{-1} \cdot min^{-1}$	Millilitres per kilogram per minute
mm	Millimeter
ms	Millisecond
MST	Motor spontaneous tempo
MTB	Mountain bike
O_2	Oxygen
OBLA	Onset of blood lactate accumulation
OS	Ordinance survey
PEF	Peak expiratory flow
PO	Power output
P_{osm}	Plasma osmolarity
$\dot{Q}$	Cardiac output
RAAM	Race across America
RC	Road cycling
REE	Resting energy expenditure
RER	Respiratory exchange ratio
RMR	Resting metabolic rate
RPE	Rating of perceived exertion
RPM	Revolutions per minute

RQ	Respiratory quotient
RV	Race velocity
s	Second
SD	Standard deviation
SV	Stroke volume
TT	Time trial
UE	Ultraendurance
UET	Ultraendurance threshold
U_{osm}	Urine osmolarity
U_{sg}	Urine specific gravity
$\dot{V}O_2$	Oxygen uptake
$\dot{V}O_{2max}$	Maximal aerobic capacity
$\dot{V}O_{2peak}$	Peak oxygen consumption
W	Watts
XC	Cross-country
XCM	Cross-country marathon
XCO	Cross-country Olympic
24XCT	24 h cross-country team relay
XCSR	Cross country stage race

GLOSSARY OF TERMS

Acrophase: The time at which the peak of a rhythm occurs.

Ad libitum: Freely available.

Anaerobic threshold: The point during exercise at which aerobic energy production is supplemented by anaerobic energy production resulting in an increase in lactate acidosis.

Bioenergetics: The investigation of energy transfer in living organisms.

Cardiovascular drift: A slow but steady increase in heart rate observed during endurance exercise at a constant workload.

Circadian: A cycle of approximately 24 h.

Cross-country: A mountain bike discipline performed on terrain that includes forest tracks, fields, gravel paths and involves significant amounts of technical climbing and descending.

Diurnal: Occurring during the daytime.

Downhill: A mountain bike discipline that involves an individual time-trial from the top of a hill to the bottom.

Endurance exercise: Exercise that last longer than 5 min but less than 4 h.

Front suspension: A mountain bike fitted with front suspension forks.

Full suspension: A mountain bike fitted with front and rear suspension.

Gross efficiency: Is the percentage of the ratio of work accomplished to energy expended.

Hardtail: A mountain bike that does not have rear suspension.

Holeshot: It is a positional advantage during racing. It occurs immediately after the mass start of a race, when, a competitor arrives at narrower confines of the singletrack in front of the other racers. A successful holeshot affords the competitor a degree of control over the tempo of the race, and avoids the ensuing bottle-neck.

Lactate threshold: The intensity of exercise that causes an increase in blood lactate concentration of 1 mmol·L^{-1} above that observed during exercise at 40-60% $\dot{V}O_{2max}$.

Masking: Disruption of a circadian rhythm caused by an external agent.

Mountain bike: A specific bicycle designed for off-road use. Typically they comprise a strong, lightweight frame, 26" wheels with wide knobbly tyres, derailleur gears, an upright riding position, and front suspension.

Nadir: The lowest value of a circadian rhythm.

Nocturnal: Occurring or active during the night time.

Nycthemeral: A full period of alternating night and day.

Onset of blood lactate accumulation: The intensity of exercise corresponding to a blood lactate level of 4 mmol·L^{-1}.

Optimal performance: The race speed at which the power supply from all available energy sources closely matches the power demand.

Pumping: Is an advanced skill during which the rider "weights" and "un-weights" the bicycle through powerful shifts in body position. It is used to traverse a rhythm section.

Racing line: Is the route the rider must take in order to minimise the time taken to complete the course.

Rhythm section: A succession of close bumps on a trail.

Singletrack: A technically demanding section of trail typically 30-50 cm wide. Riders predominantly must ride in single file and there is little opportunity for overtaking.

Work-shift: A single period of racing for a team member during a 24 h relay race. It comprises two laps.

Ultraendurance exercise: Exercise duration that exceeds 4 h.

Ultraendurance threshold: Is the theoretical exercise intensity which guarantees achievement of optimal performance.

CHAPTER ONE
Introduction

1.1 A brief history of mountain biking

The evolution of mountain bike racing has been closely linked to the mechanical development of the mountain bike (Williams, 2001). This introduction will provide an overview of the history of the sport and in particular the growth of ultraendurance mountain bike racing.

The term “mountain bike” (MTB) is thought to have first been used in 1978 when Charlie Kelly coined the phrase to describe a 12-geared bicycle he had built to race at Mount Tamalpais in Marin County, USA (Williams, 2001; Berto, 1999; Savre *et al.*, 2010). Three years later Mike Sinyard, the founder of *Specialized* bicycles, built the first production mountain bike, the *Stumpjumper* (Berto, 1999; Savre *et al.*, 2010). During these formative years mountain bike races rapidly increased in popularity and were a meeting of minds for the competitors and innovative bicycle builders of the day. These events provided the most severe environments for testing the new designs and equipment, and enabled the sport to rapidly evolve (Williams, 2001). A pivotal year in the development of mountain bike racing was 1987; this was the first year that off-road specific machines being sold in the United Kingdom out-performed the combined sales of all other bicycles; Paul Turner (later to be the founder of *RockShox*) introduced the first pair of mountain bike specific suspension forks at a US trade exhibition; and it was the first year that World Cup racing was hosted in Europe (Berto, 1999; Williams, 2001; Savre *et al.*, 2010).

In 1990 the cross-country (XC) and downhill (DH) disciplines had their first World Championships (Savre *et al.*, 2010), and it was during this year in Eschlikon, Sweden that the inaugural mountain bike marathon event was held (Wirnitzer and Kornexl, 2008). The following year the Union Cycliste Internationale (UCI) recognised mountain biking as an international sport. Mountain biking became a truly global phenomenon in 1996 when the cross-country discipline was inaugurated into the Atlanta Summer Olympic Games, and it is now established as a high-performance endurance sport (Stapelfeldt *et al*., 2004; Titlestad *et al*., 2006).

During the last 30 years the sport has continually evolved and diversified resulting in the UCI recognising eleven separate mountain bike categories (Appendix A). Cross-country is the most popular race discipline (Wilber *et al.*, 1997; Berto, 2001; Williams, 2001), and it is now possible for a rider to compete in one competition per week for nine months of the year (Impellizzeri and Marcora, 2007). Cross-country mountain biking (termed Olympic Cross Country (XCO) by the UCI) is a mass participant competition that is waged on off-road courses. According to UCI regulations the course should include forest roads, tracks, fields, and gravel paths, and involve significant amounts of climbing and descending (Union Cycliste Internationale, 2006). The average lap distance of an international course is 7 km, and the UCI advises a differentiated number of laps in order to give an approximate winning time of 2 h 15 min to 3 h (Union Cycliste Internationale, 2006).

In recent years XCO racing has seen a downturn in race entrants. However there has been a concomitant increase in the popularity of longer, ultra-endurance cross-country races. The two most common types of ultraendurance mountain bike races are 24 h team relay (24XCT) and cross-country marathon (XCM). The inaugural Red Bull[1] 24 hour mountain bike race took place in 1998 during which teams of four competed relay-style with the winning team being determined by the one that completed the greatest number of full laps. The turn of the millennium saw the first Schwinn[2] 100 km mountain bike marathon race, and since then the ultraendurance cross-country race calendar has increased further to include multi-day stage races (XCSR). Ultraendurance cross-country mountain biking has also become a staple discipline in the burgeoning adventure racing calendar with athletes being required to exercise for prolonged periods, often in extreme conditions (Neumayr *et al*., 2002; Linderman *et al.*, 2003; Metcalfe, 2004).

1.1.1 A brief review of the history of mountain bike research

Data that describe the physiological responses to, and factors that contribute to success in, ultraendurance mountain bike races are rare (Laursen *et al*., 2003a). Due to cross-country mountain biking being a relatively new sport it has received scant research attention (Wilber *et al.*, 1997; Impellizzeri *et al.,* 2005a; Gregory *et al.,* 2007). However, in recent years, investigation into this area has slowly begun to gather momentum and a small but growing number of physiological studies have been published (Baron, 2001; Stapelfeldt *et al.*,

[1] the current sponsor is Original Source
[2] the current sponsor is Chain Reaction Cycles

2004; Gregory *et al.*, 2007; Impellizzeri and Marcora, 2007). This increase in empirical knowledge appears to have been stimulated by the inclusion of mountain biking in the Olympics. This has resulted in very little research focussing on durations outside that of the XCO.

Although influenced by the progression of the other competitors, ultraendurance cross-country racing is largely self-paced. In many of the laboratory studies the exercise intensity is externally-paced and governed by the experimenter. This is often required to meet the demands of controlled data collection in specifiable and repeatable conditions (Mastroianni *et al*., 2000). Whilst this gives insight into the relationships of physiological variables under laboratory conditions, such data often lacks authenticity, and does not provide an understanding of what happens under self-governed race conditions. Mastroianni *et al*. (2000) suggest that this is often due to the logistical and methodological obstacles encountered when measuring performance outside of the laboratory. During field testing a trade-off often exists between internal and ecological validity. Due to few variables being controlled it is often inconclusive as to which of the independent variables, if any, have influenced the dependent variable. Furthermore, recruiting elite participants for study during competition is challenging and often results in small sample sizes (Impellizeri *et al.*, 2002; Laursen *et al.*, 2003a; Wirnitzer and Kornexl, 2008). Mastroianni *et al*. (2000) note that authentic field-data would be more prevalent if accurate testing protocols under authentic field conditions were developed. Due to the absence of accurate testing methods the bioenergetics and physiological factors that affect ultraendurance mountain bike performance have not been addressed. Such information is valuable for sports scientists, coaches, and athletes in order to develop strategies to help enhance performance. In addition this information is of great practical relevance to race organisers and health professionals involved with supporting the athletes. It was therefore the purpose of this thesis to address the dearth of knowledge regarding the physiology and bioenergetics of ulltraendurance mountain bike racing. The two ultraendurance disciplines that this thesis focuses on are cross-country marathon and 24 h cross-country team relay.

1.2 Aims of the thesis

The purpose of this thesis is to develop the understanding of the physiology and bioenergetics of ultraendurance cross-country mountain bike racing. The driving philosophy is for the outcomes to be applied, have external validity and be accessible in a currency that is relevant to coaches and athletes. The specific aims of this thesis are detailed below:

1. To provide an analysis of the anthropometric and physiological characteristics of competitive ultraendurance mountain bikers.
2. To analyse the exercise intensity and estimate the energy expenditure during ultraendurance mountain bike racing.
3. To develop a robust and unobtrusive protocol for field-testing during races.

4. To provide an analysis of the key physiological and performance variables, and the nutritional requirements of a 24 h ultraendurance mountain bike relay race.
5. To examine the influence of circadian variation during a 24 h ultraendurance mountain bike relay race.
6. To propose a model for the factors affecting ultraendurance mountain bike racing.

1.3 Organisation of the thesis

The first section of this thesis provides a review of the literature regarding the physiological factors that influence cross-country mountain biking and in particular ultraendurance performance. Following this a general methods section provides details of the testing methods that were common to the studies. Study-specific methods are detailed in the relevant chapters. Studies One and Two are concerned with addressing the physiology and bioenergetics of XCM racing. The remaining studies focus on 24XCT racing. Study Three is a laboratory-based investigation that addresses variables that potentially affect 24XCT racing at different times of the day. Study Four is concerned with the validation of field-based testing equipment, and details the methods for testing during the 24XCT race. Study Five addresses the physiological and performance aspects of 24XCT racing, whilst Study Six focuses on the nutritional aspects. The final chapter provides a synthesis of the findings and proposes an integrated model of the factors that influence ultraendurance mountain bike performance.

CHAPTER TWO
Review of literature

2.1 Ultraendurance mountain biking

This chapter will review the current literature relating to the factors that potentially affect performance during ultraendurance mountain bike racing. These factors include anthropometric and physiological characteristics, exercise intensity, fatigue, circadian rhythms, sleep deprivation, light intensity and nutritional factors.

2.1.1 Defining ultraendurance

Athletic performance sits on a continuum ranging from short-duration explosive events to prolonged activities. Between these two extremes lie a plethora of sports whose energy demands are met by contributions from the anaerobic and aerobic metabolic pathways. Whyte (2006) describes endurance activity as events lasting longer than 5 min but less than 4 h. Longer duration events are classified as ultraendurance (UE) activities (Kreider, 1991; Hawley and Hopkins, 1995; Laursen and Rhodes, 1999; Laursen and Rhodes, 2001; Neumayr *et al.*, 2002; Linderman *et al.*, 2003; Whyte, 2006).

Ultraendurance events are increasing in frequency and popularity (Kimber *et al*., 2002). They can incorporate different modes of exercise and typically include mountain biking, road cycling (RC), running, triathlons and adventure racing. Ultraendurance mountain bike races range from a 90 km circuit on off-road terrain, to 24 h races, to multi-day stage races (British Cycling, 2010).

With regard to 24 h mountain biking, the most prevalent race format is that of teams of four employing shift-based relay strategies. Races usually start at midday, and a typical race-strategy may have one team rider completing two laps of the course, and then the next rider completes two laps and so on in a sequential manner for the duration of the event. In this instance each rider will complete 6 h of intermittent exercise over the course of the day. In between race-shifts the riders apportion their time between eating, hydrating, undertaking ongoing maintenance work on their bicycles, discussing tactics and sleeping. For the purpose of this thesis, 24 h team mountain bike racing will be classified as ultraendurance.

2.2 Physiological and anthropometric characteristics of mountain bikers

Ascertaining the anthropometrical and physiological characteristics of successful athletes in a sport is important because it establishes common prerequisites for performance at the highest standard of competition (Lee *et al.*, 2002). Event-specific physiological traits are evident in the wider context of sport, yet even within cycling, studies have shown that anthropometrical and physiological characteristics vary according to the sub-disciplines. Time-trialists, climbing-specialists, and mountain bikers have each been shown to have different and specific physiological and anthropometric profiles (Swain, 1994; Wilber *et al.*, 1997; Padilla *et al.*, 1999; Lucìa *et al*., 2000; Lee *et al.*, 2002). Table 2.1 summarises contemporary research on the various anthropometric and physiological characteristics of mountain bikers, with most research centred on XCO[3] racing. In contrast the XCM[4], 24XCT[5] and XCSR[6] disciplines have received scant attention. Table 2.2 summarises the same characteristics for ultraendurance running, cycling and triathlon.

2.2.1 Age characteristics of XC mountain biking

The mean ages of ultraendurance XC riders tend to be greater than those of their XCO counterparts. This trend is also reflected in the current UCI rankings; at the time of writing the mean ages of the UCI top 15 riders for the XCO and XCM disciplines were 28.3 ± 3.6 years and 32.4 ± 4.2 years respectively (Union Cycliste Internationale, 2010). The mean ages of the ultraendurance athletes represented in Table 2.2 also mirror the tendency for an elevated age. Zalcman *et al*. (2007) note that it is common for competitors in ultraendurance sports to be older than competitors in typical endurance and resistance sports. They suggest that this may be due to the athletes possessing greater maturity and emotional balance. It may also be due to a prolonged accumulated endurance training base, and the experience to pace themselves over a protracted period.

[3] Olympic cross-country.
[4] Cross-country marathon.
[5] 24h cross-country team relay.
[6] Cross-country stage race.

Table 2.1: Selected anthropometric and physiological characteristics of mountain bikers

Study	Sport	Level	Age (yrs)	Stature (m)	Body mass (kg)	Body fat (%)	$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	Peak power (W)	Peak Power (W·kg^{-1})	HRmax (beats·min^{-1})
Baron (2001)	XCO	Elite (n = 25)	22.5 ± 4.4	1.79 ± 0.05	69.4 ± 6.5	Not specified	68.4 ± 3.8	Not specified	5.5 ± 0.4	Not specified
Carpes *et al.* (2007)	XC	Highly trained. Case study	21	1.85	72.1	6.63	75.4	475	6.59	200
Costa and De-Oliveira (2008)	XCO	Elite (n = 6)	26.5 ± 0.6	1.74 ± 0.01	69.1 ± 2.1	5.9 ± 0.9	69.8 ± 3.5	349.2 ± 15.6	5.1 ± 0.2	192 ± 4
Cramp *et al.* (2004)	XCO	Trained (n = 8)	22 ± 6.3	1.79 ± 0.06	69 ± 7.6	Not specified	60 ± 3.7	Not specified	Not specified	Not specified
Gregory *et al.* (2007)	XCO	Elite (n = 11)	25.1 ± 4.9	1.80 ± 0.04	71.6 ± 6.3	9.2 ± 2.8	64.8 ± 8.2	368 ± 32	5.1 ± 0.4	191 ± 7
Impellizzeri *et al.* (2002).	XCO	Amateur (n = 5)	21.0 ± 4	1.74 ± 0.03	64.3 ± 4.8	4.7 ± 1.4	75.2 ± 7.4	368 ± 31	5.7 ± 0.5	192 ± 5
Impellizzeri *et al.* (2005a)	XCO	High level (n = 12)	24.9 ± 2.9	1.76 ± 0.07	66.4 ± 5.7	Not specified	76.9 ± 5.3	426 ± 40	6.4 ± 0.6	183 ± 8
Impellizzeri *et al.* (2005b)	XCO	National / international (n = 13)	20 ± 1.0	1.77 ± 0.08	65 ± 6.0	5.3 ± 1.6	72.1 (peak) ± 7.4	392 ± 35	Not specified	190 ± 7

Table 2.1 continued

Study	**Sport**	**Level**	**Age (yrs)**	**Stature (m)**	**Body mass (kg)**	**Body fat (%)**	**$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)**	**Peak power (W)**	**Peak power ($W \cdot kg^{-1}$)**	**HRmax ($beats \cdot min^{-1}$)**
Knechtle and Rosemann (2009)	XCM	Rec. (n = 36)	38.8 ± 9.0	1.79 ± 0.06	74.8 ± 7.7	12.3 ± 2.7	Not specified	Not specified	Not specified	Not specified
Laursen *et al.* (2003a).	24XCT	Trained (n = 4)	24.0 ± 2.1	1.83 ± 0.03	75.0 ± 2.7	Not specified	69.8 (peak) ± 3.4	453 ± 15	Not specified	198 ± 4
Lee *et al*. (2002)	XCO	International (n = 7)	24.4 ± 3.4	1.78 ± 0.07	65.3 ± 6.5	6.1 ± 1.0	78.3 (peak) ± 4.4	413 ± 36	6.3 ± 0.5	189 ± 5
Prins *et al*. (2007)	XC	Competitive (n = 8)	28 ± 5	Not specified	72.9 ± 5.6	Not specified	63.6 ± 5.7	372 ± 37	5.1 ± 0.4	189 ± 5
Rose *et al.* (2007)	XCSR	(n = 412)	39.0 ± 7.6	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified	Not specified
Rose and Peters (2008)	XCSR	Not specified (n = 18)	40 ± 1.4	1.82 ± 0.02	81.8 ± 2.2	18.1 ± 0.8	Not specified	Not specified	Not specified	Not specified
Sewall and Fernhall (1995)	XCO	Elite / Intermediate (n = 18)	27 ± 4.4	1.77 ± 0.05	70.8 ± 7.4	10.5 ± 3.5	67.2 ± 5.4	Not specified	Not specified	193 ± 7
Stapelfeldt *et al*. (2004)*	XCO	Elite (n = 9)	21.2 ± 1.8	1.80 ± 0.06	69.4 ± 4.7	Not specified	66.5 ± 2.6	368 ± 25	5.3 ± 0.3	193 ± 10

Table 2.1 continued

Study	**Sport**	**Level**	**Age (yrs)**	**Stature (m)**	**Body mass (kg)**	**Body fat (%)**	$\dot{V}O_{2max}$ **(ml·kg^{-1}·min^{-1})**	**Peak power (W)**	**Peak power (W·kg^{-1})**	**HR_{max} (beats·min^{-1})**
Warner *et al*. (2002)	XCO	Expert / elite (n = 16)	26.2 ± 5.0	1.77 ± 0.05	71.1 ± 5.1	11.5 ± 2.7	67.4 ± 4.6	Not specified	Not specified	Not specified
Wilber *et al*. (1997)*	XCO	National (n = 10)	29 ± 4.0	1.72 ± 0.07	71.5 ± 7.8	5.8 ± 1.1	70.0 ± 3.7	420 ± 42	5.9 ± 0.3	192 ± 12
Wirnitzer and Kornexl (2008)*	XCSR	Amateur (n = 5)	34.7 ± 3.1	1.71 ± 0.04	63.3 ± 10.1	Not specified	Not specified	314 ± 43	4.8 ± 0.3	174 ± 2

Rec. = recreational
* studies included male and female athletes, however only males are represented in the table.

Table 2.2: Selected anthropometric and physiological characteristics of ultraendurance athletes

Study	Sport	Level	Age (yrs)	Stature (m)	Body mass (kg)	Body fat (%)	$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	Peak power ($W \cdot kg^{-1}$)	HRmax ($beats \cdot min^{-1}$)
Bowen *et al.* (2006)	Advent. race	Elite (Case study)	29	1.75	80	Not specified	59	Not specified	184
Callard *et al.* (2000)	24 h RC	Competitive	33.4 ± 3.7	1.77 ± 0.05	70.3 ± 4.5	12.1 ± 1.8	52.2 ± 2.2	Not specified	Not specified
Colombani *et al.* (2002)	Advent. race	Amateur (n = 12)	34 (median)	Not specified	74	Not specified	Not specified	Not specified	Not specified
Kimber *et al*. (2002)*	Triathlon	Ironman (n = 10)	36.2 ± 9.6	1.77 ± 0.08	74.4 ± 9.1	15.1 ± 3.6	C 54.5 ± 3.7 R 58.3 ± 3.9	Not specified	Not specified
Kruseman *et al.* (2005)	UE run	Amateur (n = 42)	42 ± 9.7	Not specified	71 ± 7.8	Not specified	Not specified	Not specified	Not specified
Neumayr *et al*. (2002)	UE RC	Case study	36	1.78	70	Not specified	70	5.7	184
Neumayr *et al*. (2004)	UE RC	Elite (n = 10)	35 ± 7	1.77 ± 0.05	71 ± 7	Not specified	Not specified	Not specified	Not specified
O'Toole *et al.* (1987)*	Triathlon	Ironman (n = 8)	30.5 ± 8.8	1.79 ± 0.06	74.7 ± 10.0	9.9 ± 3.5	73.8 ± 8.8	Not specified	178 ± 8
Wu *et al.* (2004)	24 h run	(n = 11; 1 x ♀, 10 x ♂)	45.1 ± 2.6	1.67 ± 0.06	60.6 ± 9.7	Not specified	Not specified	Not specified	Not specified
Zalcman *et al.* (2007)*	Advent. race	National/ international (n = 18)	30.9 ± 5.8	1.76 ± 0.05	75.5 ± 5.5	12.5 ± 3.5	58.6 ± 6.6	Not specified	Not specified

R = Run; C = cycle; Advent. = adventure; RC = Road Cycling. * studies included male and female athletes, however only males are represented in the table.

2.2.2 Body mass characteristics of XC mountain biking

Body mass is generally considered an influencing factor in any sport where there is movement against gravity (Jeukendrup *et al*., 2000a). However, the research regarding the effects of body mass on XCO mountain bike performance is equivocal. Some authors have reported stronger correlations when secondary predictors of performance (such as peak power output and aerobic capacity) are normalised to body mass (Baron, 2001; Lee *et al*., 2002; Impellizzeri *et al.*, 2005a; Impellizzeri *et al.*, 2005b; Gregory *et al*., 2007), whereas others have not (Laursen *et al*., 2003a). This has led other researchers to suggest that it is not body mass per se that affects performance; rather it is body composition that is of greater relevance (Impellizzeri and Marcora, 2007). The lack of relationship between absolute body mass and performance is no more evident than when comparing cross-country Olympic gold medallists Miguel Martinez and Bart Bretjens, who at the time of the 2004 Olympic Games, had body masses of 55 kg and 77 kg respectively (Impellizzeri and Marcora, 2007). These two athletes were able to compete successfully at the top of the sport with considerably different body masses. It may be that body composition has a greater influence on cross-country performance than body mass.

2.2.3 Body composition characteristics of XC mountain biking

The influence of body composition has intuitive appeal as World Cup cross-country courses typically include uphill sections equivalent to approximately 40% of the race distance (Lee *et al.*, 2002). Furthermore, riders must be able to accelerate and decelerate at will during technical sections. A low inert body mass in these situations would clearly be advantageous (Martin *et al.*, 1998) and would support the longstanding adage amongst coaches and riders that races are often "won on the climbs" (Overend, 1999). In a study examining various physiological characteristics of intermediate and elite Pro-Am XCO mountain bikers, Sewall and Fernhall (1995) found that the only significant difference between the two groups was the elite Pro-Am riders had a lower percentage of body fat. The range of body fat percentage for the XCO riders highlighted in Table 2.1 is between 4.7-11.5%. This suggests a lean body type is a characteristic of XCO mountain bikers. However, the bandwidth is relatively large and it is not apparent in the literature whether low body fat affects performance or whether it is a by-product of the energy expended during large-volume macrocycle training. Interestingly, Knechtle and Rosemann (2009) reported no correlation between skinfold thickness and race performance in recreational ultraendurance mountain bikers. Whilst a low inert body mass may be beneficial in XCO racing, Zalcman *et al.* (2007) note that ultraendurance exercise seems to favour greater body fat stores in response to the high metabolic demands and associated high-energy intake. However this is merely a hypothesis as they do not provide any causal evidence.

2.2.4 Aerobic capacity characteristics of XC mountain biking

Maximum oxygen uptake ($\dot{V}O_{2max}$) is regarded as a valid gauge of the integrated functionality of the cardiovascular, respiratory, and muscular systems during exercise (Bassett and Howley, 2000; Impellizzeri and Marcora, 2007). Several studies have reported $\dot{V}O_{2max}$ to be a good predictor of performance in endurance sports (Costill *et al.*, 1973; Foster *et al.*, 1978; Malhotra *et al.*, 1984; Miller and Manfredi, 1989), whereas other authors question its predictive ability (Conley and Krahenbuhl, 1980; Noakes, 2000a). The influence of $\dot{V}O_{2max}$ on mountain bike performance is also equivocal. Some researchers have found maximal aerobic capacity to be a good predictor of XCO performance (Impellizzeri *et al.*, 2005b) whereas others have not (Sewall and Fernhall, 1995; Laursen *et al.*, 2003a; Impellizzeri *et al.*, 2005a). This may be due to several factors. Firstly, as can be seen from Table 2.1, there is a lack of consensus in the scientific literature as to what constitutes "level" of performance, thus making comparisons between studies inconclusive. Secondly, the protocols for ascertaining maximal aerobic capacity differ considerably between studies, which may contribute to the range of findings. Laursen *et al.* (2003a) employed a 15 W increase every 30 s from a starting workload of 100 W, whereas Lee *et al*. (2002) used a protocol in which workload was increased by 50 W every 5 min from a starting workload of 100 W. Thirdly, if participants with homogenous physiological characteristics are investigated it is often difficult to ascertain a relationship. Costill *et al.* (1973) found $\dot{V}O_{2max}$ to significantly correlate to running performance in a heterogenous group, whereas Morgan *et al.* (1989) found it to be a poor predictor of performance in a homogenous group of runners. Furthermore, Impellizzeri *et al.* (2005a) reported no correlation between normalised $\dot{V}O_{2max}$ and performance in a homogenous XCO cohort, but reported an association for a heterogenous group (Impellizzeri *et al.*, 2005b). Fourthly, mountain biking presents a diverse racing environment in which not only physical fitness, but also skill contributes significantly to the overall performance of the rider (British Cycling, 2010). Other variables that come to the fore that affect performance include technique, terrain, environment, equipment choice, nutrition and motivation (Sewall and Fernhall, 1995; Laursen and Rhodes, 2001; Impellizzeri *et al.*, 2005a).

Noakes (2000a) cites anecdotal evidence from the performance times and aerobic capacity values of world-class runners to suggest that $\dot{V}O_{2max}$ becomes a less sensitive predictor of performance as the distance of the event increases. He reasons that there is little commonality between the $\dot{V}O_{2max}$ test and ultraendurance performance in that the test is relatively short in duration and involves performing close to maximum for a few minutes at most. This is supported by Laursen *et al.* (2003a) who investigated various physiological characteristics of 24XCT mountain bikers and concluded that $\dot{V}O_{2peak}$ was not related to performance. Similarly Sewall and Fenhall (1995) reported no significant relationship between $\dot{V}O_{2max}$ and cross-country mountain bike performance despite a heterogeneous cohort with a large range in aerobic capacity (54.5 to 77.0 $mL \cdot kg^{-1} \cdot min^{-1}$). Furthermore, Conley and Krahenbuhl (1980) found that $\dot{V}O_{2max}$ was not a good predictor of 10 km performance in a group of highly trained runners. Rather they found that the best times were achieved by those runners who used the least oxygen at predetermined running speeds. They found that over 65% of the variation in the 10 km performance could be explained by variation in running efficiency.

Similar findings were reported by Lucía *et al*. (2001a) for elite-amateur and professional road cyclists, suggesting that $\dot{V}O_{2max}$ is not a valid performance indicator. They also noted that it is the ability to maintain a high fractional utilisation of $\dot{V}O_{2max}$ during prolonged periods that has greater relevance to success in professional road cycling. Impellizzeri and Marcora (2007) noted that cross-country mountain bikers can utilise a high percent of their maximum aerobic power to produce the intense and prolonged work rates required during competitions.

Nonetheless, the maximal oxygen uptake values highlighted in Table 2.1 indicate that cross-country mountain bikers possess high aerobic capacities (60-78.3 $mL \cdot kg^{-1} \cdot min^{-1}$). These are comparable to values reported by Lucía *et al.* (2001a) for professional road cyclists. Typical $\dot{V}O_{2max}$ values for professional road cyclists range from 70 to 80 $ml \cdot kg^{-1} \cdot min^{-1}$ and to some extent are discipline specific (Lucía *et al.,* 2001a), with uphill climbing specialists eliciting higher relative values (Padilla *et al*., 1999; Lucía *et al.,* 2000a). The maximal aerobic capacities of the ultraendurance athletes represented in Table 2.2 are somewhat lower than those of the XCO mountain bikers. It is well documented that maximum heart rate declines with advancing years (McArdle *et al.,* 2001; Tanaka *et al.*, 2001). This phenomenon is attributed to changes in cardiovascular structure and function as a result of the interaction of lifestyle, disease and genetics as the individual ages (Lakatta, 2001). Maximal aerobic capacity shows a similar trend with further declines in relative values being attributed to increases in body mass associated with aging (McArdle *et al.,* 2001). It may be that the elevated age of ultraendurance athletes contributes to an attenuated cardiovascular function.

2.2.5 Power output characteristics of XC mountain biking

The ambiguity regarding the relationship between $\dot{V}O_{2max}$ and performance, has meant some researchers have focussed their attention on the relationship between peak power output (PPO) attained at $\dot{V}O_{2max}$ and performance (Noakes, 2000a; Atkinson *et al.*, 2007a). As such peak power output values of riders has received much scrutiny in the literature, and has been shown to strongly correlate (r = 0.99) with outdoor road cycling time-trial performance (Balmer *et al.*, 2000).

Cycling is a unique endurance sport insomuch as the technology is available to directly measure the power output (PO) of the athlete via ambulatory ergometry (this point will be returned to later in the thesis). Power is the rate of work done, where work done is the product of the sum of net forces and the distance moved. The peak power output of XCO riders is highlighted Table 2.1. Interestingly Impellizzeri *et al.* (2005a) found that PPO did not correlate with cross-country race performance. Indeed several authors note that relative, rather than absolute, power output is of greater relevance to cross-country mountain biking due to the large proportion of time spent climbing (Lee *et al.*, 2002; Impellizzeri *et al.*, 2005b; Gregory *et al.*, 2007; Prins *et al.*, 2007; Costa and De-Oliveira, 2008).

A key difference in the power output profiles during mountain biking and road cycling is that the former is stochastic and the latter is more consistent. Field research on road time-trials has shown power output varies by only ± 7% (Padilla *et al*., 2000) whereas Stapelfeldt *et al.* (2004) reported a coefficient of variance of 69% for power output during a XCO race. Furthermore, Palmer *et al*. (1997) found that subsequent time trial power output is attenuated immediately following stochastic work compared to fixed intensity exercise, despite the preceding exercise bouts being of the same average power output. They suggested that the stochastic protocol may have led to a greater use of glycogen stores compared to the constant protocol. It may therefore be that the oscillatory nature of power output during cross-country racing reduces the subsequent power output a rider can generate.

2.3 Exercise intensity and XC mountain biking

The term intensity is part of the daily parlance of coaches, athletes and sports scientists, however it is often vague and ill defined. There are several ways of quantifying exercise intensity during mountain biking, these include determining power output; exercise heart rate as a percentage of maximum; energy expenditure; or the volume of exercise at or above pre-determined thresholds.

2.3.1 Heart rate and exercise intensity

It is well established that a linear relationship exists between heart rate (HR) and oxygen uptake ($\dot{V}O_2$) (McArdle *et al.*, 2001; Cooke, 2004). Under normal conditions an increase in exercise intensity must be met with a commensurate increase in energy production, and if this energy demand is to be satiated by aerobic metabolism, then the oxygen (O_2) demands of the associated tissue increases. Oxygen uptake is the product of cardiac output ($\dot{Q}$) and arterial-venous O_2 difference (Fick equation), and the increased oxygen demand is met, in part, by an increase in cardiac output. Cardiac output is the product of stroke volume (SV) and heart rate, and an increase in cardiac output is the result of increases in these components (Åstrand *et al.*, 2003; Abbiss and Laursen, 2005). Of these parameters, heart rate is the most practicable component to record, and in the day-to-day practice of training and racing, it is the standard measure of exercise intensity (Jeukendrup and Van Diemen, 1998; O'Toole *et al.*, 1998; Lucía *et al.*, 1999; Myburgh, 2003).

2.3.1.1 Efficacy of heart rate monitoring

As early as 1954 Åstrand and Ryhming validated heart rate as a predictor of energy expenditure (EE) in cycling. In 1984 Karvonen and co-workers compared heart rates measured by an electrocardiogram (ECG) with those measured by the Polar PE2000 wireless heart rate monitor (HRM) over a wide range of intensities and found heart rates differed at most by only 5 beats·min^{-1} between the two systems. Later studies, again examining the accuracy of wireless heart rate monitors compared to ECGs, reported correlation coefficients of >0.93 (Treiber *et al.*, 1989) and 0.99 (Seaward *et al.,* 1990) over a wide range of heart rates.

2.3.1.2 Heart rate and ultraendurance

During road cycling (RC) heart rate generally follows the topographical profile of the course (Fernandez-Garcia *et al*., 2000), or during flat-profile races, it reflects the pace as dictated by the real-time tactics as the race unfolds (Palmer *et al.,* 1994). As such, heart rate is an established gauge of exercise intensity during road cycling.

Laursen and Rhodes (2001) suggest that heart rate values during an ultraendurance competition may provide key information which could be used to maximise performance. They propose a unique ultraendurance threshold (UET) paradigm that exists somewhere below the individual's anaerobic threshold (AT) that can be monitored via heart rate. It is a theoretical exercise intensity that maintains a constant energy contribution from carbohydrate and fat throughout the race resulting in optimal performance. Currently this is just a concept, and methodological issues prevail for ascertaining the threshold for mountain biking due to the nature of the sport and the amount of variables that potentially influence performance. Their proposed method for road cycling is to manipulate individual laboratory-based ultraendurance paces in order to identify the optimal threshold for determining the best performance intensity. Using a cycle ergometer has ecological validity for road cycling and triathlon events; however there is an intuitive lack of authenticity for mountain biking. In road time-trials it is reported that performances will always be worse on hilly or windy courses compared to flat, no-wind conditions even for the same amount of work done (White, 1994; Martin *et al*., 1998), and there are considerably more variables to take into account during mountain biking (British Cycling, 2010). Although the ultraendurance threshold is not a well established concept, it does have appeal and there is growing support for its existence (O'Toole *et al.,* 1987; Laursen and Rhodes, 2001). Neumayr *et al.* (2004) investigated the heart rate response of ten elite ultraendurance road cyclists during the 525 km Race across the Alps and reported a HR_{mean} / HR_{max} value of 0.68. They concluded that an ultraendurance threshold exists and that it is approximately 70% of HR_{max}.

2.3.1.3 Limitations of heart rate monitoring

During 16.1 km laboratory-based time-trials with simulated headwinds and tailwinds, Atkinson and Brunskill (2000) reported that heart rate and subjective feelings of exertion are not sensitive enough to register subtle but relevant changes in power output. Stapelfeldt *et al.* (2004) reported that the heart rate profiles of cross-country riders were in contrast to their respective power output profiles, with the former displaying an almost constant intensity whilst the latter was variable. Indeed they found no significant difference between the heart rates recorded on the climbs and those on the descents; a distinct contrast to those observed during road cycling races. This highlights a discrepancy between heart rate and power output as tools to measure exercise intensity during mountain biking. They suggest that this may be due to i) the regulatory systems of the cardiovascular (CV) system being somewhat slower than the metabolic reactions at a cellular level not reflecting the rapid changes in power output due to alterations in terrain, and ii) the isometric contractions of the limbs used to absorb trail induced vibrations allied to the psychological factors associated with descending at speed (such as concentration and anxiety) contributing to an elevated heart rate. This is in accordance with the findings of Jeukendrup and Van Diemen (1998) and Hurst and Atkins (2006a) who noted that power output is much more variable than heart rate.

However, Seifert *et al.* (1997) showed that using a mountain bike fitted with front suspension significantly reduces the mean heart rate compared to a rigid mountain bike. Impellizzeri *et al*. (2002) also reported that potential increases in heart rate induced by isometric exercise are smaller at higher workloads and are attenuated in trained individuals. These findings suggest that the elevated heart rate typically observed during isometric muscle contraction will be lessened during competitive cross-country mountain biking when elite riders are using front suspension, and that the potential discrepancy between power output and heart rate will be reduced.

In a further study investigating the effects of front and full suspension mountain bikes on uphill off-road performance MacRae *et al.* (2000) concluded that despite significant differences in power output between the two conditions the differences did not translate into significant differences in $\dot{V}O_2$. Care should be exercised when interpreting these results as the off-road course was only 1.38 km, was entirely uphill and produced mean time trials of only 8.3 ± 0.7 min for the front suspension and 8.4 ± 1.1 min for the full suspension conditions.

2.3.1.4 Cardiovascular drift

Prolonged exercise at a constant intensity can place an increasing load on the heart, resulting in a progressive rise in heart rate. O'Toole *et al*. (1998) observed an increasing heart rate during ultraendurance exercise at a constant work rate. Boulay *et al*. (1997) found that when subjects exercised at a fixed heart rate, work rate had to be reduced significantly over time. This phenomenon is termed cardiovascular drift and has been linked to thermoregulatory compensation mechanisms increasing the distribution of systemic blood flow to the skin for cooling (Abbiss and Laursen, 2005). It is suggested that during prolonged activity there is a progressive reduction in stroke volume resulting from a reduction in plasma volume due to fluid losses and volume shifts. Therefore an increase in heart rate is required to maintain a steady cardiac output (Laursen and Rhodes, 2001). Cardiovascular drift is exacerbated when exercising in hot humid environments (Coyle and Montain, 1992). Figure 2.1 illustrates a hypothetical plot of heart rate during an ultraendurance event.

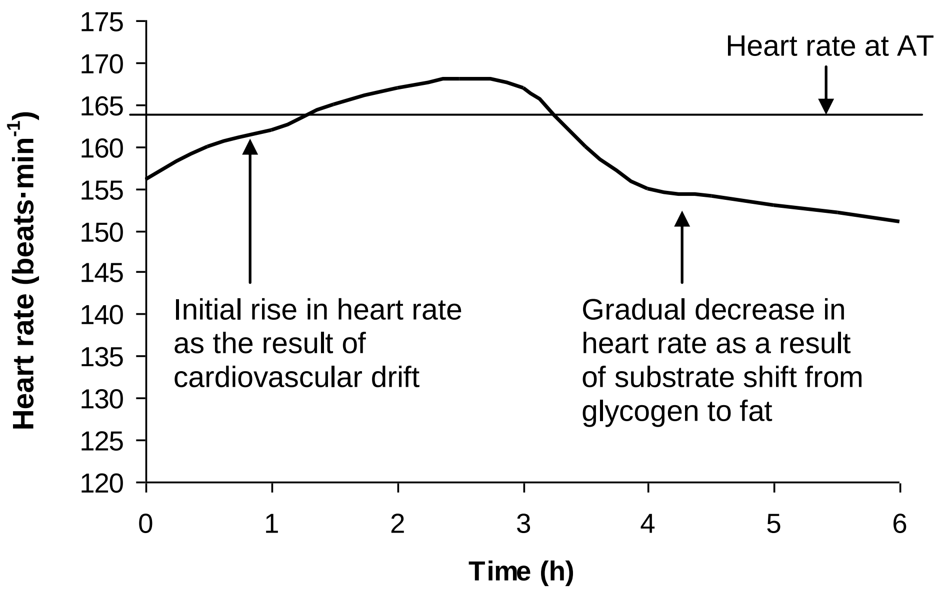


Figure 2.1: A hypothetical plot of heart rate during an ultraendurance event. Redrawn from Laursen and Rhodes (2001, p. 206.). AT = anaerobic threshold.

Some field studies have reported a reduction in heart rate during prolonged exercise. A further factor that may affect heart rate during ultraendurance events is exercise induced cardiac fatigue (EICF) (Dawson *et al.*, 2003). Exercise induced cardiac fatigue is a reduction in left ventricular function as a result of prolonged exercise in otherwise healthy humans. Dawson *et al.* (2003) opined that confounding factors that could affect left ventricular function include exercise intensity, exercise duration, fitness status, and environmental conditions. Vanoverschelde *et al.* (1991) reported that EICF does not occur during exercise of relatively short duration, and Niemela *et al.* (1984) only found a depressed left ventricular function in subjects during the latter quartile of a 24 h run.

Laursen and Rhodes (2001) reported a gradual decrease in subjects' heart rate during an ultraendurance triathlon, which they attribute to a possible change in substrate utilisation rather than EICF. Neumayr *et al*. (2002) observed a decline in exercise intensity over the course of a race in a case study on an ultraendurance cyclist, also suggesting glycogen depletion as a possible reason.

Whilst these factors highlight the exceptions to the heart rate and $\dot{V}O_2$ relationship, Åstrand *et al.*, (2003) note that they are observed less in highly trained athletes, and that in most conditions there is a remarkable consistency between the two variables. Heart rate is generally considered an accurate means of measuring exercise intensity in the vast majority of sports. Impellizzeri and co-workers (2002) advocate heart rate over power output as a measure of exercise intensity during prolonged cross-country mountain bike training and racing because of the close association with $\dot{V}O_2$. Jeukendrup and Van Diemen (1998)

Table 2.3: Summary of key findings of heart rate response during exercise

Study	Discipline	Subjects	Event	Summary of findings
Carpes *et al.* (2007)	XC	Highly trained. Case study	80 km	Reported HR_{mean} of 173 beats·min^{-1} which was 86% of HR_{max}. They concluded that the event characterised a high intensity that was maintained for a prolonged time during the race.
Costa and De-Oliveira (2008)	XC	Elite	XCO World Cup & Nat. Champs.	Reported an EI of 89.6 ± 1.6% for a National Championship (Nat. Champs.) race and 89.7 ± 2.6% for a World Cup race.
Coyle & Montain (1992)	Review article			Reported that CV drift is exacerbated by dehydration caused by exercising in hot humid environments, and can be reduced by fluid and carbohydrate replacement.
Gregory *et al.* (2007)	XC	Elite (n = 11)	15 km off-road time-trial	Found that HR was strongly related to terrain type, with a HR_{mean} of 174 ± 7 beats·min^{-1} and a HR_{min} not falling below 78.5% of HR_{peak}.
Impellizzeri *et al.* (2002)	XC	Elite (n = 5)	XCO	Reported a HR_{mean} of 171 ± 6 beats·min^{-1} which equated to 90% HR_{max} and 84% $\dot{V}O_{2max}$. They found the highest HR values (near maximal) were at the beginning of the race. Also reported 16%, 57% and 27% of time spent above LT*, between LT* and OBLA†, and above OBLA respectively.
Lee *et al.* (2002)	XC	International & national (n = 7)	Laboratory testing	Reported an EI of 90% of HR_{peak} for a 30 min laboratory-based time-trial.
Linderman *et al*. (2003)	XC	Trained (n = 6; 4 x ♂, 2 x ♀)	12 h race	Subjects lost nearly 4% of their body mass pre- to post-race and this was not accompanied by an increase in HR. Between hours 1 and 3 HR declined (157 vs. 141 beats·min^{-1}) then remained unchanged. Consideration: subjects relayed HR at a specific point location lap on the course rather than continuously.

Table 2.3 - continued

Study	Discipline	Subjects	Event	Summary of findings
Neumayr *et al.* (2004)	RC	Elite (n = 10)	Race across the Alps	Reported a HR_{mean} of 126 beats·min^{-1}. HR_{mean}/ HR_{max} ratio = 0.68 and suggested that a UE threshold is about 70% of HR_{max}. HR declined significantly during the event.
Stapelfeldt *et al.* (2004)	XC	Elite (n = 9)	XCO (15 races)	Found no relationship between HR and course profile. HR_{mean} of 177 ± 6 beats·min^{-1} which represented 91% of HR_{max} and corresponded to 104% of the HR at anaerobic threshold. The highest HR values were observed during the first lap of the race, with near maximal HRs at the start.
Wirnitzer and Kornexl (2008)	XC	Amateur (n = 7; 5 x ♂, 2 x ♀)	XCSR Trans Alp	Pooled data: Mean HR was 79% HR_{max}. 6% of race time was spent above LT4‡. They concluded that XCSR is physiologically very demanding, involving both the aerobic and anaerobic energy systems.

LT* = Lactate threshold (Impellizzeri *et al.* (2002) defined this as the exercise intensity that elicited a 1 mmol·L^{-1} increase in blood lactate concentration above resting values). **OBLA†** = Onset of blood lactate accumulation (Impellizzeri *et al.* (2002) defined this as the exercise intensity corresponding to a blood lactate concentration of 4 mmol·L^{-1}; **XCSR** = cross-country stage race; **LT4‡** = Lactate threshold equivalent to 4 mmol·L^{-1} as defined by Wirnitzer and Kornexl (2008). **EI** = exercise intensity.

highlight that it is important to determine whether one is interested in monitoring the output of muscular work per se or measuring whole-body stress. They go on to note that whilst power output may be a better indicator of exercise intensity, heart rate may be a more appropriate gauge of whole-body stress. For example, power output as a determinant of exercise intensity in mountain biking only measures the power deployed by the rider’s legs and does not include work done by the upper body. Furthermore, on a descent a rider may not be pedalling, and thus not registering any power output, yet may be producing considerable work due to the muscular contractions required for stabilisation and bike handling. Table 2.3 summarises the relevant ultraendurance and cross-country mountain bike studies that have employed heart rate as a measure of exercise intensity. The data suggest that XCO races require high rates of energy production characterised by intermittent effort (Impellizzeri *et al*., 2002; Stapelfeldt *et al*., 2004; Gregory *et al.*, 2007). However few data are available for ultraendurance mountain bike racing.

2.3.2 Overview of determining energy expenditure

Jeukendrup and Van Diemen (1998) suggest that the exercise intensity of a task is best described by the amount of energy expended per minute. Human energy expenditure can be determined by several methods, which are generally classified as either direct or indirect calorimetry. Direct calorimetry measures the amount of heat loss from the body, whereas indirect calorimetry measures the energy produced by the body (Ainslie *et al.*, 2003a). Whilst direct calorimetry is highly accurate and of great theoretical importance, subjects are restricted to the artificial laboratory environment in which the testing must take place (Ceesay *et al.*, 1989). For obvious reasons, this method of determining energy expenditure is impractical during free-ranging mountain biking. Indirect calorimetry however, is based on the premise that all energy expenditure in the human body ultimately depends upon the utilisation of oxygen. Given that a substrate-specific[7] amount of energy is liberated per litre of O_2 consumed, oxygen utilisation is an indirect means of calculating energy expenditure (McArdle*, et al.,* 2001; Ainslie *et al.*, 2003a). Therefore this method has the potential for determining energy expenditure during free-ranging activities, providing $\dot{V}O_2$ can be practicably measured.

2.3.2.1 Portable spirometry

Portable spirometry is a potentially viable indirect calorimetry method for evaluating energy expenditure in some free ranging activities. Portable spirometers, such as the Cosmed K4 b^2 (Cosmed, Rome, Italy), typically comprise a soft facemask and a breath-by-breath gas analysis system. They are worn in a chest harness and are relatively light weight (~600g). Metcalfe (2002) used portable spirometry to ascertain the energy cost of cross-country mountain bike time-trials under different suspension conditions. Whilst this provided useful data, the use of such equipment is not appropriate in full-duration ultraendurance

[7] Values for carbohydrate, fat and protein are 21.13, 19.62 and 20.2 kJ respectively (McArdle *et al*., 2001)

mountain bike racing due to the facemask interfering with the riders' ad libitum food and drink consumption, and the general discomfort of wearing the facemask for prolonged periods (Carpes *et al.*, 2007). This concurs with the view of the American College of Sports Medicine (ACSM) (2006) in that measuring $\dot{V}O_2$ in most non-laboratory situations is impractical.

2.3.2.2 Doubly-labelled water

Energy expenditure can also be measured using the doubly-labelled water technique. This currently appears to be the most widely accepted method for accuracy in free-ranging subjects (Spurr *et al.,* 1988; Ceesay *et al*., 1989; Hiilloskorpi *et al*., 1999; Ainslie *et al.*, 2003a). This process requires the individual to consume water containing a known quantity of the isotopes of hydrogen (^{2}H) and oxygen (^{18}O) which readily mixes with body water within a few hours. When the individual expends energy carbon dioxide and water are produced. ^{18}O is therefore lost from the body at a greater rate than ^{2}H because it is present in both carbon dioxide and water (Ainslie *et al*., 2003). This difference in the rate of loss of the two isotopes is indicative of the rate at which carbon dioxide is produced and can subsequently be used to estimate the energy that has been expended (Ainslie *et al*., 2003). This method can be made more accurate if the respiratory quotient (RQ) is determined, however if it is not known Westerterp (1999) reported the method may have an error of approximately 5%.

Using doubly-labelled water is costly both in terms of the materials required and the permanent equipment needed for analysis of the two isotopes (^{2}H and ^{18}O) (Spurr *et al.*, 1988). In addition it requires great expertise (Ceesay *et al*., 1989) and does not provide the temporal pattern of the intensity or the type of activity (Spurr *et al.*, 1988; Ainslie *et al.*, 2003a). Furthermore, as there is no practicable way of measuring RQ during mountain bike racing employing this method will potentially incur a 5% error (Westerterp, 1999).

2.3.2.3 Energy-cost tables

An alternative method for measuring energy expenditure is to maintain detailed activity diaries for the analysis period. Data are subsequently converted to energy expenditure values using energy-cost tables for the specific activities (Colombani *et al.*, 2002; Ainslie *et al.*, 2003a). As no specific energy-cost values exist for competitive mountain biking, this method would require validation.

2.3.2.4 Using heart rate to estimate energy expenditure during activity

The robust linear relationship between $\dot{V}O_2$ and heart rate provides an additional indirect method for measuring energy expenditure in a field setting (Hiilloskorpi *et al.*, 1999; Ainslie *et al.*, 2003a). Once this exact relationship for an individual has been established in the laboratory, exercise heart rate can then be used to estimate $\dot{V}O_2$ during free-ranging activities in which $\dot{V}O_2$ cannot normally be measured directly (McArdle *et al*., 2001). Due to the relative ease of recording and downloading heart rate data, this method has potential use during ultraendurance mountain biking (Laursen *et al.*, 2003a). Researchers are in agreement that there are two key precursors required in order to accurately predict energy expenditure from heart rate, and without which the data are spurious. These are: (i) the need to define a heart rate flex point (HR_{flex}) for each subject, and (ii) the need to obtain an individual calibration curve for each subject (Ceesay *et al*., 1989; Ainslie *et al.*, 2003a).

In essence, HR_{flex} is a heart rate threshold that separates sedentary activities from exercise (Hiilloskorpi *et al.,* 1999; Ainslie *et al.*, 2003a). Above HR_{flex} there is a strong relationship between heart rate and $\dot{V}O_2$, and below which there is no discernable correlation. Hiilloskorpi *et al.* (1999) reported that HR_{100} (HR = 100 beats·min^{-1}) is above HR_{flex} and as such is a useful marker to define the threshold. In addition a ceiling limit of 85% individual HR_{max} exists, above which the correlation between heart rate and $\dot{V}O_2$ is not valid (Hiilloskorpi *et al*., 1999). Within this bandwidth the ACSM (2006) note that a $\dot{V}O_2$ measurement for a given work rate is highly reproducible for a specific individual. It is therefore necessary to calibrate each individual within this workable bandwidth. Furthermore, it is important to calibrate during an activity mode that is specific to the exercise to which it will be applied (McArdle *et al*., 2001; Ainslie *et al.*, 2003a).

Energy expenditure is subsequently calculated from $\dot{V}O_2$ using the modified Weir (1949) formula. This assigns 20.2 kJ (4.83 kcal) per litre of oxygen consumed

(Ceesay *et al*., 1989; Kimber *et al.,* 2002; Ainslie *et al.*, 2003a; Laursen *et al*., 2003a) and is in accordance with research showing that 20.2 kJ of heat are liberated when a carbohydrate, fat and protein blend are burned in a bomb calorimeter (Cooke, 2004). This is based on a nonprotein respiratory quotient of 0.82, which assumes that a 40% carbohydrate and 60% fat mixture is being metabolised (McArdle *et al.,* 2001; Cooke, 2004). As there is no practical way of knowing what the individual substrate blend is during a mountain bike race, it may be argued that this is a significant and possibly erroneous assumption upon which to base subsequent calculations. However, as McArdle *et al.* (2001) and Cooke (2004) note, by using this midpoint nonprotein RQ (range: 0.707 – 1.00) to estimate energy expenditure from $\dot{V}O_2$, the greatest possible error would mathematically be less than 4% (minimum nonprotein RQ of 0.707 = 19.62 kJ (4.686kcal) / litre of O_2 consumed; maximum nonprotein RQ of 1.00 = 21.13 kJ (5.047 kcal) / litre of O_2 consumed).

From the above nonprotein RQ range it can be seen that despite large variations in the substrate composition, the energy value for oxygen varies only slightly and the margin of error is relatively small. Indeed, McArdle *et al.* (2001) note that it is from employing this method that the energy expenditure for most activities has been calculated.

Respiratory quotient assumes that the gaseous exchange measured in the lungs reflects that at the cell (McArdle *et al.*, 2001). This is valid during rest and steady-state submaximal exercise where there is little contribution from anaerobic metabolism. However during intermittent, intense exercise this assumption does not necessarily hold true. Under these circumstances respiratory exchange ratio (RER) should be used (even though it is calculated in exactly the same way as RQ). As the nature of ultraendurance cross-country mountain biking is intermittent, and the prerequisites for using RQ cannot be assumed, RER will be the term used in this thesis.

During exercise at an intensity of 50% $\dot{V}O_{2max}$, blood lactate production (and utilisation) is equivalent to glucose oxidation, and as exercise intensity increases, there is a concomitant increase in lactate production (Brooks *et al.*, 2005). For XCO mountain bike racing, Impellizzeri *et al.* (2002) found that participants exercised at an intensity equivalent to 84% $\dot{V}O_{2max}$. The intensity of cross-country racing may bring into question the efficacy of using $\dot{V}O_2$ as a predictor of energy expenditure due to the anaerobic contribution. However, this method still holds true as a measure of energy flux as approximately three quarters of the lactate produced is oxidised (primarily in the working muscle). When compared to aerobic metabolism, the net contribution of lactate accumulation to energy production is very small (Brooks *et al.*, 2005).

2.3.2.5 Using heart rate to estimate energy expenditure during ultraendurance cross-country mountain biking.

This method has great potential for XCM mountain biking as the literature on other ultraendurance races report mean heart rates to be in the workable bandwidth of the calibration curve (i.e. > 100 beats·min^{-1} and < 85% HR_{max}). However, during 24XCT the relay format is discontinuous in nature and as such individual heart rates can be expected to fall below HR_{flex} during the recovery intervals. During these rest periods it is not appropriate to use the HR and $\dot{V}O_2$ relationship to estimate energy expenditure as the relationship is spurious at such low heart rates (Hiilloskorpi *et al.,* 1999). During these periods an alternative method of estimating energy expenditure is required.

Resting energy expenditure (REE) is the sum of the metabolic processes needed to maintain normal body functions at rest (McArdle *et al.,* 2001). There are several indirect ways of estimating REE. Over 150 years ago the "surface law" of metabolism highlighted that metabolism is proportional to body surface area (BSA) (Cunningham, 1991). Body surface area in turn is proportional to stature and body mass and as such provides a convenient way of measuring REE (Cunningham, 1991; Cooke, 2004).

As early as 1919 Harris and Benedict produced a gender-specific formula based on measurements taken from 136 lean males and 103 lean females. The formulas, which have been used in large numbers of clinical trials, are based on body mass, stature, age and gender (Cunningham, 1980). Critics of the Harris and Benedict (1919) formula report that the data set is restricted to lean and normal weight adults, and is not applicable to obese populations, and thus not representative of contemporary Western societies in clinical situations. On a sample size of 498 Mifflin *et al.* (1990) reported the Harris and Benedict (1919) formula predicted REE within 5% of laboratory measured values. It was highlighted in Table 2.1 that cross-country mountain bikers are lean, and as such this formula would be appropriate for estimating REE during recovery intervals in a 24XCT race. The formula for males is shown below:

$$REE = 655 + 9.6(BM) + 1.85(st) - 4.68(age)$$ **Equation 1**

Where: BM = body mass, and st = stature

(Harris-Benedict, 1919)

2.3.2.6 Energy expenditure and XC mountain biking

At the time of writing, no validated energy cost ($kJ \cdot min^{-1}$) value exists for ultraendurance cross-country mountain bike *racing*. Metcalfe (2002) established a mean energy expenditure for cross-country mountain biking time-trials of 55.5 ± 9.0 $kJ \cdot min^{-1}$ (13.3 ± 2.1 $kcal \cdot min^{-1}$) using portable spirometry. In this study a Cosmed K4 b^2 was used, during which $\dot{V}O_2$ and RER were analysed per breath, and the appropriate RER-related energy cost per litre of oxygen was applied. Although Hausswirth *et al.* (1997) found the Cosmed K4 to be a valid device for measuring oxygen uptake, due to the aforementioned constraints of the equipment, the mean duration of the off-road time-trials was limited to 35.2 ± 3.9 min. As such care must be exercised if extrapolating these findings to ultraendurance race scenarios where durations of exercise are somewhat longer. Mastroianni *et al.* (2000) also employed the heart rate and $\dot{V}O_2$ relationship method for estimating energy expenditure and reported a value of 68.2 $kJ \cdot min^{-1}$ (16.3 $kcal \cdot min^{-1}$). However the riders were not trained cyclists, the route was not representative of a cross-country mountain bike course ("*the surface was generally firm, with scattered short sandy and rocky portions*" p. 480) and it was a time-trial format with a mean duration of only 32.5 minutes. Laursen *et al*. (2003a) attempted to estimate the energy expenditure during a 24 h four-man cross-country race (however, the data collection was subsequently reduced to 12 h due to inclement weather). The authors again employed the Weir (1949) formula to the average heart rate for the race period and reported an extrapolated estimated energy expenditure for the full event (24 h) of 33 639 ± 2488 kJ (8048 ± 594 kcal). It is not clear if they applied the formula during resting periods (when the individuals' heart rates may have fallen below their HR_{flex}). Colombani *et al.* (2002) attempted to estimate the energy expenditure during a mountain bike section of an ultraendurance adventure race using energy cost values (road cycling rather than specific mountain bike values must have been employed). They factored in the mass of the bicycle and the cumulative altitude climbed, and estimated the energy expenditure to be 48.3 $kJ \cdot min^{-1}$ (11.5 $kcal \cdot min^{-1}$). The mean duration of the mountain bike section was 4 h and the overall race was 18.6 h, as such the relatively low energy expenditure value may be due to riders employing pacing strategies.

2.3.2.7 Further factors influencing the energy cost of mountain biking

Resistive forces to forward movement influence energy expenditure during cycling. The road bicycle is a relatively efficient machine with more than 90% of the energy supplied by the rider being transferred to the rear wheel for forward motion (Abbott and Wilson, 1995; Rafoth, 1998; Jeukendrup *et al.*, 2000). The energy loss is due to the friction of moving parts (chain, bearings etc.) and rolling resistance (load, riding surface, and tyre construction, diameter and pressure). There are considerable distinctions between road cycling and mountain biking with regard to these factors. In addition to the obvious differences in terrain, the mass of a mountain bike is considerably greater than that of a road bicycle (~ 9.23 kg compared to 5.95 kg[8]), the tyre diameters are less, the tyre widths are greater (5.3 cm compared to < 2.5 cm), the tyre compound is softer with deeper tread patterns, and the tyre pressures are less (~ 2.7 bar compared to ~ 6.2 bar) (Carpes *et al.*, 2007). The major retarding force when cycling on flat terrain is air resistance. It becomes influential at speeds of 15 $km \cdot h^{-1}$ and increases as a squared function of speed thereafter (Kyle, 1986). The frontal surface area of a rider that is exposed to air molecules influences air resistance, and an aerodynamic riding position greatly reduces the retarding effect (Bassett *et al*., 1999). The design of the mountain bike and the technical demands of the terrain do not facilitate an aerodynamic riding position. Furthermore the stochastic nature of cross-country mountain biking would theoretically require more energy than road cycling in order to overcome inertia when accelerating and

[8] Manufacturer's claimed weight of 2010 Specialized S-Works Stumpjumper mountain bike and 2010 Specialized S-Works Tarmac road bike.

decelerating. However there is no empirical research to date to support this concept.

A further factor influencing the energy cost of riding a mountain bike is the type of suspension employed in the bicycle design. In theory suspending the rider should reduce the levels of physical stress encountered when impacting obstacles and make for a more expedient traverse of the terrain (Seifert *et al*., 1997). However, according to Abbott and Wilson (1995) and Richards (1999) a trade-off exists; the transfer of power generated by the rider to propel the bicycle is made less efficient with the addition of suspension. According to lay literature and testimonials from elite mountain bikers (personal communication) a major cause of the energy loss is due to the suspension unit itself absorbing energy as the rider pedals (Richards, 1999). Most suspension manufacturers claim that their suspension systems isolate rider-pedalling action from the suspension movement, however Richards (1999) argues that it can never be completely discarded.

Several studies have estimated the energy costs of using different designs of suspension, and they are summarised in Table 2.4. In these studies a change in $\dot{V}O_2$ was used to indicate a change in energy expenditure, and none of them were conducted under racing conditions (indeed some were conducted under simulated mountain bike conditions and some in the laboratory). Whilst this was appropriate for their respective research questions insofar as conditioning

Table 2.4: Summary of key findings on the effects of suspension on energy expenditure

Study	Discipline	Subjects	Event	Summary of findings
Berry *et al*. (2000)	XC	(n = 8♂ & 1 = ♀)	Laboratory-based, simulated task	Examined the effects of bicycle mass, riding speed, and grade on $\dot{V}O_2$ and reported no significant interaction among the variables. Considerations: the MTB was ridden on a treadmill with a 3.8 cm 'bump' affixed to the belt.
MacRae *et al.* (2000)	XC	Trained (n = 6)	Off-road time trial	Reported a significant lower average PO for front versus full suspension, though no difference were observed in $\dot{V}O_2$ or performance (time). Considerations: off-road time trial (TT) distance was 1.38km and was uphill; average time was 8 min.
Mastroianni *et al.* (2000)	XC	Recreational (n = 10)	Fire-road time-trials	Reported energy demand of off-road running and cycling are similar (EE for MTB = 16.3 kcal·min^{-1}). Subjects were recreational cyclists, and the course was not representative of a XC MTB race course (mean duration of the trials was 32.5 minutes). They also noted that variation in skill level may account for variability in descent speed.
Metcalfe (2002)	XC	Elite (n = 6)	Off-road time trial	Reported that the effects of front and rear suspension on $\dot{V}O_2$ was found to be significantly greater in the fully-suspended condition than the rigid condition. Reported a mean EE for XC mountain biking of 55.48 kJ·min^{-1}.
Neilens and LeJeune (2001)	XC	Competitive (n = 12)	Laboratory-based, simulated task	Reported no significant difference in $\dot{V}O_2$ when subjects rode a rigid, front-suspended, or fully suspended MTB. Considerations: the separate trials were performed in a laboratory with the bicycle mounted in a turbo trainer, and the subjects were required to remain seated at all times.

Table 2.4 - continued

Study	Discipline	Subjects	Event	Summary of findings
Neilens and LeJeune (2004)	Leading article	N/A	N/A	Suggested that any cyclist-generated power that is dissipated by suspension units is probably negligible on most terrains. They noted that the scarce studies on the topic, as well as the limitations in the conclusions that can be drawn from most of them, indicate that caution should be exercised when supporting the use of suspension bicycles on all course types and for all cyclists.
Seifert *et al.* (1997)	XC	Intermediate-elite (n = 12)	Simulated task	No significant differences for $\dot{V}O_2$ during rigid, front suspension and full suspension conditions. Considerations: course was on hard level ground comprising 45 5cm x 10cm wooded blocks to act as 'bumps'; terrain was predictable; riders wore Douglas bags on their backs.
Titlestad *et al.* (2006)	XC	Fit non-MTBers (n = 20)	Laboratory-based, simulated task	Found that $\dot{V}O_2$ was significantly lower in a non-suspension compared to a suspension condition when riding sub-maximally on 'bumps'. Considerations: bicycle was stationary jig; only rear wheel was subjected to 'bumps'; subjects remained seated.

confounding variables, their findings do not allow for an estimation of the energy cost of cross-country *racing*.

2.3.2.8 Efficacy of using heart rate to estimate energy expenditure and exercise intensity

Whilst using heart rate may not be as accurate as the use of doubly labelled water to estimate energy expenditure, Hiilloskorpi *et al*. (1999) state that most methods available for measuring energy expenditure in the field are impractical and expensive. Jeukendrup and Van Diemen (1998) concur with this view, and Padilla *et al.* (2008) note that since no measures of exercise intensity exist that are free from potential limitations, heart rate is acceptable for quantifying exercise intensity during cycle races. Furthermore, it also provides information on the temporal pattern of the activity not provided by the doubly labelled water technique (Ceesay *et al.,* 1989; Hiilloskorpi *et al.,* 1999; Ainslie *et al.*, 2003a).

A further practical consideration is that heart rate monitors are unobtrusive and do not interfere with performance. This is of great importance when field testing during a race as any interference with the riders' normal performances may affect their compliance and the authenticity of the data. A key philosophy of this thesis is for the findings to be readily applied by coaches and competitors, and heart rate information is a more accessible currency as opposed to other measurements. There is large support amongst researchers that heart rate is the most practical method for estimating energy expenditure in an applied setting (Ceesay *et al.*,1989; Spurr *et al.,* 1988; Hiilloskorpi *et al*., 1999; Mastroianni *et al.*, 2000; McArdle *et al.,* 2001; Brooks *et al*., 2005). Furthermore, it can also play a role in the avoidance of fatigue (Jeukendrup and Van Diemen, 1998).

2.4 Fatigue and ultraendurance mountain biking

Optimal performance during an endurance race is influenced by the ability to fully use endogenous fuel stores before the end of the competition without causing fatigue and a reduction in speed (Atkinson *et al.*, 2007a). The aetiology of fatigue during exercise generates much debate amongst researchers, with two main mechanisms being proposed: (i) a reductionist, linear approach where fatigue is viewed as a catastrophic failure of a sole peripheral system, and (ii) a complex systems model that integrates the physical peripheral systems and the brain (Abbiss and Laursen, 2005). Table 2.5 summarises the current models of fatigue.

The catastrophic model has by and large been discredited during self-paced work due to the absolute failure of a peripheral system rarely being observed. For example Noakes and St Clair Gibson (2004) note that prolonged exercise is terminated without evidence for substantive ATP (typical levels 5-8 $\mu mol\cdot g^{-1}$ muscle tissue) or energy depletion in the exercising muscles. Tucker *et al.* (2004) reported that during self-paced work in the heat (35ºC, 60% relative humidity and 10 $km\cdot h^{-1}$ windspeed) power output and integrated electromyographic (EMG) activity were reduced compared with exercise in a cool environment (15ºC, 60% relative humidity and 10 $km\cdot h^{-1}$ windspeed). They noted that the reduction

Table 2.5: Models of fatigue

Model	Summary	Selected references
Cardiovascular/ anaerobic model	Here fatigue is said to occur when the CV system fails to supply oxygen to, and remove waste products from, the exercising muscles.	Jeukendrup *et al.* (2000a); Lucia *et al*. (2000a).
Energy supply/ depletion model	This models purports that fatigue occurs when there is an inadequate supply of ATP from the metabolic pathways, or there is a depletion of endogenous substrates.	Green (1997); Hawley *et al.* (1997a).
Neuromuscular fatigue model	This model includes three theories: 1) central activation failure theory involves a reduction in the neural drive; 2) neuromuscular propagation failure theory purports the muscles have a reduced response to electrical stimuli; and 3) peripheral failure involves fatigue of the excitation-contraction mechanism.	Davis *et al.* (2000); Pinniger *et al*. (2000); Cairns *et al*. (2005).
Muscle trauma model	It is suggested that exercise-induced muscle trauma causes fatigue that is divided into three categories: 1) type I includes swelling and stiffness that is associated with delayed onset of muscle soreness; 2) type II refers to tearing of the muscle fibres; and 3) type III includes soreness and cramps that occur during or after exercise.	Hamlin and Quigley (2001).
Biomechanical model	This model is based on the premise that increased cycling efficiency is more economical and less stress is placed on other physiological mechanisms that may bring about fatigue.	Passfield and Doust (2000); Lucia *et al.* (2002a).

Table 2.5 - continued

Model	Summary	Selected references
Thermoregulatory model	The increase in core body temperature reduces exercise and places stress on other physiological mechanisms that may bring about fatigue.	Nielsen (1993).
Psychological/ motivational model	Fatigue is the result of a reduction in central drive brought about by lowered enthusiasm and motivation for the task. This may be influenced by afferent sensory feedback.	Kayser (1997).
Central governor model	The activation of skeletal muscle is controlled by a regulator (the location of which is unknown, but may be in the heart, brain or along the neuromuscular pathway). Its role is to down-regulate exercise intensity to prevent damage to vital organs.	Ulmer (1996); Noakes (2000a).
Complex systems model	Fatigue is the result of the complex, non-linear interaction of multiple peripheral physiological systems and the brain. Fatigue is a sensory perception, rather than a physical phenomenon.	Lambert *et al.* (2005)

Adapted from Abbiss and Laursen (2005)

occurred before there was any abnormal increase in rectal temperature (>40ºC), heart rate or perceived effort. In both of these examples conscious or unconscious measures were taken in order to avoid catastrophic failure, suggesting that rather than being a physical phenomenon, fatigue is a sensory perception (Lambert *et al.*, 2005).

Hill *et al.* (1924) hypothesised that during exercise it is the heart and not skeletal muscle that is at risk of ischaemia during exercise. Ulmer (1996) proposed that, in order to prevent myocardial ischaemia, a "central governor" modulates exercise intensity based on task anticipation and continuous feedback from somatosensory pathways. More recently other researchers have extended this to the complex-systems model (Noakes and St Clair Gibson, 2004; Lambert *et al*., 2005). This model is based on a feedback control loop in which the intensity of exercise is determined by efferent signals containing information on parameters such as motion, power output, and metabolism. Information in afferent signals, from mechanoreceptors and chemoreceptors, are then used to fine tune exercise intensity in order to optimise performance. Afferent feedback may also come from muscles and peripheral organs, and from endogenous reference signals such as training status, prior experience, muscle reserves, and metabolic rate. These data are processed in a "black box" algorithm and, in conjunction with projected finishing points, are taken into account when interpreting the afferent feedback and the subsequent calculation of efferent commands (Abbiss and Laursen, 2005). This enables a real-time optimum pacing strategy to be selected so that the task can be completed in the most efficient way whilst simultaneously maintaining internal homeostasis and a metabolic and physiological reserve capacity.

A key distinction between the linear models of fatigue and the complex systems model is that in the former metabolic changes occur as result of attempting to maintain an exercise intensity, whereas in the latter the exercise intensity is the result of changes in metabolic activity in order to maintain homeostasis of the physiological systems (Lambert *et al.*, 2005). In a complex model of fatigue, metabolic systems operate in an oscillatory fashion and are governed such that these systems never operate at maximal capacity or to failure.

A successful pacing strategy involves the optimum ‘within race distribution of work rate’ (Atkinson and Brunskill, 2000, p. 1450). At the start of an XCM race this would involve the central governor algorithm processing information about core temperature, metabolic reserve capacity, environmental conditions, race duration and other factors. Then once the race is underway, the algorithm makes adjustments in efferent power output control based on the metabolic changes that occur during exercise and any unexpected eventualities that may require adjustment to the pre-planned strategy. This ensures optimal exertion and avoids early exhaustion before the end of the race (Ulmer, 1996). For 24XCT races a successful pacing strategy would not only require within work-shift pacing, but also across work-shifts.

Teleoanticipation, or unconscious pacing, is central to the complex systems model and the knowledge of the finishing, or end point of the exercise is crucial. Antecedent factors and prior learning are also incorporated. This is supported by observations investigating fixed-distance tasks (‘closed-loop’ design) and time-to-exhaustion (‘open-loop’ design) tasks, and helps explain how end spurts in performance can occur.

Laursen *et al.* (2003b) reported a significant increase in performance on the second of two time-to-exhaustion trials for trained cyclists. They noted that the increased performance in the final test, despite no significant differences in $\dot{V}O_2$, RER, and heart rate was probably not caused by acute neuromuscular training adaptation, but suggested it was more likely due to the psychological effect associated with performing the “final test”. This is consistent with the conclusion of Hickey *et al*. (1992) who reported that the last of four time trials, for eight well-trained cyclists, were completed in a significantly faster time than the first three despite a lack of difference in measured physiological variables between trials. They could only attribute the performance difference to psychological factors, in that awareness of the “last task” somehow influenced performance time.

Callard *et al.* (2000) investigated neuromuscular efficiency in competitive cyclists during a 24 h continuous cycle ergometer test compared to continuous rest. To separate the roles of central and peripheral mechanisms they recorded changes in torque and EMG activity of the quadriceps during maximal isometric contraction every four hours. They reported a rise in EMG activity of the quadriceps and a concomitant increase in performance during the last hours of the test. They suggested that this occurrence may be due to an increase in the subjects' motivation and an increased ability to tolerate discomfort. They also suggested that it may have been due to the "clock" determining the activity and that the knowledge of the last hours somehow contributed to a central reactivation. This phenomenon may play a role in determining the work rate of competitors during the latter stages of an ultraendurance mountain bike race.

In addition to the physiological strains across multiple systems observed during XCM mountain biking, 24XCT competitors incur the stressors of circadian rhythm disruption, sleep disturbance and deprivation, and changes in illumination. These additional factors have the potential to adversely affect performance.

2.5 Circadian rhythms, sleep deprivation and light intensity

2.5.1 Circadian Rhythms

Many of the body's biological processes exhibit rhythmical changes over the course of a solar day. The neural and cellular machinery responsible for this is often referred to as the biological clock. The endogenous oscillation of this clock, if allowed to free-run, is slightly slower than 24 h and as such requires daily resetting by external cues (zeitgebers); a process known as entrainment (Vander, *et al.* 1998). The light-dark cycle of a 24 h solar day is the main environmental cue entraining the biological clock, and the temporal organisation of a biological function is referred to as a circadian rhythm.

The most robust circadian rhythm in humans is resting core temperature (Waterhouse *et al*., 2007), which is typically at its lowest (~36.6˚C) between 04:00 and 06:00 h and subsequently rises throughout the day (~37.4˚C) reaching a plateau between 14:00 to 20:00 h (Waterhouse *et al*., 2005; Atkinson *et al*., 2008). It should be noted that the trend is actually the observable product of circadian variation in core temperature and the effects of the sleep-wake cycle (Waterhouse *et al*., 2005). The robustness of this pattern has even been shown to persist after a warm-up, albeit in an attenuated form (Atkinson *et al*., 2005).

The presence of a rhythm despite exercise indicates there is an endogenous component to core temperature (Waterhouse *et al*., 2005). Physical performance tasks have been shown to mirror this rhythm, and the putative view amongst scientists is that body temperature plays a causal role (Reilly *et al*., 1997). Table 2.6 summarises research on variables relevant to 24XCT racing.

Furthermore, mood and cognitive functioning have also been reported to follow circadian patterns, with aspects such as alertness and reaction time generally being in phase with core temperature (Edwards *et al*., 2007).

Table 2.6: Summary of circadian effects on selected secondary performance related variables

Variable	Time of best performance	Study
Power output	Afternoon	Atkinson *et al.* (2005)
Torque during 24 h cycling	Evening	Callard *et al.* (2000)
Self-chosen work rate	Evening	Coldwells *et al.* (1993)
Strength	Afternoon / evening	Gifford (1987); Coldwells *et al.* (1993)
Joint flexibility	Afternoon / evening	Gifford (1987)
Anaerobic power	Evening	Hill and Smith (1991)
Rating of perceived exertion	Evening (lowest values)	Faria and Drummond (1982)
Explosive power	Afternoon	Reilly and Down (1992)
$\dot{V}O_{2max}$.	Stable	Reilly and Down (1982)
Simple reaction time	Early evening	Winget *et al*. (1985)

2.5.1.1 Motor spontaneous tempo

Cycling requires the rider to adopt a spontaneous cadence which involves fine temporal coordination for prolonged periods (Moussay *et al.,* 2002). This is based on an innate frequency and some researchers have proposed that it is regulated by an internal clock that acts as a time reference and emits periodic signals. When self-selected, the signals occur at a frequency specific to the individual and has been termed ‘motor spontaneous tempo’ (MST) (Moussay *et al.*, 2002). The average MST is approximately 600 ms and high intra-individual stability from day to day is commonly observed.

Cadence is widely accepted as an important factor affecting cycling performance (Faria *et al.*, 2005) and studies have found that the preferred cadence of trained cyclists during laboratory testing is typically between 90-100 revolutions per min (rpm) (Palmer *et al.*, 1999). Cadences in this range are associated with reduced muscle force per crank revolution (Faria *et al.*, 2005). Interestingly cadences of 90-100 rpm equate to a single crank revolution of between 667 and 600 ms which is in accordance with average MST observations. Moussay *et al.* (2002) investigated the circadian fluctuation of self-selected pedal rate and MST (determined via a finger-tapping test) for ten highly trained cyclists. The subjects exercised for 15 min at 50% of their W_{max} at 06:00, 10:00, 14:00, 18:00 and 22:00 h. They observed a circadian variation for oral temperature, heart rate and MST, and noted that cadence strongly correlated with oral temperature. Furthermore the authors found a strong positive correlation between MST and cadence leading them to suggest that a common brain oscillator may control them both. In order to avoid sleep deprivation, the researchers omitted testing at 02:00 h and thus the dynamics of MST during this period are unknown. In a separate study investigating preferred cadence and time-of-day Moussay *et al.* (2003) found that preferred pedal rate at 06:00 h was significantly lower than at 18:00 h. They suggested this might be due to the time to contract and relax a muscle which has been shown to decrease throughout the day (Martin *et al.*, 1999). Cadence is a function of power output, thus if it is subject to circadian variation, it would be logical to suggest that it may influence power output during a 24 h mountain bike race.

2.5.2 Sleep deprivation

A typical strategy during 24XCT racing requires team members to perform cyclical bouts of exercise (~90 mins) and recovery (~270 mins) throughout the 24 h period. Therefore the competitors' normal sleep patterns are disturbed and the quality of sleep is often reduced to just "napping". This additional stressor may have potentially deleterious affects on race performance (personal observations).

The human sleep-wake cycle is regulated by two interactive processes. One is the endogenous circadian rhythm of sleep. It is based on time of day and aims to promote sleep nocturnally and wakefulness diurnally. Conceptually the process provides a "pressure" to be awake, with an acrophase around early evening and a nadir in the early morning. The second process concerns the body's desire to maintain a homeostatic ratio between time spent awake and time spent asleep. In essence there is an increasing build up of "pressure" for sleep as a function of time spent awake, and a subsequent reduction during time spent asleep (Doran *et al.*, 2001; Van Dongen and Dinges, 2005). A typical 24 h sleep pattern is governed thus: after waking there is little circadian pressure for sleep and the homeostatic drive for sleep is also attenuated. Throughout the day the circadian influence on wakefulness increases whilst the homeostatic pressure for sleep accrues. These competing processes allow for a stable period of wakefulness throughout the day. At night, the circadian pressure for wakefulness is attenuated coupled with an accumulating homeostatic pressure for sleep. The net result is an increased pressure for sleep and under facilitative circumstances sleep occurs (Van Dongen and Dinges, 2005). Interestingly circadian variation is persistent during sleep deprivation vigilance tasks, with deterioration in overall performance being less during the day (when the circadian drive for sleep is attenuated) compared to night time (when both processes are exerting a pressure to sleep) (Doran *et al.,* 2001).

Despite considerable research, the effects of sleep deprivation are still unresolved (VanHelder and Radomski, 1989). Most research is concerned with chronic, accumulated sleep loss from lifestyles that involve shift work (Harma, 1995), sustained military operations (Young *et al.,* 1998; Nindl *et al.*, 2002), or transmeridian travel. However, these are not applicable to 24XCT mountain bike racing where sleep loss is ephemeral and has the potential to be punctuated with naps.

Generally, a deterioration of cognitive function is evident under conditions of sleep deprivation and there is an additive dose-response (VanHelder and

Radomski, 1989). However, it is a temporary condition and the effects are ameliorated by subsequent sleep (Van Dongen and Dinges, 2005). The state instability hypothesis posits that this deterioration is not a reduction in the ability to perform per se; rather there is an increase in performance variability (Doran *et al.*, 2001). Sleep deprivation results in three possible responses to a stimuli: (i) normal responses; (ii) lapses in response time; and (iii) response errors, with a reduction in frequency of the former as a function of sleep loss (Doran *et al.*, 2001). Doran and co-workers (2001) investigated the effects of 88 h sleep deprivation on vigilance tasks and reported that performance variability increases as a function of exposure to sleep deprivation, and that participants who had a 2 h "power nap" every 12 h showed less variability. This latter point highlights the recuperative potential of "napping". There is also evidence to suggest that short naps (as little at 10 min in duration) may provide some recuperative power without incurring any sleep inertia (Tietzel and Lack, 2001). Sleep inertia is the cognitive performance impairment experienced immediately after awakening and is increased under conditions of sleep loss and during the night.

Several studies have investigated the effects of sleep deprivation coupled with restricted energy intake on military field-training exercises (Young *et al.*, 1998; Nindl *et al.*, 2002). Findings show that even in extreme situations of sleep and energy deficit prolonged exercise capacity can be maintained and precision tasks including marksmanship and grenade throwing are not impaired.

Meney *et al.* (1998) investigated the effect of one night's sleep deprivation on temperature, mood state, muscle strength, self-chosen work rate, perceived exertion, and heart rate of eleven subjects while exercising for 5 min on a cycle ergometer. They reported that sleep deprivation had a significant detrimental effect on mood, but had no effect on the other variables. They also noted that there was considerable inter-individual variation in the responses to sleep deprivation. Borden *et al.* (1994) investigated aerobic and anaerobic contributions to exhaustive high intensity exercise after 25-30 h sleep deprivation. They reported no changes in total workload or the contributions of the energy systems following one night’s sleep deprivation. Callard *et al.* (2000) measured the maximal isometric torque of the leg extensor muscles every four hours during a 24 h cycle ergometry test at 50% maximal aerobic power compared with a no exercise condition. They reported that sleep deprivation did not appear to influence torque development. VanHelder and Radomski (1989) note that sleep deprivation of between 30 to 72 hours does not affect cardiorespiratory responses to exercise of varying intensity, or the anaerobic and muscular strength performance capability of individuals.

One performance component that does appear to be adversely affected by sleep deprivation is time to exhaustion. This may be due to elevated perceived exertion ratings commonly observed during sleep deprivation. Martin (1981) investigated exercise performance after 36 h of sleep deprivation compared with that after normal sleep. Eight subjects performed prolonged treadmill walking at 80% of

$\dot{V}O_{2max}$. The results showed that sleep deprivation reduced work time to exhaustion by an average of 11%. The author also noted that the subjects appeared to be "resistant" or "susceptible" to sleep loss insofar as four subjects showed less than a 5% change in performance after sleep loss, while the remaining four subjects had decrements ranging from 15 to 40%. Despite a lack of changes in heart rate or metabolic rate, Martin (1981) reported a significant increase in the RPE of subjects following sleep loss, concluding that the decreased tolerance of prolonged exercise following acute sleep deprivation may be due to psychological effects.

The adverse affects of sleep deprivation are mainly evident in the mental performance of subjects, and in those studies where a reduction in physical performance were observed the cause was largely due to an increased perception of exertion that was independent from the physical demands of the task. Although few studies have addressed how sleep deprivation may affect high-level performance, research indicates that active individuals are more tolerant of night-shift work (Harma, 1995) and sleep loss (Meney *et al.*, 1998) than those of average activity levels. Taken together it would appear that sleep deprivation would have no adverse physiological performance effects during 24XCT competition, more so as the race format is not open-ended and it allows for napping during the recovery periods. However, mood and perceived exertion may be adversely affected.

Sleep disturbance and time of day effects can also affect hormone secretion. Cortisol is a steroid hormone that is subject to such fluctuations and is relevant to 24XCT racing.

2.5.3 Cortisol

Cortisol is secreted from the adrenal cortex following stimulation from adrenocorticotrophic hormone (Lucía *et al.,* 2001b). It has multiple functions across multiple systems that enable the body to draw on its resources to deal with stressful situations (Åstrand *et al.*, 2003). Cortisol levels are subject to circadian variations with concentrations peaking in the early morning (3.37 to 42.28 nmol·L^{-1}; Salimetrics, 2010) and dropping to their lowest between midnight and 02:00-04:00 h (none detected to 9.91 nmol·L^{-1}; Åstrand *et al.*, 2003; Kudielka *et al*., 2007; Salimetrics, 2010). However cortisol concentrations can rise independently of circadian rhythm in response to stress (Van Cauter, 1990; Brooks *et al.*, 2005; Kudielka *et al*., 2007; Salimetrics, 2010). The primary pathway for cortisol secretion is through stimulation of the hypothalamus by the central nervous system as a result of exercise, hypoglycaemia, or the flight or fight response (Kraemer *et al*., 2008).

2.5.3.1 Cortisol and exercise

Pertinent to the line of inquiry of this thesis is that elevated cortisol levels are associated with the regulation of glucose and glycogen metabolism during exercise. In times of prolonged exercise and / or declining blood glucose concentrations, cortisol secretion accelerates the mobilization of fat for use as an energy substrate by promoting triglyceride breakdown in adipose tissue to glycerol and fatty acids (Turner *et al.*, 2010). It also promotes the breakdown of protein to amino acids (Loebel and Kraemer, 1998; Dickerson and Kemeny, 2004; Brooks *et al.*, 2005). The circulation then delivers these amino acids to the liver for the synthesis of glucose via gluconeogenesis.

Cortisol turnover in response to exercise is dependant on such factors as exercise intensity and duration, fitness level, nutritional status, and circadian rhythm (McArdle *et al.*, 2001). Generally, cortisol output increases with exercise stress and athletes involved in long duration exercise often display extremely high cortisol concentrations. Even during more moderate exercise, plasma cortisol concentrations rise as exercise duration increases (Turner *et al.*, 2010).

Cortisol also has permissive effects which allow the cardiovascular system to function effectively. Certain concentrations of cortisol are necessary for the catecholamines and other sympathetic products to induce vasoconstriction and tachycardia (Dickerson and Kemeny, 2004). It enhances the vasoconstriction of blood vessels in organs of lesser importance in the body’s general reaction to the stress, such as the skin, stomach, and intestines causing blood shunting to the skeletal muscles, liver, brain, heart and adrenals. Cortisol also enhances the performance of cardiac muscle cells and has a protective effect on cellular membranes by counteracting the harmful effects of a shortage of oxygen (Åstrand *et al.*, 2003).

Research focusing on highly trained endurance athletes indicates that a state of hypercortisolism occurs and that concentrations can remain elevated for as long as two hours following exercise. These post-exercise elevated concentrations have been associated with tissue recovery and repair (Turner *et al.*, 2010). Elevated basal cortisol concentrations have been reported after long-term training. They have been found to correlate with serum creatine kinase concentrations and have been associated with overtraining (Lucía *et al.,* 2001b; McArdle *et al.,* 2001; Samilios *et al.,* 2003, Turner *et al.,* 2010). Temporal monitoring of cortisol during an ultraendurance mountain bike race would therefore give an indication of how the individual is responding to the stress over the duration of the event.

2.5.4 Cognitive functioning

Mood states and subjective alertness are important during mountain bike performance since they may alter a rider's predisposition for strenuous physical efforts. With regard to circadian rhythms, mood and mental performance are influenced by three main factors; circadian rhythmicity, the quantity of recent sleep, and the amount of time spent awake (Reilly *et al.*, 1997). It is well documented that adrenaline and noradrenaline both exhibit a distinct circadian rhythm (Reilly *et al*., 1997) and increases are often linked with feelings of arousal and inversely related to feelings of fatigue. In general, positive mood states and alertness tend to be at their peak in the evening whereas fatigue and drowsiness peak in the early hours of the morning. It may be that mood states are influenced by circadian variations in cortisol and catecholamine concentrations. Elevated concentrations of noradrenaline in the central nervous system (CNS) are allied to increased mood states especially drive and aggression (Reilly *et al.,* 1997). Diurnal fluctuations in cortisol may influence mood states by increasing levels of alertness in the morning and help deal with stress later on in the day.

2.5.4.1 Mood and perceived exertion

A common tool used to assess the mood of athletes is the profile of mood states (POMS) questionnaire. The relevance of this is debatable as the questionnaire was originally devised for use in a clinical setting for individuals with psychological disorders (Shaw *et al.*, 2004). Watson *et al*. (1988) validated a twenty item questionnaire that assesses positive and negative affects in healthy individuals. A copy of the PANAS questionnaire can be found in Appendix B.

A rider's work rate during a 24 h mountain bike race is partly influenced by that of the competitors, but is largely self-selected. Coldwells *et al.* (1993) found that self-selected work rates on a cycle ergometer show circadian variations with peak work-rates being selected in the evening. Interestingly these increased work-rates were not accompanied by increases in ratings of perceived exertion

(RPE). They reported that the amplitude of the acrophase in work rate was approximately 7% of the 24 h mean, which is a considerable variation in output without a change in perceived exertion. Similarly Faria and Drummond (1982) found that during steady-state exercise subjects reported higher ratings of perceived exertion in the early morning than in the evening.

In addition, perceptions of time also vary throughout the day. Once again this appears to be linked to body temperature with overestimations of duration being observed in the evening when body temperature is greatest (Reilly *et al.*, 1997). These circadian variations in mood and perceived exertion may affect the performance of riders in a 24XCT race.

2.5.5 Effects of bright light

Twenty four hour team mountain bike racing requires the competitors to perform at various times throughout the light-dark cycle. Lloyd *et al.* (1977) reported a marked improvement in the performance of runners during a 24 h relay in line with the return of daylight following the nocturnal shift. Linderman *et al.* (2003) found similar results during a 12 h XCM race. Following a midnight start, they reported a steady reduction in race speed until 07:00 h after which there was a subsequent upturn. They noted that although not reflected in the group mean, some subjects reported a euphoric feeling at sunrise and indicated a temporary increase in vigour. Illumination has been shown to significantly decrease perceptions of fatigue and improve visual acuity and performance (Maas *et al.*, 1974). It has also been reported to relieve symptoms of depression by increasing vigour and mental performance (Portonen and Lonnquist, 1993). The combination of elevated mood and increased visual acuity following sunrise is a plausible reason for the observed increases in performance.

O'Brien and O'Connor (2000) note that in rats there are a number of small afferent nerves that project from the retina to the periaqueductal grey area of the brain. This area is important in nociception and opioid modulation of pain. An early study by Hosobuchi *et al.* (1977) reported that electrical stimulation of the periaqueductal grey induces analgesia in humans, and O'Brien and O'Connor (2000) suggest that if light stimulates the periaqueductal grey, then light may improve endurance performance by improving pain tolerance. Subjective intensity of muscle pain during moderate-to-intense exercise covaries as a function of power output (Cook *et al.*, 1997) and nociceptive afferent activity may inhibit either the ability to generate adequate central drive or the ability of muscle fibres to contract (Enoka and Stuart, 1992).

O'Brien and O'Connor (2000) examined the effect of exposure to three levels of light intensity (estimated as 1411, 2788, and 6434 lux) on average power output during a 20 min all-out bout of cycle ergometry. They found that the experimental manipulation had no statistically significant relationship on average power output. However they suggested that although not statistically significant the differences

(4.6 W between the highest and lowest light intensity) may have practical significance in races where small performance margins are important. Ohkuma *et al*. (2001) tested subjects on a 45 s Wingate test in 500 lux light levels following 90 min exposure to 50 lux and 500 lux light levels. They reported no differences in power outputs between the trials. The light intensity range they employed was relatively narrow, whereas during a 24 h period outdoor light intensities can vary from 0 lux (total darkness) to 30 000+ lux (direct sunlight). Notwithstanding this, it would appear that light intensity may affect mood states but has little ergogenic effect on cycle performance.

Taken together the literature suggests that any circadian variation in race speed during a 24XCT race will be the complex product of integrated rhythms of many variables. The literature suggests that rhythms associated with physiological functioning and power output will be in synchrony with core temperature, and that the psychological components linked to mountain bike performance will diminish as time awake increases. It is unclear whether any benefits resulting from a rise in body temperature could be negated by the effects of increasing time spent awake.

In addition to the demands placed on the physiological systems of the competitors during ultraendurance mountain bike racing, further limiting factors include substrate availability and the rate of energy provision.

2.6 Nutritional demands of mountain biking

2.6.1 Energy intake

A characteristic of the dietary patterns of ultraendurance athletes is a high energy intake, with values in excess of 250 $kJ \cdot kg^{-1} \cdot BM \cdot d^{-1}$ being commonplace (Jeukendrup *et al*., 2000a; Burke, 2001). When athletes require large daily intakes they will typically have to consume and digest the food during the competition (Brouns *et al.*, 1989a; Brouns *et al.*, 1989b; Linderman *et al*., 2003; Stewart and Stewart, 2007). Whilst the nature of some sports lend themselves to energy consumption during the event, mountain biking has inherent issues for the competitors to overcome. Both the intensity and the technical difficulty of mountain biking often make the physical act of feeding whilst racing somewhat challenging. This may subsequently compromise the amount of energy an ultraendurance cross-country competitor can consume ad libitum whilst racing (Cramp *et al*., 2004; Impellizzeri and Marcora, 2007). Table 2.7 summarises the key nutritional studies on mountain biking to date.

2.6.2 Carbohydrate

Carbohydrate (CHO) significantly contributes to meeting the energy demand when exercise lasts more than 90 min at an intensity of 60-85% $\dot{V}O_{2max}$ (Thomas *et al.*, 1991; Cramp *et al*., 2004), and provided there is an adequate supply, intense exercise can be maintained for prolonged periods (Laursen *et al.*, 2001).

Table 2.7: Summary of key studies on nutrition and cross-country mountain biking

Study	Discipline	Subjects	Event	Summary of findings
Cramp *et al*. (2004)	XC	Trained (n = 8)	Laboratory testing	Found that there was no significant difference in performance between ingesting 3.0 $g{\cdot}kg^{-1}$ BM and 1.0 $g{\cdot}kg^{-1}$ BM of CHO 3 h before a 93 min event. Considerations: simulated MTB course on an ergometer based on power data from a field test.
Knechtle *et al*. (2009a)	XC	Trained (n = 37)	120 km race	Reported that the cyclists drank 6500 mL of fluids during the race equating to 700 $mL{\cdot}h^{-1}$. They concluded that the riders suffered a significant decrease in body mass and skeletal muscle mass but no dehydration.
Laursen *et al.* (2003a)	XC	Highly trained (n = 4)	24 h race reduced to 12 h	Reported that riders' estimated EE and energy intake for the race were 33 639 and 15 246 kJ respectively, with CHO being consumed at a rate of $60{\cdot}gh^{-1}$. Riders' mean fluid intake was 6400 mL (~537 mL h^{-1}). Estimates were extrapolated from 12 h data.
Linderman *et al.* (2003)	XC	Trained (n = 6; 4 x ♂, 2 x ♀)	12 h race	Reported that riders consumed 6280-13 816 kJ (1550-3300 kcal) during the event with an average CHO consumption of 662 g. Riders consumed 4500-6400 mL of fluid and had 4% loss in BM.
Rose *et al.* (2008)	XC	Amateur (n = 18)	3-day stage race	Reported that the ad libitum consumption of fluids during the event was sufficient to maintain hydration status.
Wingo *et al.* (2004)	XC	(n = 12)	48 km simulated race	After glycerol pre-hydration, cyclists showed less dehydration and thirst sensation compared with those who had consumed water only. However, no performance benefit was demonstrated. Consideration: MTB individual time-trial.

BM = Body mass; **CHO** = carbohydrate; **MTB** = Mountain bike: **EE** = Energy expenditure.

There is only a finite store of endogenous carbohydrate in the human body. For a well-nourished 80 kg male this comprises approximately 400 g stored as muscle glycogen; 100 g stored as hepatic glycogen; and 2-3 g circulating as blood glucose. This equates to 8370 kJ (2000 kcal) stored in the form of carbohydrate (McArdle *et al.,* 2001; Noakes, 2000a). The majority of endogenous carbohydrate as an energy source comes from intramuscular glycogen, but under the regulation of phosphatase, hepatic glycogen is reconverted to glucose and released into the blood, providing a further extramuscular supply of glucose (McArdle *et al*., 2001). Figure 2.2 shows a schematic representation of substrate utilisation over time whist cycling at 70% $\dot{V}O_{2max}$.

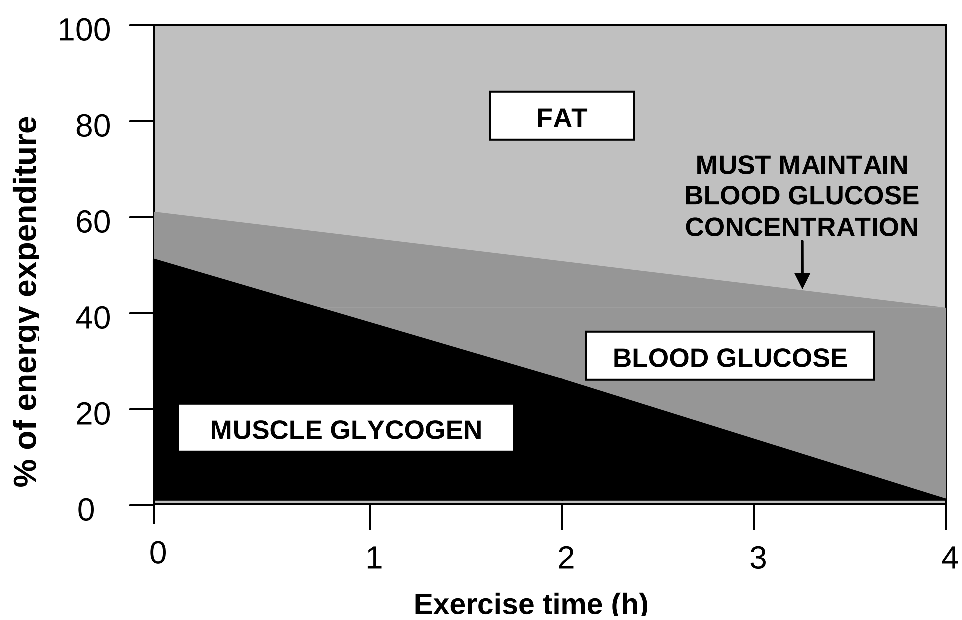


Figure 2.2: Energy sources during cycling at 70% $\dot{V}O_{2max}$. Adapted form Coyle and Montain (1992, p. 672).

It is well documented that exogenous carbohydrate supplementation maintains blood glucose concentrations (Anderson *et al.*, 1994; Fallowfield *et al.*, 1995; Rauch *et al.,* 1999; Laursen *et al.*, 2001) and that during exercise it delays both fatigue (Coggan and Coyle, 1987; Coggan and Swanson, 1992; Linderman *et al.*, 2003) and the perception of fatigue (Kreider *et al*., 1995; Utter *et al.*, 1999). In addition, performance increases when carbohydrates are consumed before and during exercise (Dennis *et al*, 1997; Manore and Thompson, 2000).

The nutritional goal for the ultraendurance athlete is to maximise initial glycogen stores and subsequently consume enough energy via the diet in the form of carbohydrate during the race in order to offset the expended energy (Laursen *et al.*, 2001). However, the amount of carbohydrate that is available for absorption into the bloodstream is limited by the rate of gastric emptying (GE). Gastric emptying is the process of nutrients passing from the stomach to the duodenum for absorption and is in turn affected by meal volume, meal temperature, particle size, fibre content and osmolality (Rehrer *et al.*, 1990a). In general, solid foodstuffs take longer to be mechanically and chemically broken down, and have slower emptying rates than liquid meals; high fibre content delays gastric emptying; and cooler drinks have faster emptying rates than warmer ones (Laursen *et al.*, 2001). Of particular relevance to 24XCT mountain biking, are the findings of Goo and co-workers (1987) who reported that gastric motility is subject to circadian variation. They reported a reduction in gastric emptying of 50% at 20:00 h compared with the same meal at 08:00 h.

In an attempt to consume enough calories while competing and to avoid abdominal distress, athletes often consume energy dense food, gels and liquids. A strategy widely adopted by mountain bikers, and indeed most endurance athletes, is to consume fluid-replacement beverages with added carbohydrate as a means of providing energy during exercise when the endogenous carbohydrate supply is inadequate (Coyle and Montain, 1992). This enables gastric volumes to be kept at a comfortable level and reduces the likelihood of dehydration (Brouns *et al.*, 1989a; Stewart and Stewart, 2007).

2.6.2.1 Carbohydrate intake pre-exercise

Ingesting only small volumes of carbohydrate prior to exercise does not supply sufficient glucose to sustain moderate-to-high-intensity prolonged exercise, especially if the initial glycogen stores are limited (Hawley and Burke, 1997; Cramp *et al*., 2004). Under these circumstances the athlete will not be able to maintain exercise at a constant intensity as exercise duration increases. Neufer *et al.* (1987) found that feeding immediately prior to, and during, exercise improved performance. They observed that the consumption of 200 g of carbohydrate four hours before exercise elicited the greatest increase. This concurs with the findings of Coyle and Montain (1992) who reported that a carbohydrate threshold of 200 g must be achieved for ergogenic benefits to be observed. In theory the 24XCT competitors would have the opportunity to consume sufficient carbohydrate during the recovery periods in between work-shifts, even if their during-exercise feeding is compromised due to the technical nature of the sport. Table 2.8 highlights the recommended carbohydrate intake guidelines pre and post competition in order to maximise performance.

Table 2.8: Carbohydrate (CHO) intake guidelines for pre, during and post competition (Adapted from Burke, 2001, p 269)

Nutritional goal	Recommended CHO intake	Study
Optimal muscle glycogen storage (pre and post)	7-12 $g \cdot kg^{-1} BM \cdot d^{-1}$	Costill *et al*. (1981).
	Training diet of 60-70% CHO	Walberg-Rankin (1995)
CHO intake during exercise > 1 h	0.5 -1.0 $g \cdot kg^{-1} \cdot h^{-1}$	ACSM (2006); Hawley *et al*. (1992); Jeukendrup *et al.* (2000).
Rapid post-race recovery in less than 8 h	1$g \cdot kg^{-1}$BM immediately, then repeated after 2 h.	Ivy *et al.* (1988).
	40-60g CHO consumed as soon as possible then repeated every hour for 5 h.	Walberg-Rankin (1995)

BM = body mass; **CHO** = Carbohydrate

2.6.2.2 Carbohydrate intake during exercise

In an experiment using intravenous glucose infusion to restore and maintain blood glucose availability late into exercise, Coggan and Coyle (1987) reported that a carbohydrate infusion of > 1 $g \cdot min^{-1}$ delayed fatigue by 45 minutes. Later studies by Jeukendrup and Jentjens (2000) and Couture *et al*. (2002) showed similar results for maximal oxidation rates for exogenous carbohydrates, reporting values of 1.0-1.5 $g \cdot min^{-1}$ and 1.0-1.2 $g \cdot min^{-1}$ respectively. Jeukendrup *et al.* (1999) reported that the ingestion rate of 35 $g \cdot h^{-1}$ during an exercise bout at

50% $\dot{V}O_{2max}$ reduced hepatic glucose production by approximately 60%, and an ingestion of 175 $g \cdot h^{-1}$ completely blocked hepatic glucose production.

The majority of the commercially available carbohydrate supplements comprise maltodextrin. However, research suggests that the type of carbohydrate, whether it is maltodextrin, glucose, sucrose or a combination, have a similar effect on blood glucose concentration, oxidation rates, and the ability to improve performance (Coyle and Montain, 1992). A benefit of maltodextrin is that it does not have a sweet taste which makes the beverage more palatable, potentially incurring less flavour fatigue over a prolonged period. Furthermore solid carbohydrates when taken in conjunction with water have a very similar response to a carbohydrate beverage, however the latter may cause a feeling of fullness and gastrointestinal distress whilst mountain biking (Coyle and Montain, 1992).

2.6.2.3 Nutritional practices

The timing of carbohydrate supplementation is of importance to the ultraendurance mountain biker. Whilst maintaining the aforementioned recommended rate of 1 $g \cdot min^{-1}$ throughout prolonged exercise has been shown to have a beneficial effect, so too has consuming carbohydrates only 30 minutes prior to expected fatigue. However, if left any later the ingested carbohydrate may not enter the bloodstream in time to be of any use (Coggan and Coyle, 1989). This approach may mean that a more concentrated form of carbohydrate may be needed to maintain the desired blood glucose concentration (Coyle and

Montain, 1992). Whilst this strategy would not be applicable to XCM mountain bikers, due to the continuous nature of the race, 24XCT competitors may be able to take advantage. They could potentially sacrifice a constant rate of exogenous carbohydrate supplementation throughout the work-shift in favour of a more concentrated intake during the latter stages of the shift, and thus reduce the frequency of feeding whist racing.

Linderman *et al.* (2003) examined the nutritional and hydration status of six mountain bikers competing in a 12 h race during which the riders consumed food and drink ad libitum. They reported an average carbohydrate consumption rate of 0.9 ± 0.1 $g \cdot min^{-1}$, which is similar to the maximal oxidation rates for exogenous carbohydrates as reported by Couture *et al*. (2002) and Jeukendrup and Jentjens (2000). Linderman *et al*. (2003) also reported no significant difference between pre and post-race blood glucose concentrations, concluding that the subjects were able to closely match carbohydrate supplementation with use. However, the researchers did not measure energy expenditure, so there may have been a disparity between overall energy intake and the total expenditure despite the favourable carbohydrate ingestion rates. This seems probable as other studies have reported an inability of subjects to match intake with expenditure. Colombani *et al*. (2002) noted that the energy intake of competitors in a 244 km adventure race (of which mountain biking was a discipline) corresponded to about 45% of the energy expenditure despite a mean carbohydrate intake of 1.0 $g \cdot min^{-1}$. This concurs with the research of Kimber *et al.* (2002) who reported optimal carbohydrate ingestion rates during an Ironman triathlon despite energy consumption contributing to only 40% of energy expenditure. Similarly White *et al.* (1984) reported an energy consumption of 54% of the energy expenditure for a cyclist during a 24 h cycling time-trial.

Aside from the logistical constraints of consuming food and drink whilst mountain biking, ultraendurance athletes in general, often encounter further issues when attempting to maintain an energy balance during the event. Reasons for this include inappropriate food choices; exercise-induced suppression of appetite; food and flavour fatigue; limited digestive capacity; poor nutritional knowledge; and the practical difficulty of consuming the required energy (Kreider, 1991; Burke, 2001; Stewart and Stewart, 2007).

Gastro-intestinal (GI) complaints are not uncommon among ultraendurance athletes. The symptoms include nausea, disorientation, stomach cramps, diarrhoea and vomiting (Jeukendrup *et al*., 2005). In a study on 158 runners competing in a 67 km event, Rehrer *et al*. (1992) found 14% to suffer from nausea and 2.5% reported vomiting. The grounds of the condition are unknown, but dehydration equivalent to 4-5% reduction in body mass has been linked to increased gastro-intestinal discomfort in marathon runners (Rehrer *et al.*, 1990). Other possible causes include gut ischemia due to blood shunting (Jeukendrup *et al*., 2005) and hyponatremia (Bowen *et al.*, 2006).

Athletes will often show confusion regarding when and what to eat prior to competition (Cramp *et al.*, 2004; Zalcman *et al.*, 2007). Cramp *et al.* (2004) purport that individual perceptions influence dietary intake insofar as some athletes may prefer a light meal beforehand due to pre-competition anxiety or fear of gastrointestinal discomfort, whereas other may prefer a large meal with a view to maximising energy availability for the event. Studies have reported that the types of food ultraendurance athletes consume vary widely. Gabel *et al.* (1995) found that a cohort of ultraendurance cyclists derived their exogenous carbohydrates from biscuits, sweetened drinks and confectionery. Garcia-Roves *et al.* (1998) reported fruit, milk, and orange juice as key sources for professional road cyclists. Whereas Clark *et al.* (1992) found that RAAM competitors relied mainly on carbohydrate drinks and bars. The variation and types of foodstuffs consumed by ultraendurance athletes are detailed in studies by Garcia-Roves *et al.* (1998) and Saris *et al.* (1989).

Linderman *et al.* (2003) reported that the subjects' individual energy consumption ranged considerably from 6280 and 13816 kJ (1500 and 3300 kcal) and that during the course of the event energy intake significantly decreased. During the first hour of the event subjects consumed 1888 ± 314 kJ (451 ± 75 kcal), then by the second hour it had decreased to 929 ± 247kJ (222 ± 59 kcal), by the sixth hour it had decreased further to 632 ± 339 kJ (151 ± 81 kcal), and during the final hour the subjects consumed only 105 ± 92 kJ (25 ± 22 kcal). It seems that even though carbohydrate intake rates during ultraendurance exercise can be near optimal, the absolute energy consumption fails to match expenditure, and that a large portion of the energy provision must come from endogenous stores. Stewart and Stewart (2007) found that few athletes are able to successfully self-regulate their energy consumption during ultraendurance exercise, which may account for the wide range of energy intakes observed in most studies.

Research investigating road cycling stage races have seen a shift from large amounts of carbohydrate (94 $g \cdot h^{-1}$) being consumed during the race (Saris *et al*., 1989) to lesser amounts (~25 $g \cdot h^{-1}$) in more recent years (Garcia-Roves *et al*., 1998). The reason for this is a change in contemporary race tactics, with a more aggressive style of racing now limiting the consumption of foodstuffs whilst competing. Interestingly both studies reported a similar total daily intake value despite the differing nutritional strategies. Garcia-Roves *et al*. (1998) noted that a greater reliance was placed on the pre and post-race meals. In light of the practical feeding issues during mountain biking, it would seem logical that this type of nutritional strategy would also be most appropriate for 24XCT mountain bikers.

2.6.3 Lipids

It is well documented that fat is the main substrate during exercise of low intensity and long duration (Stroud, 1998; McArdle *et al.*, 2001), and that fat also contributes a substantial amount during higher intensity ultraendurance events

(Kreider, 1991). Increased lipid oxidation is clearly of benefit to ultraendurance mountain bikers as it has a carbohydrate sparing effect during submaximal exercise (Laursen and Rhodes, 2001; Abbiss and Laursen, 2005). Energy from fat stores within the body are effectively endless and are not considered a limiting factor during ultraendurance mountain biking (Impellizzeri and Marcora, 2007) therefore fat metabolism was not the focus of this thesis.

2.6.4 Micronutrients

Zalcman *et al.* (2007) reported that vitamin and mineral losses can occur during exercise as a result of the greater sweat rates and urinary loss. These losses may be 1.5 to 3 times greater in ultraendurance athletes compared with non-athletes. However, they note that ultraendurance athletes generally have an adequate intake of vitamins and minerals resulting from their nutritional consumption during competition. In studies reporting estimated intakes of micronutrients, male cyclists consumed mean daily totals in excess of recommended dietary intake levels during training (van Erp-Baart *et al*., 1989; Jensen *et al.*, 1992). This is achieved mainly as a by-product of the large throughput of food in order to meet the high energy intake (Burke, 2001).

2.7 Hydration and exercise

2.7.1 Measuring hydration status

The criterion method for assessing hydration status is plasma osmolarity (P_{osm}), with a value of 280–290 mOsm·L^{-1} representing a state of euhydration (Seney, 1979). However it is not always suitable for field testing as the process is time consuming, and requires expensive equipment (Popowski *et al*., 2001). This method is unsuitable for assessing mountain bikers during a race primarily due to the process interfering with their normal free-ranging race activities. Under such circumstances, other proxy measures can provide an appropriate alternative, including changes in body mass and urinary indices (Shirreffs and Maughan, 1998; Armstrong, 2005).

2.7.1.1 Changes in body mass

Serial changes in pre and post-exercise body mass are frequently employed as estimate measures of acute body water loss in field settings (Linderman *et al.*, 2003; Wingo *et al.*, 2004; Rose and Peters, 2008; Knechtle *et al.*, 2009) and have been shown to be acceptable markers of body fluid status (Armstrong, 2005). If baseline body mass is considered to represent a state of euhydration, an acute decrease in body mass of more than 2% is considered an indicator of excessive dehydration (Sawka *et al.*, 2007; Rose and Peters, 2008). Changes in body mass have also been used to estimate sweat rates when factoring in exercise time, fluid consumed and urine volume and faecal matter voided (Cox *et al.,* 2002; Wingo *et al.,* 2004).

2.7.1.2 Urine osmolarity and specific gravity

Popowski *et al*. (2001) investigated the efficacy of urinary markers (urine specific gravity (U_{sg}) and urine osmolarity (U_{osm})) as an estimate of hydration status in field-based analysis. They compared the urinary indices to plasma osmolarity at various levels of acute dehydration. Plasma osmolality increased from 288 ± 4 $mOsm \cdot L^{-1}$ (euhydration) to 305 ± 4 $mOsm \cdot L^{-1}$ following dehydration (equivalent to 5% body mass loss) and U_{osm} increased from 325 ± 218 $mOsm \cdot L^{-1}$ to 728 ± 216 $mOsm \cdot L^{-1}$ respectively. They concluded that urinary measurements are sensitive to changes in hydration status during acute dehydration. However they observed a time lag behind P_{osm}, and purported that it may have been due to the subjects beginning the dehydration trials in a hypohydrated state thus increasing the biological time lag before the kidneys promote the conservation of extracellular fluid. Smith (2006) notes that U_{osm} can be used to classify the level of hydration status of amateur boxers using the following guidelines: well hydrated < 399 $mOsm \cdot kg^{-1}$; hydrated 400-799 $mOsm \cdot kg^{-1}$; dehydrated 800-1199 $mOsm \cdot kg^{-1}$ and severely dehydrated > 1200 $mOsm \cdot kg^{-1}$.

Popowski *et al*. (2001) also compared the use of reagent strips and refractometry as methods of urinary measurement and noted that, although reagent strips compared reasonably well with refractometry, the latter should be used for research or in situations where accuracy is required.

2.7.2 Hydration guidelines

It is well documented that prolonged exercise results in considerable metabolic heat production, and that the primary method of heat loss is via the evaporation of sweat (McArdle *et al*., 2001; Coyle and Montain, 1992; Linderman *et al*., 2003). In addition to exercise, sweat rate increases in response to elevations in ambient temperature and humidity (Sawka *et al*., 1985; McArdle *et al*., 2001). Dehydration, as a result of water loss through sweating, impairs the process of heat dissipation which can cause increases in core temperature and heart rate, and decreases in exercise performance, tolerance to work, $\dot{V}O_{2max}$, stroke volume and cognitive function (Coyle and Montain, 1992; Linderman *et al.,* 2003). Dehydration can be attenuated by ingesting fluids whilst exercising; and is often achieved in the form of a carbohydrate beverage as mentioned previously (Coyle and Montain, 1992).

The aims of fluid ingestion during exercise are to provide supplementary carbohydrate for fuel and to supply water to replace the losses incurred by sweating, whilst minimising gastrointestinal distress (Maughan and Noakes, 1991).

The rate of gastric emptying of a carbohydrate beverage is influenced by the volume of the fluid, and the carbohydrate concentration within the solution. Greater volumes promote gastric emptying, with optimum rates being between 1000 and 1200 $mL \cdot h^{-1}$ (Coyle and Montain, 1992). Tour de France cyclists have been reported to ingest approximately 1000 $mL \cdot h^{-1}$ (Saris *et al.*, 1989). Solutions containing up to 8-10% carbohydrate do not appear to affect gastric emptying rates, whereas greater concentrations have been shown to attenuate them (Noakes *et al.,* 1991; Coyle and Montain, 1992). In order to meet the aforementioned optimum exogenous carbohydrate intake of 1.0 $g \cdot min^{-1}$ without compromising gastric emptying, Coyle and Montain (1992) recommend consuming 1000 $mL \cdot h^{-1}$ of a 6%, 750 $mL \cdot h^{-1}$ of an 8%, or 600 $mL \cdot h^{-1}$ of a 10% carbohydrate solution. A weaker solution would require a gastric emptying rate in excess of 1000 $mL \cdot h^{-1}$, which would necessitate large volumes of fluid and higher rates of consumption and would likely result in gastrointestinal discomfort during exercise (Coyle and Montain, 1992). It is therefore theoretically possible to ingest the recommended 30-60 g of exogenous carbohydrate whilst simultaneously replacing up to 1000 mL of fluid per hour. The composition of the carbohydrate beverage can be altered based upon the relative importance of the need to supply fuel and water. This should be governed by the intensity and duration of the exercise, the ambient temperature and humidity of the environment, and the physiological characteristics of the athlete (Maughan and Noakes, 1991).

It is not uncommon during prolonged continuous exercise (50-80% $\dot{V}O_{2max}$) for sweat rates to exceed 1 $L \cdot h^{-1}$ (Coyle and Montain, 1992), with values of up to 3 $L \cdot h^{-1}$ having been reported in the literature (Horswill, 1998). This is equal to (and in the latter example, above) the optimum rate of fluid absorption, making some degree of dehydration a real and probable situation for ultraendurance competitors.

Coyle and Montain (1992) report that if fluid ingestion is sufficient to match the rate of sweating, increases in core temperature and heart rate are attenuated and a decline in stroke volume during exercise is avoided. Thus reducing the potential affect of cardiovascular drift. They go on to note that matching fluid replacement with sweat rate is more effective than ad libitum fluid replacement. Wingo *et al.* (2004) are in agreement, but note that in practice this is not always feasible, similarly Coutts *et al*. (2002) highlighted the practical difficulty of consuming fluids at an optimal rate for competitors during an Olympic-distance triathlon.

Noakes (2007) does not concur with the school of thought that replacing all of the water lost through sweating is more effective than ad libitum drinking, citing a lack of supporting evidence. Daries *et al*. (2000) reported that fluid ingestion at rates greater than ad libitum drinking did not improve 2 h running performances in a 25°C environment and had no measurable effects on plasma volume and osmolality. Rose and Peters (2008) noted that the fluid intake of competitors, as dictated by thirst, during a 3-day mountain bike stage race was associated with euhydration, despite intakes being at lower end of recommended amounts. Deschamps *et al.* (1989) reported that fluid replacement does not attenuate rises in core temperature or enhance performance when the exercise is performed at a relative high intensity that would normally result in fatigue within an hour. Noakes (2003) recommends that athletes do not drink as much as possible, rather they should drink according to the dictates of thirst and no more than 400-800 $mL \cdot h^{-1}$. In theory this could replace an average of 60% of water loss, even during sweat rates of up to 1000 $mL \cdot h^{-1}$. This is in accordance with the findings of Cheuvront and Haymes (2001) who reported that the thermoregulatory responses of female distance runners to exercise in hot, moderate and cool environments were well maintained when ad libitum fluid intakes replaced approximately 60-70% of sweat losses. The current American College of Sports Medicine (ACSM) guidelines recommend that endurance athletes should begin exercise in a euhydrated state and drink ad libitum within the range of 400 to 800 $mL \cdot h^{-1}$ (Sawka *et al.*, 2007). Furthermore, Noakes (2007) suggests that a reduced body mass as a result of ad libitum drinking may even have an ergogenic effect on weight-bearing sports such as running and uphill cycling where a reduced inert mass is an advantage.

Kempton *et al.* (2010) compared brain structure and function following body mass loss (1.6 ± 0.26%) via perspiration during a thermal-exercise condition compared with a control-exercise condition. They reported no change in cognitive performance as determined by an executive function task (Tower of London).

However the reduction in body mass was shown to correlate with lateral ventricle enlargement, and an increase in fronto-parietal blood-oxygen-level-dependent response was reported during the cognitive task. The researchers concluded that the participants required a greater level of neuronal activity following dehydration in order to maintain their cognitive performance. They suggested that there is an increased inefficiency of the brain following dehydration and that the participants may experience this as increased effort. Furthermore they suggested that prolonged reduced water intake may negatively affect executive functions including visuo-spatial processing and planning. These effects on cognitive processing therefore have the potential to effect ultraendurance mountain bike performance if the competitors become dehydrated.

The American College of Sports Medicine and the American Dietetic Association and Dieticians of Canada (2000) jointly recommend a fluid intake of 150-350 mL of an 8-10% carbohydrate beverage every 15-20 minutes. At the extremes, this recommendation equates to between 450 and 1400 $mL{\cdot}h^{-1}$. This is a considerable variation and reflects the difficulties of having a standard formula as it must take account individual variation, exercise intensity and environmental conditions. Not surprisingly, Sawka *et al.* (2007) recommends that fluid replacement protocols should be individualised, and Maughan and Noakes (1991) note that it in all practicality, the athlete must determine the most suitable hydration strategy by trial and error.

2.7.2.1 Hydration studies and mountain biking

Linderman *et al.* (2003) monitored the voluntary drinking of six (4 male, 2 female) cross-country mountain bikers during a 12 h race. Competitors consumed between 4500 and 6400 mL of fluid during the course of the event giving a mean rate of 460 ± 26 $mL \cdot h^{-1}$. Of interest is the highly variable temporal pattern of fluid ingestion with a mean consumption of 748 ± 211 mL in the first hour dropping significantly to 295 ± 74 mL by the fifth hour. The authors did not give an explanation for this, but noted that the subjects were dehydrated by the end of the race as determined by a reduction in body mass (~4%), however no change in haematocrit (42.4 – 44.1%) was observed. Although being able to maintain a near-optimal exogenous carbohydrate rate of 0.9 ± 0.1 $g \cdot min^{-1}$, the competitors were unable to balance fluid intake with sweat rate despite unrestricted access to fluid. This was not reflected in race speed, as following a nadir at the midpoint of the race (06:00-07:00 h), speed subsequently increased during the remaining five hours.

Rose and Peters (2008) investigated the ad libitum fluid intake of competitors during a 3-day mountain bike stage race in a relatively cool environment (6-21°C). Mean fluid intake rates for days 1 to 3 were 341, 408, and 551 $mL \cdot h^{-1}$ respectively. Relative mean decreases in body mass ranged from 0.99% to 2.02% over the three days, however urine specific gravity remained ≤1.025 indicating a euhydrated state. They concluded that ad libitum fluid intake during the event maintained an adequate hydration status. This also demonstrates the inconsistencies between the two methods of hydration assessment, and that changes in body mass do not account for fluid compartment shifts to protect plasma osmolarity. Schenk *et al.* (2010) investigated the drinking behaviour of participants during an 8-day mountain bike stage race. They reported that mean fluid intake ranged between 494 and 754 $mL·h^{-1}$ and found that fluid intake correlated with air temperature. They concluded that ad libitum fluid consumption during competition was spontaneously adjusted to the varying weather conditions during the race. They also found an inverse linear relationship between hourly fluid intake and post-race serum sodium concentrations (range 137.2 to 148.5 $mmol·L^{-1}$) suggesting that the riders were under drinking. In a similar study, Wirnitzer and Kornexl (2008) reported a fluid intake of 4.24 ± 1.1 L (approximately 580 $mL·h^{-1}$) and no significant difference with regard to body mass, concluding that significant dehydration did not occur. Rose *et al*. (2007) reviewed questionnaires from 412 participants (13% elite; 73% serious amateur; 14% amateur/other) in a 3-day mountain bike race, regarding their normal fluid intake practices. They reported that 70% of the competitors based their fluid intake on personal past experiences, with only 43% being aware of sport-specific guidelines. Fifty-three per cent of the male respondents reported a routine intake of ≥ 750 ml per hour during endurance rides. Despite this ad-hoc approach to hydration, out of the whole survey only 2% reported having ever received medical care for dehydration after previous mountain bike rides, indicating that ad libitum drinking may be a sufficient means of hydration.

Wingo and co-workers (2004) examined the effects of a pre-exercise glycerol hydration strategy compared to a water only hydration strategy on a simulated (off-road time-trial) mountain bike race in the heat. Subjects following the glycerol protocol showed less dehydration and reported a reduced sensation of thirst compared to the water-only group, however there were no significant differences in cardiovascular and thermoregulatory responses, and performance was unaffected. Mitchell and Currell (2009) assessed the hydration status of elite mountain bike riders during a training camp. They compared measures of urine osmolality on three consecutive mornings and reported no significant difference between the three days (521 ± 156; 550 ± 107; and 588 ± 115 $mOsmol \cdot kg^{-1} H_20$ respectively). They also recorded fluid intake for the first two days and reported no significant difference (Day 1: 4.2 ± 0.7 L; Day 2: 4.6 ± 1.7 L). These studies suggest that ad libitum drinking does not appear to have a negative affect on mountain bike performance and that there may be a volume of fluid that can be lost before performance is affected.

Taken together the above studies suggest that ultraendurance competitors will not be able to match energy intake to energy expenditure and that ad libitum fluid intake will not replace all of the body water through sweat. However, at the time of writing scant information is available regarding the nutritional dynamics during 24XCT mountain bike racing.

2.8 Summary of literature

From the above review of literature two aspects are clearly evident. Firstly, there are a myriad of factors that potentially affect competitive ultraendurance mountain bike performance. Secondly, empirical evidence addressing this subject is scarce. It is therefore the purpose of the subsequent studies in this thesis to address these issues and investigate the physiological and bioenergetics of ultraendurance mountain bike competition. The first direction of focus is on XCM racing and the second is on 24XCT competition.

CHAPTER THREE

General methods

This chapter details the methods that were common to two or more of the studies in this thesis. Additional, specific methods are described in the relevant chapters.

3.1 Participant information

Prior to each test, participants were provided with written information detailing the purpose of the research, how it was to be undertaken and what was required of them. Approval for all testing was obtained from the University of Central Lancashire ethics committee along with written informed consent from each participant. Prior to testing, participants completed a Physical Activity and Readiness Questionnaire (PARQ) and a University of Central Lancashire Sports Science Laboratory Health-screening Questionnaire (Appendix D), and were fully familiarised with all testing procedures. Participants abstained from strenuous exercise 24 h prior to their testing sessions and arrived at the laboratory two hours postprandial.

3.2 Instrumentation

3.2.1 Anthropometry

Body mass was determined to the nearest 0.01 kg using balance beam scales (Avery Type 3306, Avery Ltd, Birmingham, UK). Measurements were taken with participants wearing only their cycling shorts. Stature was measured to the nearest 0.001 m using a stadiometer (Harpenden, Avery Ltd, Birmingham, UK). Participants stood erect, arms relaxed, with their back, heels, buttocks and cranium touching the back of the stadiometer. The head was oriented in the Frankfurt plane, and the participant was instructed to take a full breath and hold it. The head beam was lowered until it firmly touched the participant’s vertex and a measurement was taken (Duquet and Carter, 2005).

Skinfold measurements were taken from seven sites (pectoral, mid-axillary, abdominal, suprailium, subscapular, triceps and mid-thigh) using skinfold callipers (Harpenden, Body Care, Kenilworth, UK). The seven site method was chosen as it includes arm, leg and trunk measurements and improves the detection of fat patterning compared with those employing fewer sites (Hawes and Martin, 2001). The location of the skinfold sites were determined using the methods detailed by Hawes and Martin (2005) and Heyward (1991) as detailed in Appendix D. Each site was marked with a non-permanent felt pen in order to ensure consistency of measurement. Measurements were taken from the right-hand side of the body when the participants were standing erect and relaxed. A skinfold was raised between the thumb and forefinger and the underlying muscle tissue was left undisturbed. The pressure plates of the calliper were held in place for 2 s perpendicular to the skinfold. Measurements were taken in triplicate and the median value recorded. The measurements were taken sequentially around the sites, thus allowing time for the adipose tissue to restore to its uncompressed state. Body density was predicted using the Jackson and Pollock (1978) equation based on the sum of the seven skinfolds. They reported that the equation was accurate and valid for use with adult men varying in age and body density.

$$\text{Body density} = 1.112 - 0.00043499(\Sigma 7) + 0.00000055(\Sigma 7)^2 - 0.00028826(\text{age})$$

Equation 2

Where: $\Sigma 7$ = sum of skinfolds (mm)

This was then converted to percent body fat using the following equation:

$$\%\text{Fat} = \left[\left(\frac{4.95}{\text{Body density}}\right) - 4.5\right] \times 100$$

Equation 3

(Siri, 1956)

In order to avoid the assumptions inherent in the calculations used to estimate body fat percentage from skinfolds, some researchers have reported solely the sum of skinfolds (Lee *et al.*, 2002). This approach is useful when comparing against normative values (Hawes and Martin, 2001). However as the vast majority of mountain bike XC research has reported percentage body fat (Table 2.1) the methods in this thesis are analogous and body fat percentage was estimated from the sum of skinfolds. This approach enabled comparisons between to be made with previous research.

Muscle mass was estimated using the equation proposed by Martin *et al.* (1990). To do this a further skinfold measurement was taken at the midcalf, and girth measurements were taken at the midcalf and at the widest point on the forearm.

$$MM = St\ (0.0553CTG2 + 0.0987FG2 + 0.0331CCG2) - 2445$$

Equation 4

Where: St = stature (cm); CTG = corrected thigh girth (cm); FG = forearm girth (cm); and CCG = corrected calf girth (cm).

3.2.1.1 Reliability data for skinfold measurements

Tester reliability was determined prior to commencing the investigations. Ten skinfold measurements were taken at the seven sites on a single participant. The mean, standard deviation (S.D.) and coefficient of variation (CoV) for the measurements are presented overleaf:

Table 3.1: Reliability data for skin-fold measurements

Measurement (mm)	Mean	S.D.	CoV (%)
Pectoral	9.8	0.09	0.94
Axilla	14.6	0.12	0.79
Abdominal	13.4	0.12	0.89
Supraillium	14.4	0.10	0.72
Triceps	8.7	0.07	0.85
Subscapular	11.1	0.09	0.85
Mid thigh	7.8	0.10	1.28

The small coefficient of variance indicates little variation of measurement of the tester. Coefficient of variation[9] was calculated using the following equation:

$$CoV = \frac{S.D. \times 100}{mean} \qquad \textbf{Equation 5}$$

(Fallowfield *et al.*, 2005)

3.2.2 Intra-aural temperature

Intra-aural temperature was measured using a Radiant TH809 Infrared Tympanic Thermometer (Radiant Innovation Inc., Taiwan). This method uses a thermopile sensor to measure temperature near to the tympanum, with a measurement temperature range of 34 to 42.2°C and a manufacturer's reported accuracy of 0.06°C. This method has been shown to be a valid and reliable measure of body

[9] Low values (<2%) indicate measurement competency provided no bias or systematic measurement error in present (Fallowfield *et al.*, 2005)

temperature (Sato *et al*., 1996; Smith and Fehling, 1996; Newsham *et al.*, 2002; Edwards *et al.*, 2007).

3.2.3 Salivary cortisol

Salivary cortisol levels are reliable estimates of serum cortisol levels (Hiramatsu, 1981). Salimetrics (2010) report a high correlation (*r* = 0.91) between the Salimetrics High Sensitivity Salivary Cortisol Enzyme Immunoassay and the Diagnostic Systems Laboratories Serum Cortisol Enzyme Immunoassay. The minimal concentration the saliva enzyme immunoassay can distinguish is less than 0.003 $\mu g \cdot dL^{-1}$ (0.08 $nmol \cdot L^{-1}$) (Salimetrics, 2010). Vining and McGinley (1987) note that salivary flow rate and the presence of salivary enzymes do not affect salivary cortisol levels.

Salivary cortisol samples were collected using Salivette cotton wool swabs (Sarstedt AG and Co., Nümbrecht, Germany). Ten minutes prior to collection, the participants rinsed their mouths with water. Each participant was instructed to place the cotton wool swab under the tongue for 5 min. The swab was then returned to the Salivette receptacle and immediately frozen (-20^{o}C). Later the samples were thawed, centrifuged at 1500 x g (@ 3000 rpm) for 15 min and analysed using a competitive immunoassay (Item No. 1-3002, Salimetrics Euorope Ltd., Suffolk, U.K.). The test principle is detailed in Appendix E.

3.2.4 Heart rate telemetry

Heart rate data were recorded during the field analysis studies at 15 s intervals using Polar X-Trainer monitors (Polar Electro, Oy, Finland). Polar coded chest transmitters were placed inferiorly to the xiphosternal joint. The corresponding watch-receiver was worn on the right wrist of each subject. The recorded data were analysed using Polar Training Advisor software (version 1.05.016, Polar Electro, Oy, Finland).

3.2.5 Predicted maximum heart rate

Predicted maximum heart rates were calculated using the equation developed by Tanaka *et al.* (2001). This equation has been validated against controlled laboratory measures (Tanaka *et al.*, 2001):

$$HR_{max} \text{ (predicted)} = 208 - 0.7 \times \text{age} \qquad \textbf{Equation 6}$$

3.2.6 Blood pressure

Blood pressure was measured using a Boso Medicus Prestige sphygmomanometer (Bosch and Sohn GmbH. Co., Jungingen, Germany). The unit incorporates an oscillometric measuring principle and clinical tests have reported maximum deviations of cuff pressure and pulse rate to be $\pm$ 3 mmHg and ± 5% respectively (Bosch and Sohn GmbH. Co., 2008). Measurements were taken when the participant was in a seated relaxed position. The participant was instructed to remain completely still. The cuff was placed over the brachial artery on the left arm in accordance with the manufacturer's guidelines and was inflated to supra-systolic pressure. Pressure was automatically released from the cuff and systolic and diastolic pressures were recorded.

3.2.7 Blood lactate

In order to measure blood lactate a 5 µL finger-prick blood sample was taken from the participant's left index finger and analysed using a Lactate Pro analyser (Lactate Pro, Arkray Inc, Kyoto, Japan). This method involves colorimetry with an enzymatic reaction and has been shown to be highly accurate for monitoring lactate concentrations (Pyne *et al.*, 2000; Saunders *et al*., 2005). To ensure the participant's finger was clear of any debris, it was first cleaned using a Steret alcohol wipe (Southern Syringe Ltd., Manchester, UK). The finger was then punctured using a BD Microtainer lancet (Becton, Dickinson & Co., Plymouth, UK) and the first drop of blood wiped off to ensure any remaining alcohol did not affect the sample. Capillary blood was then applied to a reagent strip (Lactate Pro Test Strip, Arkray, Kyoto, Japan) and measured in $mmol \cdot L^{-1}$. Prior to testing, the Lactate Pro was calibrated in accordance with the manufacturer's guidelines.

3.2.8 Cycle ergometry

In order to measure peak oxygen uptake participants performed a continuous, progressive incremental test to exhaustion on an electromagnetically braked cycle ergometer (Lode Excalibur, Groningen, The Netherlands). The ergometer was adjusted to replicate the dimensions of the participant's own mountain bike and was fitted with a racing saddle and the participant's own pedal system.

3.2.9 Expired gas collection and analysis

Expired gas was continuously recorded using an online breath-by-breath gas analysis system (MetaLyzer 3B, Cortex, Leipzig, Germany). The gas analysers were calibrated before each test by sampling a 15% O_2, 5% CO_2 certified gas mixture (BOC, Guildford, UK) and ambient air. The ventilometer was calibrated using a 3 L syringe in accordance with the manufacturer's instructions. The system was calibrated for atmospheric pressure which was determined by a laboratory barometer (F. Darton and Co. Ltd., Watford, England). A standard face mask (Cortex, Leipzig, Germany) was fitted over the participant's nose and mouth and securely held in place with an adult head cap (Cortex, Leipzig, Germany). Before the flow sensor and sample line were fitted, the mask was checked for leaks by placing a hand over the exhalation port and asking the participant to gently exhale. If a leak was present the head cap was adjusted accordingly. The MetaLyzer 3B determines oxygen concentration by an electrochemical cell (manufacturer's reported accuracy of ± 0.1% volume), carbon dioxide by neutral density infrared (manufacturer's reported accuracy of ± 0.1% volume) and flow by digital turbine (manufacturer's reported accuracy of ± 2%). Meyer *et al.* (2001) reported the MetaLyzer 3B to be a reliable instrument for exercise testing in sports research. Heart rate was recorded using short-range telemetry and data were transmitted to a heart rate receiver housed in the body of the MetaLyzer 3B. Data were downloaded using MetaSoft CPX software (Cortex, Leipzig, Germany) and exported to an Excel spreadsheet for analysis.

3.2.10 Rating of perceived exertion

The Rating of Perceived Exertion scale developed by Borg (1978) was used to assess the participants' perceived exertion. This method is effective at gauging fatigue during graded exercise (ACSM, 2006), and Stoudemire *et al.* (1996) found it to be valid for steady state exercise corresponding to blood lactate concentrations. Chen *et al*. (2002) conducted a meta-analysis on 437 studies of validity of the scale and found that the greatest validity was when the 15-point RPE scale was used. The 15 point scale ranges from 6 (very, very light) to 20 (very, very hard). The scale was used for all tests, and participants were familiarised with the scale beforehand.

3.3 Exercise protocol

3.3.1 Continuous peak oxygen uptake test

Prior to starting the maximal incremental test, the participants performed a seven minute warm-up consisting of five minutes at 80 W followed by two minutes at 25 W. They then immediately commenced the maximal incremental test with a starting intensity of 80 W. Resistance was increased by 30 W every two minutes (Cooke, 2004). Similar protocols have been employed in previous research (Green *et al.*, 2003; Prins *et al.*, 2007). The participants were required to maintain a pedalling cadence of ~ 90 rpm throughout the duration of the test (Palmer *et al.* (1999) reported that the preferred cadence of trained cyclists during laboratory testing is typically between 90-100 rpm). Expired gases were collected throughout the test, and averaged over 30 s. At the end of each stage, rating of perceived exertion and blood lactate concentrations were recorded. The British Association of Sport and Exercise Sciences (BASES) recommendations for the termination of a maximal oxygen uptake test are i) an increase in $\dot{V}O_2$ of ≤ 2 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$a plateau, ii) a final RER > 1.15, iii) a final heart rate within 10 $beats{\cdot}min^{-1}$ of predicted maximum, iv) volitional exhaustion, and v) a RPE rating of 19 or 20 (Cooke, 2004). As these recommendations were not fully met, the highest aerobic power was expressed as $\dot{V}O_{2peak}$ not $\dot{V}O_{2max}$.

3.3.1.1 Peak power output

Peak power output was measured in conjunction with the maximal incremental test. If the final work rate was not completed peak power output (PPO) was calculated using the formula below (Kuipers *et al*., 1985; Baron, 2001):

$$PPO = W_E + (30W / t \times t_E), \qquad \textbf{Equation 7}$$

Where W_E is the PO of the last completed workload, t is the workload duration in seconds, and t_E is the duration of the final uncompleted workload.

3.3.1.2 Calibration of participants for $\dot{V}O_2$ estimation

Data from the peak oxygen uptake tests were also used to individually calibrate the participants. Only data in excess of HR_{100} and below 85% HR_{max} for each individual were included in the regression analysis for each calibration curve (sample data in Appendix F). As calibration is dependent on individual fitness-status (McArdle *et al.*, 2001; Kimber *et al.*, 2002), all participants were calibrated within three weeks of the race. Correlation coefficients need to be of at least 0.7 for a regression equation to be of predictive value (Fallowfield *et al.,* 2005). Only those participants with a correlation value ≥ 0.7 for $\dot{V}O_{2peak}$ and HR were calibrated. Energy expenditure for each participant was subsequently estimated by assigning 20.2 kJ to every litre of oxygen consumed (Weir, 1949).

3.3.1.3 Blood lactate thresholds

In the last 15 s of each workload during the peak oxygen uptake test, a 5 µL finger-prick blood sample was taken from the participant's left index finger and analysed for lactate using the method described previously. Blood lactate and heart rate values were plotted to ascertain a blood lactate - heart rate curve for each participant. From the blood lactate - heart rate curves the lactate threshold (LT) and onset of blood lactate accumulation (OBLA) for each participant were calculated. There are several ways of determining these thresholds (McArdle *et al*., 2001). The method used by Impellizzeri *et al*. (2002) was employed in the present studies as they investigated XCO mountain bikers and the analogous protocol would allow for comparisons to be made. Lactate threshold was defined as the intensity of exercise that caused an increase in blood lactate concentrations of 1 $mmol \cdot L^{-1}$ above those observed during exercise at 40-60% $\dot{V}O_{2peak}$. Onset of blood lactate accumulation was defined as the intensity of exercise corresponding to a blood lactate level of 4 $mmol \cdot L^{-1}$ (Impellizzeri *et al*., 2002). Interpolation from a visual plot of the data by the author was used to determine the thresholds. This was then confirmed by an independent experienced researcher. These data were then used to define exercise intensity zones. Several methods exist for this, and again the method used by Impellizzeri and co-workers (2002) was employed for the reason stated above. The intensity zones were based on corresponding heart rates and defined as:

1) EASY$_{ZONE}$: the exercise intensity below LT;

2) MODERATE$_{ZONE}$: the exercise intensity above LT but below OBLA; and

3) HARD$_{ZONE}$: the intensity above OBLA

3.4 Course profile

Global positioning system (GPS) data were collected from a singe participant on each course using a FRWD F500 receiver (FRWD Technologies, Oulu, Finland) and downloaded using FRWD PRO Replayer (Build 70, Version 1.3.5, FRWD Technologies, Oulu, Finland) software. As GPS data only give a location to within a few metres, the data were manually overlaid onto a digital Ordinance Survey (OS) map (Memory-Map OS Edition Version 5.2.7) in order to improve accuracy. Screen prints of the FRWD PRO Replayer software and Memory Map software can be found in Appendix G.

CHAPTER FOUR

Study One: The anthropometric and physiological characteristics of cross-country marathon mountain bikers

4.1 Introduction

Ultraendurance mountain biking requires athletic performance in a variety of off-road terrains for protracted durations. Research on road cycling has demonstrated that successful performance in different types of terrain is partly determined by individual anthropometric and physiological characteristics (Padilla *et al.*, 1999; Lucìa *et al.*, 2001a). Whether the sub-disciplines of cross-country mountain biking require specific anthropometric and physiological characteristics is open to question as no comparisons have been made to date. Therefore it was the purpose of this study to describe the anthropometric and physiological characteristics of XCM competitors and compare them to the characteristics for XCO competitors as reported in the literature.

4.1.1 Research aim

The aim of this study was to investigate whether the anthropometric and physiological characteristics of XCM racers differ from those of XCO competitors.

4.2 Specific methods

4.2.1 Experimental design

A laboratory-based, cross-sectional research design was used in this study. Similar designs have been used in previous research for XCO mountain bikers (Sewall and Fernhall, 1995; Wilber *et al.*, 1997; Baron, 2001; Lee *et al.*, 2002; Impellizzeri *et al.*, 2002; Stapelfeldt *et al.*, 2004).

4.2.2 Participants

Eighteen well-trained, male XCM mountain bikers volunteered to take part in the study (age 38.1 ± 7.5 years; stature 1.77 ± 6.0 m; body mass 72.8 ± 6.7 kg). The participants were recruited via requests on relevant mountain bike Internet forums. The structure of ultraendurance mountain biking in the UK is such that riders are not nationally ranked by British Cycling (national ranking is limited to XCO competitors). Thus ultraendurance competitors are not classified by their racing licence (i.e. expert and elite). The selection criteria for this study were that the participants must have had a minimum of three consecutive years of racing and were competing in the current season (2006) of XCM races. Based on their racing background and the relative PPO data in Table 4.1, the participants can be classified as “well-trained” in accordance with the criteria for scientific cycling research proposed by Jeukendrup *et al.* (2000a).

4.2.3 Laboratory testing

4.2.3.1 Anthropometry, peak oxygen uptake and peak power output.

Anthropometric data, peak oxygen uptake and peak power output were determined in accordance with the protocols detailed in Chapter Three.

4.2.3.2 Haemoglobin and Haematocrit analysis

Two 10 µl capillary blood samples were taken from each participant's left index finger. To ensure the finger was clear of any debris, it was first cleaned using a Steret alcohol wipe (Southern Syringe Ltd., Manchester, UK). The finger was then punctured using a BD Microtainer lancet (Becton, Dickinson & Co., Plymouth, UK) and the first drop of blood wiped off to ensure any remaining alcohol did not affect the sample. For haemoglobin the cyanmethaemoglobin method was used. In this process haemoglobin is converted into cyanmethaemoglobin by potassiumhexacyanoferrate (III) and potassium cyanide. The blood sample was pipetted into a cuvette (Hach Lange, Berlin, Germany) mixed thoroughly with the reagent (Test Kit: LKM 143, Hach Lange, Berlin, Germany) and incubated at room temperature (~21˚C) for 5 minutes. The sample was mixed again and measured against a blank cuvette without blood using a Miniphotometer Plus LP20 (Hach Lange, Berlin, Germany) at a wavelength of 520 nm. For haematocrit the photometric turbidity method was employed. In this process Gower's solution (sodium sulphate and acetic acid) was used to achieve an even distribution of erythrocytes. The blood sample was pipetted into the reagent (Test Kit: LKM 144, Hach Lange, Berlin, Germany) and incubated at room temperature (~21˚C) for 15 minutes. The sample was mixed again and measured against a blank cuvette without blood using a Miniphotometer Plus LP20 (Hach Lange, Berlin, Germany) also at a wavelength of 520 nm.

4.2.3.3 Peak expiratory flow and forced vital capacity

Peak expiratory flow (PEF) and forced vital capacity (FVC) were measured using a Microloop spirometer (Micro Medical, UK). The Microloop spirometer uses a digital volume transducer, which measures expired air directly at B.T.P.S (body temperature and pressure with saturated water vapour) and avoids the need for temperature corrections. The transducer is also insensitive to the effects of condensation. The Microloop spirometer meets the American Thoracic Society recommendations (determined via independent assessment at LDS Hospital, Utah. Liistro *et al.*, 2006) and has a reported accuracy of ± 3%. It has been shown to have acceptable limits of agreement when compared with standard diagnostic equipment (Liistro *et al.*, 2006). Prior to each test a calibration check was performed in accordance with manufacturer's guidelines. The lung function tests were then performed as per the manufacturer's protocol.

4.3 Statistical analysis

All results are presented as mean ± S. D. unless otherwise stated. Significance level was set at $p \leq 0.05$, and data were analysed using the Statistical Package for the Social Sciences (SPSS) software program (SPSS Inc., version 17.0, Chicago, Illinois). The laboratory-measured maximum heart rates and the predicted HR_{max} were analysed using a paired samples t-test.

To ensure meaningful but non-significant differences were not overlooked (type II error) the data were further analysed using effect sizes (Cohen, 1988). Effect size is an objective and standardised measure of the magnitude of the observed effect (Field, 2006). Based on the classification of effect size by Cohen (1988), >0.8 was considered large, ~0.5 as moderate and <0.2 as small. Effect size for paired samples t-tests were calculated using Cohen's *d* equation:

$$d = \frac{M_1 - M_2}{S.D._{pooled}}$$ **Equation 8**

(Fallowfield *et al.*, 2005)

Where: d = effect size; M_1 = mean of data set 1; M_2 = mean of data set 2; $S.D._{pooled}$ = standard deviation of the pooled data.

4.4 Results

4.4.1 Anthropometric and physiological data for XCM mountain bikers

Table 4.1 summarises the anthropometric and physiological data for the XCM mountain bikers.

No significant difference was reported between laboratory measured maximum heart rates and predicted maximum heart rates ($t_{(17)} = 0.33$; $p = 0.74$; $d = 0.08$).

Table 4.1: Anthropometric and physiological data for XCM mountain bikers (n = 18)

Variable	Mean ± S.D.
Body Fat (%)	10.4 ± 2.4
Muscle mass (kg)	46.3 ± 4.6
Absolute PPO (W)	398 ± 40.6
Relative PPO ($W \cdot kg^{-1}$)	5.5 ± 0.7
HR_{max} ($beats \cdot min^{-1}$)	182 ± 8
Predicted HR_{max} ($beats \cdot min^{-1}$)	181 ± 5
Absolute $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	4.3 ± 0.7
Relative $\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	58.4 ± 6.3
Peak expiratory flow ($L \cdot min^{-1}$)	563 ± 66.7
Forced vital capacity (L)	5.3 ± 0.5
Hb ($mmol \cdot L^{-1}$)	9.6 ± 1.0
Hct (%)	44 ± 2

4.5 Discussion

The aim of this study was to describe the anthropometric and physiological characteristics of XCM mountain bikers and compare them to the characteristics of XCO mountain bikers as reported in the literature.

4.5.1 Age

The mean age of the participants in the present study was considerably greater than those reported for XCO competitors highlighted in Table 2.1. However, it was comparable to the mean ages reported in the literature for XCM competitors (Knechtle *et al.*, 2009), XCSR mountain bikers (Rose *et al.*, 2007; Rose and Peters, 2008; Wirnitzer and Kornexl, 2008), Ironman triathletes (Kimber *et al.*, 2002), adventure racers (Colombani *et al.*, 2002), ultraendurance road cyclists (Neumayr *et al.*, 2002; Neumayr *et al.*, 2004) ultraendurance runners (Wu *et al.*, 2004) and 24 h road cyclists (Callard *et al.,* 2000). This is supported by the observation that the current mean age of the top fifteen ranked UCI XCM riders is greater than that of the top fifteen ranked XCO riders (UCI, 2010). The XCM participants are therefore of a similar age to other ultraendurance athletes rather than XCO mountain bikers, and supports the view that ultraendurance athletes are from an older demographic. The grounds for this have not yet been established, but may be due to those described previously (Zalcman *et al.*, 2007).

4.5.2 Stature, body mass and body composition.

The mean stature of the participants in the present study falls within the range of values reported in the literature for XCO competitors as summarised in Table 2.1. This indicates that XCM mountain biking does not require a unique stature compared with XCO mountain biking. With regard to body mass, the mean value for the participants in the present study falls outside the range reported in the literature for XCO mountain biking. The value is 15% greater than the lightest cohort (Impellizzeri *et al.*, 2002) and 3% greater than the heaviest (Gregory *et al.*, 2007). With regard to body fat percentage, the mean value for the participants falls within the range reported in previous XCO studies (Table 2.1), and is comparable to other data in the literature regarding XCM athletes (Knechtle *et al.*, 2009) and Ironman triathletes (Kimber *et al.*, 2002).

If stature, body mass, and body fat percentage are interpreted together it would appear that the XCM participants possess a similar stature, and are slightly heavier than their XCO counterparts and that the additional body mass comprises adipose tissue. Several interpretations may be drawn from this. Body mass may not be a limiting factor in XCM mountain biking insomuch as a three percent increase in body mass may not have a detrimental effect on performance. In absolute terms this equates to 2.5 kg which is approximately 20% of the mass of a typical competition cross-country mountain bike. Carrying additional load during military exercises increases the physiological burden (Nolte *et al.,* 2010) and increased mass (body mass and/or bicycle mass) adversely affects the rate of acceleration and climbing performance in road cycling (Martin *et al.*, 1998; Jeukendrup *et al*., 2000a). Considering the concerted efforts that riders and manufacturers go to in order to reduce bicycle mass it would seem unlikely that body mass is not closely regulated. Nonetheless it may be that body mass is not as influencing a factor in XCM racing as it is in XCO racing. This may be due to the steeper gradients and greater speeds that characterise XCO mountain biking (Gregory *et al.*, 2007) where the ability to swiftly accelerate and decelerate and quickly ascend steep climbs against gravity might be a greater limiting factor.

4.5.3 Cardio respiratory system

The forced vital capacity of the participants was comparable with that previously published in the literature for elite road cyclists (Frolinsbee *et al.*, 1983) and XCO competitors (Sewall and Fernhall, 1995). The peak expiratory flow is within the range reported by Rose and Peters (2008) for XCSR mountain bikers. The haematocrit and haemoglobin values are also comparable to previously published values for XCO mountain bikers (Linderman *et al.*, 2003; Wu *et al.*, 2004; Wirnitzer and Faulhaber, 2007). Thus the XCM mountain bikers in the present study appear to have a similar lung function and blood composition to previous research on cross-country mountain bikers.

The mean $\dot{V}O_{2peak}$ reported in the present study is lower than the values for all of the XCO studies summarised in Table 2.1. However it is comparable to that reported by Kimber *et al.* (2002) for Ironman triathletes and Callard *et al.* (2000) for 24 h road cyclists and to those of elite and international adventure racers (Bowen *et al*., 2006; Zalcman *et al*., 2007). There are several plausible explanations for this. Firstly, it is well documented that HR_{max} and aerobic capacity decline with advancing years (McArdle *et al.,* 2001; Tanaka *et al.*, 2001), so the observed reduction in aerobic power may be due to the relatively elevated mean age of the participants rather than an anomaly; indeed there was no significant difference between the laboratory-measured HR_{max} and that predicted by the age-related equation proposed by Tanaka *et al.* (2001). This is further supported by the observation that the participants' mean HR_{max} as determined during a laboratory incremental test was lower than those highlighted in Table 2.1 for XCO mountain biking, but was similar to those reported by Colombani *et al.* (2002) and Bowen *et al.* (2006) for ultraendurance adventure racers. Secondly, there may be a difference in the standard of the participants between the studies. This is difficult to ascertain due to the cross-country disciplines being different (XCO and XCM) and the non-standardised classification of level of competition (Table 2.1). Finally the exercise intensity of XCM mountain biking maybe of a lesser intensity than that of XCO and thus maximal aerobic capacity may be less relevant to performance. This latter point is addressed in detail in Study Two.

4.5.4 Peak power output

The absolute peak power output produced by the XCM participants in this study was greater than that of previous published research for XCO mountain bikers (Table 2.1). However when normalised to body mass, the relative power output for the two disciplines is similar. It can be concluded that both disciplines require a similar power to weight ratio, and that the heavier body mass of the XCM riders is compensated for by a greater absolute power output. This is supported by the findings of Laursen *et al.* (2003a) who also reported a higher peak power output for 24XCT mountain bikers, which when normalised to body mass was comparable with those reported for XCO competitors.

4.6 Conclusions

The purpose of this study was to establish anthropometric and physiological data for XCM mountain bikers and compare them to XCO values. Whilst this database of information is of interest and importance in its own right, it is necessary to look beyond straightforward comparisons of data and examine the relationships of key physiological variables to performance. Accordingly the following study addresses this with regard to XCM competition.

CHAPTER FIVE

Study Two: Heart rate response and estimated energy expenditure during a cross-country mountain bike marathon race.

5.1 Introduction

The primary goal of the competitive ultraendurance cross-country mountain biker is to outperform the other competitors. Depending upon the race format this is achieved in one of two ways: completing a fixed distance (e.g. 95 km) in the least possible time, or completing the greatest distance in a fixed timeframe (e.g. 24 h team relay). In both of these examples success involves riding the bicycle at the fastest average speed for the duration of the event. The energy to do this is generated by the rider and as such the energetics of mountain biking, and the ability to quantify the intensity of racing is a key area of investigation (Lucia *et al.*, 2001a). Furthermore the fundamental components of athletic training are duration, frequency and exercise intensity. For ultraendurance mountain biking, duration and frequency are relatively straightforward to measure whereas exercise intensity is not. It is therefore necessary for coaches and riders to have a practical means of monitoring exercise intensity during training and competition. Previous research has addressed the exercise intensity of XCO mountain biking (Impellizzeri *et al*., 2002; Stapelfeldt *et al*., 2004; Gregory *et al*., 2007; Costa and De-Oliveira, 2008) and XCSR mountain biking (Wirnitzer and Kornexl, 2008), but no research to date has fully analysed the exercise intensity of XCM races. The aim of this study was to quantify and describe the exercise intensity of a XCM race by monitoring the heart rate responses of a group of well-trained mountain bikers. Subsidiary aims of this study were to determine the energy cost of XCM racing and to ascertain if there were any anthropometric or physiological correlates to XCM performance.

5.1.1 Research aim

Results from the literature are equivocal regarding heart rate response to ultraendurance exercise. Some report a gradual increase over time due to cardiovascular drift, whilst others have found a gradual reduction perhaps due to a change in substrate utilisation or a central governor protective measure. Exercise intensity can be expressed as a percentage of maximum heart rate. The aim of this study was to investigate whether exercise intensity (as a percentage of maximum heart rate) changes over time during a cross-country mountain bike marathon race.

5.2 Specific methods

5.2.1 Experimental design

A field-based, cross-sectional research design was used in this study. Similar methods have been successfully employed by previous researchers for XCO

(Impellizzeri *et al.*, 2002) and XCSR mountain biking (Wirnitzer and Kornexl, 2008).

5.2.2 Participants

In line with the philosophy of this thesis, it was necessary that the participants were authentic mountain bike competitors fully trained and prepared for the race. Participants were recruited via the race organiser's promotional email newsletter and requests on relevant mountain bike Internet forums. Ten well-trained male XCM mountain bikers volunteered to participate in the study (age 36.9 ± 8.5 years; stature 1.76 ± 0.07 m; body mass 73.9 ± 7.3 kg). The cohort was drawn from the population in the previous study. Two participants were excluded from the final analysis. This was because of incomplete heart rate data for one participant and bicycle mechanical failure for another. Participants used their own bicycles during the race, with all opting to use front-suspension, hardtail mountain bikes. The race organisers provided medical support for all of the race entrants. Table 5.2 summarises the physiological characteristics of the participants.

5.2.3 Preliminary testing

5.2.3.1 Anthropometric and physiological data.

Anthropometric data, peak oxygen uptake, peak power output, the calibration of participants for $\dot{V}O_2$ estimation, and blood lactate thresholds were determined in accordance with the protocols detailed in Chapter Three.

5.2.4 Field testing

5.2.4.1 Course profile and environmental information

The field testing took place during one round of a mountain bike marathon series comprising a single 95 km loop of trails in the Clwydian Hills in North Wales, UK. The environmental data are summarised in Table 5.1, and the profile of the course is represented in Figure 5.1. Environmental data were collected via an Oregon Scientific Weather Station (Oregon Scientific Ltd., Berkshire, UK).

Table 5.1: Environmental and course data for the XCM race

Variable	Value
Total vertical distance climbed (m)	2426
Mean gradient (%)	2.6
Starting point altitude from sea level (m)	127
Altitude range (m)	121 - 451
Temperature range (Celsius)	18 - 21
Mean atmospheric pressure (mbar)	984.0
Precipitation	none

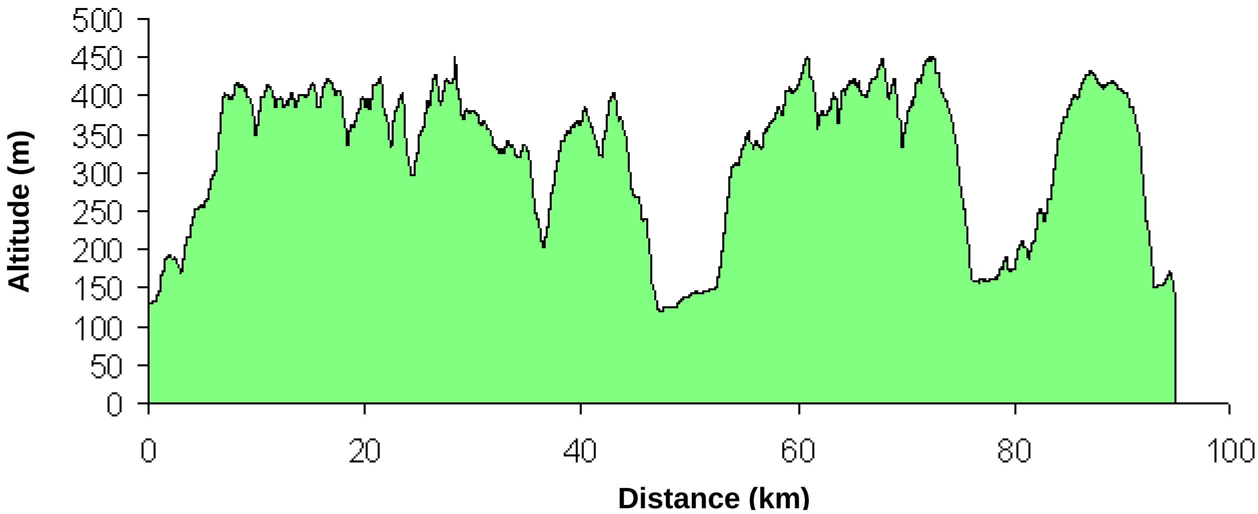


Figure 5.1: Profile of the 95 km cross-country mountain bike course.

5.2.4.2 Data collection

Race completion time was used as the primary measure of performance. Heart rate data were recorded throughout the race at 15 second intervals using Polar X-Trainer monitors (Polar Electro, Oy, Finland). Polar coded chest transmitters were used and worn in accordance with the manufacturer's guidelines.

Pre and post-race body mass were recorded using Seca 761 floor scales (Seca, Hamburg, Germany). The scales were placed on a level 10 mm plywood base (1 m x 1 m) in order to allow for a constant, stable surface. The pre-race measurements were taken immediately prior to the participants' warm-up routines and they were then free to ingest food and drinks. Post-race body mass was recorded less than 3 min after the participants crossed the finish line. Participants wore only their cycling shorts when the measurements were taken.

Participants did not consume food or drink prior to post-race body mass measurements.

5.3 Statistical Analysis

5.3.1 Heart rate dynamics

Eight participants had complete sets of data and were included in the analysis. All results are presented as mean ± S.D. unless otherwise stated. Significance level was set at $p \leq 0.05$, and data were analysed using the Statistical Package for the Social Sciences (SPSS) software program (SPSS Inc., version 17.0, Chicago, Illinois).

In order to observe the heart rate dynamics throughout the event, data were split into four aliquots based on the individuals' race duration. This was calculated on an individual basis and then an average for each quartile for the cohort was generated. The same process was applied when calculating exercise intensity (expressed as percentage of maximum heart rate). Data were checked for normal distribution using skewness and kurtosis ratios, and for homogeneity of variance using Mauchly's test of sphericity. The data were checked for outliers and missing values. Heart rate values of zero were omitted from the analysis. Differences in HR_{mean} for each quartile were statistically analysed using a repeated measures analysis of variance (ANOVA). The same process was applied to exercise intensity. To ensure meaningful but non-significant differences were not overlooked (type II error) the data were further analysed using effect sizes (eta squared, η^2) (Cohen, 1988). The laboratory-measured maximum heart rates and the corresponding maximum heart rates recorded during the race, and the laboratory measures of HR_{max} and predicted HR_{max} (using the Tanaka *et al.* (2001) equation) were analysed using paired samples t-tests. Effect size for paired samples t-tests were calculated using Cohen's *d* equation (Equation 8).

5.3.2 Body mass.

Pre and post race body mass were analysed using a paired sample t-test.

5.3.3 Correlates to race performance

A correlation matrix was generated to compare the anthropometric and physiological variables with race performance using Pearson's Product Moment Correlations.

5.4 Results

5.4.1 Anthropometric and physiological characteristics

Table 5.2 summarises the anthropometric and physiological characteristics of the participants.

Table 5.2: Anthropometric and physiological characteristics of 8 competitors in a 95 km mountain bike marathon

Variable	Mean ± S.D.
Body Fat (%)	10.5 ± 1.4
PPO (W)	389 ± 26.5
PPO ($W \cdot kg^{-1}$)	5.3 ± 0.3
HR_{max} ($beats \cdot min^{-1}$)	183 ± 8
$\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	57.6 ± 7.5
PO_{OBLA} (W)	283 ± 22.8
PO_{OBLA} ($W \cdot kg^{-1}$)	3.8 ± 0.32
PO_{LT} (W)	229 ± 21.2
PO_{LT} ($W \cdot kg^{-1}$)	3.1 ± 0.4
HR_{LT} ($beats \cdot min^{-1}$)	146 ± 5.5
HR_{LT} (% HR_{max})	79.5 ± 3.9
HR_{OBLA} ($beats \cdot min^{-1}$)	164 ± 7.6
HR_{OBLA} (% HR_{max})	89 ± 3.8

5.4.2 Performance results

Table 5.3 summarises the mean race data during the XCM race.

Table 5.3: Race data for 8 competitors in a 95 km mountain bike marathon

Variable	Mean ± S.D.
Race duration (min)	347 ± 31
Speed ($km \cdot h^{-1}$)	16.5 ± 1.4
HR ($beats \cdot min^{-1}$)	150 ± 10
% HR_{max} (%)	82 ± 6
% $\dot{V}O_{2peak}$ (%)	70.0 ± 10.6

Table 5.4 shows the summary statistics by quartile for mean heart rate and exercise intensity.

Table 5.4: Summary statistics for heart rate and exercise intensity measured during the mountain bike marathon.

	Race period				
	Quartile 1	**Quartile 2**	**Quartile 3**	**Quartile 4**	**Main effect for quartile**
HR (beats·min^{-1})	150 ± 9	152 ± 12	150 ± 11	149 ± 12	$F_{(3,21)} = 1.211$; $p = 0.330$; $\eta^2 = 0.15$
Exercise intensity (HR_{mean}/HR_{max})	0.82 ± 0.05	0.83 ± 0.07	0.82 ± 0.06	0.81 ± 0.06	$F_{(3,21)} = 1.123$; $p = 0.362$; $\eta^2 = 0.14$

5.4.2.1 Mean heart rate and exercise intensity

Individual race times were split into quartiles and the mean heart rate and exercise intensity for each aliquot was calculated (Figure 5.2). ANOVA returned no significant difference for HR_{mean} between the race quartiles ($F_{(3, 21)} = 1.211$; $p = 0.330$; $\eta^2 = 0.15$). No significant difference was reported between laboratory-measured and predicted maximum heart rates ($t_{(7)} = -0.557$; $p = 0.528$; $d = 0.07$). The maximum heart rates measured during the race were significantly lower ($t_{(7)} = 3.320$; $p = 0.02$; $d = 1.48$) than those measured in the laboratory. ANOVA reported no significant difference for HR_{mean}/HR_{max} between the race quartiles ($F_{(3, 21)} = 1.123$; $p = 0.362$; $\eta^2 = 0.14$). The mean HR_{mean}/HR_{max} for the race was 0.82. The coefficient of variation for the heart rate responses for each participant ranged from 4.4 to 9.0%. A sample heart rate trace is presented in Appendix F.

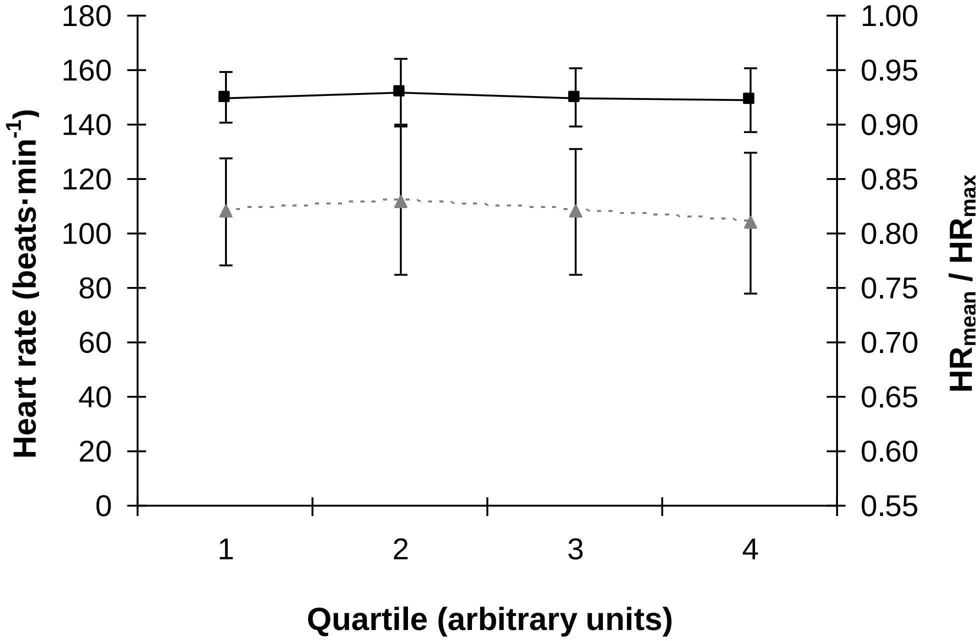


Figure 5.2: **HR_{mean} (■) and HR_{mean}/HR_{max} (▲) for each quartile of race time.**

Figure 5.3 illustrates the mean cumulative time spent at different percentages of maximum heart rate. The majority of race-time was spent above 70% HR_{max}.

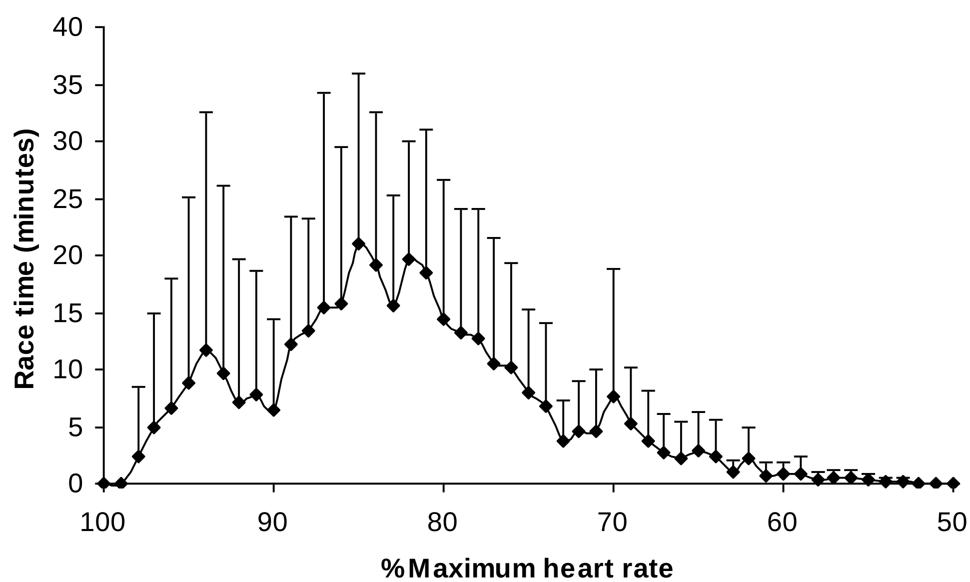


Figure 5.3: **Mean cumulative time spent at percentages of maximum heart rate (mean ± SD)**

Figure 5.4 shows the mean percentage of race time spent at different exercise intensity zones.

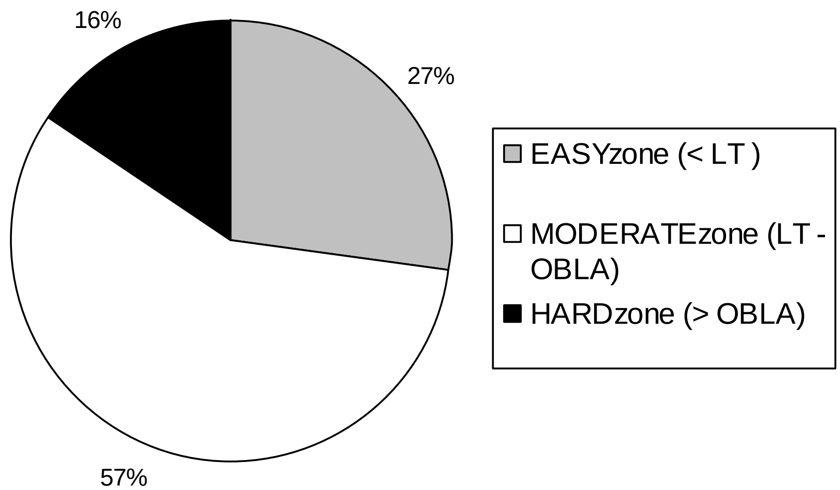


Figure 5.4: Mean percentage of race time spent at different exercise intensity zones. Based on LT and OBLA method as proposed by Impellizzeri *et al.* (2002).

Table 5.5 shows the estimated energy expenditure during the XCM race. Individual $\dot{V}O_2$ was calculated from individual heart rates measured during the race. Energy expenditure was estimated by assigning 20.2 kJ to each litre of oxygen consumed.

Table 5.5: Estimated energy expenditure (EE) during a 95 km cross-country mountain bike race

Subject	Total EE for race kJ *(kcal)*	EE $kJ\cdot min^{-1}$ *($kcal\cdot min^{-1}$)*	Relative EE $kJ\cdot min^{-1}\cdot kg^{-1}$ *($kcal\cdot min^{-1}\cdot kg^{-1}$)*
Mean	20849.7 *(5039.8)*	59.9 *(14.3)*	0.87 *(0.20)*
S.D.	3582.0 *(906.1)*	10.6 *(2.5)*	0.19 *(0.04)*

5.4.2.2 Pre and post-race body mass

Mean pre and post-race body mass were 73.9 ± 7.3 and 73.8 ± 7.3 kg respectively. The paired t-test returned a significant difference ($t_{(7)} = 2.728$; $p = 0.03$; $d = 0.01$). This equated to a 0.1% loss in body mass.

5.4.2.3 Anthropometric and physiological correlates to performance

No significant correlations to race-speed were reported for the measured physiological variables, and therefore a multiple regression was an inappropriate statistical analysis technique. Table 5.6 summarises the correlation coefficients

Table 5.6: Correlation coefficients for physiological variables and speed

		Age (y)	**BM**	**Stature**	**Fat %**	**PPO**	**PPO $W\cdot kg^{-1}$**	**POLT**	**PO OBLA**	**VO_{2peak}**
Speed	Pearson	-.21	-.04	.07	.24	.12	.20	-.41	-.08	.07
	Sig.	.96	.92	.87	.57	.78	.64	.31	.85	.86

PPO = Peak power output; **POLT** = Power output at lactate threshold; **OBLA** = Onset of blood lactate accumulation; **BM** = Body mass. (see Appendix H for full matrix).

5.5 Discussion

The main aim of this study was to investigate the heart rate responses of eight well-trained male mountain bikers during a 95 km mountain bike marathon. Also of importance were the determination of the energy cost ($kJ \cdot min^{-1}$) during the race and whether there were any anthropometric or physiological correlates to race performance. The heart rate methods employed in this study have been used by other researchers to determine the exercise intensity of XCO mountain biking (Impellizzeri *et al.*, 2002), XCSR mountain biking (Wirnitzer and Kornexl, 2008), ultraendurance road cycling (Neumayer *et al.*, 2004), and to determine the energy expenditure of various activities (Kimber *et al.*, 2002; Laursen *et al.*, 2003a). The mean race time for the participants was 5 h 47 min which exceeds the threshold criteria for an ultraendurance event (Kreider, 1991; Hawley and Hopkins, 1995; Laursen and Rhodes, 2001; Neumayr *et al*., 2002; Linderman *et al*., 2003; Whyte, 2006). The mean finishing time for the entire race entrants (n = 283) was 6 h 53 min suggesting the cohort in the present study was representative of the top half of the XCM competitors.

5.5.1 Heart rate response and exercise intensity

The main finding was that no significant difference was reported for HR_{mean} by quartile for the race. As expected there was a similar observation for HR_{mean}/HR_{max}.

The HR_{mean} for the race equated to 82 percent of HR_{max}. This is comparable to the exercise intensity reported by Wirnitzer and Kornexl (2008) for XCSR competitions. However, it is somewhat lower than those reported by Impellizzeri *et al.* (2002) and by Stapelfeldt *et al.* (2004) for XCO mountain bike racing. An important difference is that the average race time for the XCO studies were approximately only one third of the duration of the race in the present study. This is not surprising, as an inverse relationship between exercise intensity and exercise duration is typically observed for most sports (Stroud, 1998; Padilla *et al.*, 2000; McArdle *et al.,* 2001). This is supported by the heart rate dynamics by quartile during the race. In the present study the HR_{mean}/HR_{max} during the first quartile was less than that reported by Impellizzeri *et al.* (2002) for XCO racing even though the durations are similar.

The mean HR_{mean}/HR_{max} in the present study was somewhat higher than that reported by Neumayr *et al.* (2004) during the Race across the Alps. A notable difference is the Race across the Alps was 525 km and the subjects' mean completion time was 27 h 25 min, again supporting the inverse relationship between exercise intensity and race duration. Interestingly Neumayr *et al.* (2004) reported an exercise intensity of 86% of HR_{max} at the start and 66% at the finish, with heart rate response declining substantially during the event (10% every 10 hours). They suggest it may have been due to EICF and that a central governor down regulated the sympathetic nervous system in order to protect the heart from myocardial ischaemia. It is plausible that ECIF was not an influencing factor on the participants' heart rate during the XCM race as no significant difference was observed in HR_{mean}/HR_{max} over time and the duration of the event was somewhat less.

Data on other secondary performance variables, such as power output, were not monitored so it cannot be concluded that race performance was consistent as a result of the "cardiovascular pacing". For example Boulay *et al*. (1997) reported that when subjects exercised at a fixed heart rate for a prolonged period, work rate had to be reduced. This may have been the case in the present study. A major cause of this phenomemon is cardiovascular drift which is exacerbated with increasing dehydration (Coyle and Montain, 1992; Abbiss and Laursen, 2005). Although statistically significant the participants' reduction in body mass during the race was considerably less than the 2% regarded as clinical dehydration (Sawka *et al.*, 2007; Rose and Peters, 2008). Even though fluid compartmental shifts cannot be accounted for, it would indicate that the participants were not dehydrated and that cardiovascular drift was minimised.

Neumayr *et al*. (2004) suggested that an ultraendurance threshold exists and it is approximately 70% of HR_{max}. This value was not supported by the present study, indicating that if the ultraendurance threshold paradigm exists it is duration and sport specific. It would also support the proposal of Laursen and Rhodes (2001) whereby ultraendurance paces are manipulated in order to identify the optimal intensity for the event. A suitable and practical methodology needs to be established for XCM mountain biking, and is an area that future researchers may wish to explore.

In the present study the maximum heart rate recorded during the race was significantly lower than that recorded in the laboratory. Impellizzeri *et al*. (2002) reported no significant difference between HR_{max} as determined in the laboratory and the maximum heart rate of the competitors recorded during the race. These conflicting findings can be accounted for by the race format. In XCO races the start is of crucial importance to the remaining strategy of the race. It is a mass start where the competitors sprint in order to arrive at the first section of singletrack in the lead group. Not being in the lead group can compromise race performance due to a bottleneck forming and the subsequent difficulty in overtaking on crowded technical singletrack. In the XCM race (where the number of competitors was considerably larger than those of a typical XCO race) the riders were paced for approximately one half mile on an uphill road section behind a pace-car. Race rules do not permit competitors to overtake the pace car. The purpose of this incline is to separate out the riders before they reach the first section of singletrack which signifies the start of the race. Whilst physically demanding this starting procedure is not an all-out sprint for the “holeshot” as in XCO racing. This accounts for the maximum heart rates being reached in XCO races (Impellizzeri *et al.*, 2002). Nonetheless, it is doubtful that the heart rate response to an initial sprint would significantly elevate the HR_{mean} and be the sole contributing factor in the observed elevated HR_{mean}/HR_{max} in the XCO races.

Heart rate response during road cycling has been reported to reflect the terrain (Fernandez-Garcia *et al.*, 2000). The mean course gradient in the present study was 2.6% which is somewhat less than the 4.13% Gregory *et al.* (2007) reported for the mean gradient of 29 World Cup XCO courses. The cumulative vertical distance of the XCM course was 25% greater than the mean value reported for World Cup XCO courses (Gregory *et al*., 2007). Although shorter in duration the XCO course gradients are more severe which may also explain why the mean heart rate for XCO races reported in the literature are greater (Impellizzeri *et al.*, 2002; Stapelfeldt *et al.,* 2004; Gregory *et al.,* 2007) than those observed in the present study. This concurs with the subjective view of riders and coaches that XCM racing is aerobically intense, yet less so than XCO competitions (personal communication with riders and coaches).

An alternative way of defining exercise intensity during mountain bike races is to express the exercise in relation to lactate threshold and OBLA. In the present study 16%, 57% and 27% of the race time were spent in the $HARD_{ZONE}$ (above OBLA), $MODERATE_{ZONE}$ (between LT and OBLA) and $EASY_{ZONE}$ (below LT) respectively, whereas for XCO competitions, Impellizzeri *et al*. (2002) reported 31%, 51% and 18% of race time was in these respective zones. Wirnitzer and Kornexl (2008) reported values 6%, 58% and 36% of race times in these zones for XCSR, which involved prolonged cross-country racing on eight successive days. Whilst a similar proportion of time for each discipline was spent in the $MODERATE_{ZONE}$, considerably less time was spent in the $HARD_{ZONE}$ for both XCM and XCSR. Collectively these results support the contention that exercise intensity during cross-country mountain biking is inversely proportional to discipline duration. This information is of great practical relevance to competitors and coaches when designing training programmes for specific cross-country disciplines.

5.5.2 Anthropometry and physiological correlates to performance

The mean age of the participants in this study was greater than those reported by Wilber *et al.* (1997), Stapelfedlt *et al.* (2004), Impellizzeri *et al.* (2005a) and Impellizzeri *et al.* (2005b) for XCO racers. Analysis of the race entrant data for the XCM event showed that from the sample of male riders entered for the full-distance marathon (n = 283), 203 were registered in both the Masters (30 yrs+) and Veteran (40 yrs +) categories. This equates to 72% of the riders being over the age of 30 yrs. This indicates that XCM participants are generally older than their XCO counterparts and further supports the contention that ultraendurance athletes tend to be from an older demographic (Zalcman *et al.*, 2007).

The cohort in the current study was drawn from the population in Study One. It is therefore not necessary to describe and compare the anthropometrical and physiological characteristics as this has already been detailed in the previous chapter. However, the present study enabled these characteristics to be evaluated as predictors of performance. Interestingly none of the measured variables were correlated to race speed. This is in agreement with Sewall and Fernhall (1995) who reported no significant correlations between similar anthropometric and physiological measures and race performance for XCO mountain bikers. The lack of relationship between race speed and both body mass and normalised variables is in contrast with the work of Baron (2001), Lee *et al.* (2002), Impellizzeri *et al.* (2005b) and Gregory *et al.* (2007) for XCO mountain biking. However, it is in accordance with the findings of Laursen *et al.* (2003a) for ultraendurance mountain bikers. This suggests that body mass is less influential on XCM mountain biking than it is on XCO mountain biking. Furthermore, the lack of relationship with percent body fat concurs with the findings of Knechtle and Rosemann (2009) for ultraendurance mountain bikers. The reasons behind these results are unclear. One plausible explanation is that the profile of XCM course was less severe than the XCO course in the literature, and that the latter cross-country discipline is more stochastic in nature and requires more frequent acceleration and deceleration. This would mean that XCO races would favour a reduced inert body mass (Martin *et al.*, 1998). It may also be due to the large energy expenditure and metabolic demands observed during the XCM race favouring greater adipose stores (Coyle *et al.,* 2001; Zalcman *et al.*, 2007).

Of interest is the lack of predictive value of maximal aerobic capacity. This is in accordance with the majority of research on XCO mountain biking (Sewall and Fernhall, 1995; Impellizzeri *et al.*, 2005a) and the findings of Laursen *et al.* (2003a) regarding 24XCT racing. Several reasons may explain this. It may be that this physiological measure has little relevance to XCM mountain biking. This would concur with Noakes (2000a) who suggests that as exercise duration increases the relevance of a maximal aerobic test diminishes and its predictive power is lessened. In addition Lucía *et al.* (2001a) reported that $\dot{V}O_{2max}$ is not a valid performance indicator in professional road cycling per se; rather it is the ability to work at a high percentage of it.

Impellizzeri *et al.* (2002) reported that elite level XCO mountain bikers raced at an intensity equivalent to 84% $\dot{V}O_{2max}$ (for an average duration of 147 min). Whereas, the participants in the present study worked at the lower average intensity of 70% $\dot{V}O_{2peak}$ (for an average duration of 347 min). This would suggest that, due to the lower exercise intensity, maximal aerobic capacity was less of a limiting factor (and predictor of performance) in the XCM race than it is in XCO races. It may also be that if a relationship was present it was masked by homogeneity of the participants. Myburgh (2003) reported that maximal oxygen consumption (indeed many physiological parameters) was not effective as a performance predictor amongst homogenous groups of elite, or sub-elite athletes. Impellizzeri *et al.* (2005a) found that despite having high aerobic capacities, aerobic fitness explained only 40% of the variance in high-level XCO mountain bike performance. They suggest that, in a homogenous group, technical ability may contribute substantially to the remaining variance. Laursen and Rhodes (2001) reported that as exercise duration increases, typical physiological laboratory measures, such as aerobic power, are not strongly related to performance and that other potentially limiting and defeating factors come to the fore. This is supported by the results of the present study, however it should be noted that although the participants were representative of the top half of the XCM racing field they may not be as physiologically homogenous as those reported in the literature (Impellizzeri *et al.*, 2002). Furthermore, the elevated mean age of the participants may have contributed to a blunting of aerobic capacity. Notwithstanding the above, the results indicate that peak oxygen uptake was unable to predict XCM race performance.

5.5.3 Energy expenditure

A further aim of this study was to establish the energy expenditure during the race. A shared characteristic of the participants was the ability to sustain a high rate of energy expenditure for a prolonged duration. This rate was estimated to be 59.9 ± 10.6 $kJ \cdot min^{-1}$ (14.3 ± 2.5 $kcal \cdot min^{-1}$). At the time of writing, this is the first study to ascertain the energy cost of XCM mountain bike racing. Several assumptions were inherent in the calculations that led to this value; a key one being that the energy contribution for the activity was largely aerobic. The average percentage of HR_{max} for the race was 82% which suggests the race was mainly aerobic and that the exercise intensity was within the HR_{100} – 85% HR_{max} bandwidth used for the calibration of the participants (Figure 5.3). However, Figure 5.4 shows that a considerable percentage of race time was spent above lactate threshold. Brooks *et al.* (2005) note that three quarters of lactate is oxidised in the working muscles, and when compared to aerobic metabolism the net contribution of lactate accumulation to energy production is small. As such the energy cost value can be considered an accurate representation.

The absolute energy expenditure values of XCM racing varied between participants, but the data were more homogenous when normalised to body mass. Nonetheless inter-individual differences remained. These differences may be accounted for by economy, gross efficiency, line choice, tactical decisions, tyre choice, tyre pressure, cycle design, environmental conditions, plus other factors. An energy expenditure value of 59.9 $kJ \cdot min^{-1}$ (14.3 $kcal \cdot min^{-1}$) is comparable with previous findings using portable breath-by-breath spirometry (Metcalfe, 2002). The only other studies that have attempted to quantify the energy cost of mountain biking are by Mastroianni *et al*. (2000) and Colombani *et al.* (2002). Mastroianni and co workers (2000) reported an energy cost of 68.2 $kJ \cdot min^{-1}$. There are several factors that may have contributed to the higher value; the subjects they tested were physically fit, but crucially they were not trained mountain bikers. It would be reasonable to assume that they were less efficient and expended more energy than skilful riders. In addition, the mean duration for trials in their study was 32.5 min (compared to 5 h 47 min in the present study), so it is likely the subjects worked at a higher intensity due to the shorter duration. Colombani *et al.* (2002) estimated an energy cost for the mountain bike section of a 244 km adventure race as being 48.3 $kJ \cdot min^{-1}$. This attenuated value is most likely due to the protracted nature of the event and the subjects having employed pacing strategies. It may also be a result of potential errors using proxy energy-cost calculations.

5.6 Conclusions

The exercise intensity and energy expenditure during the XCM mountain bike race was unlike that of its XCO counterpart as reported in the literature. These data suggest that the XCM competition was of a high aerobic intensity though less than that of typical XCO races. This can be easily explained by the much longer duration of the XCM race. Despite the activity being largely aerobic in nature $\dot{V}O_{2max}$ was not correlated with race time and was not a predictor of race performance. This may be due, in part, to the observation that the XCM participants were exercising at a relatively lower intensity compared with shorter duration XCO races and that maximal capabilities may have had less of an impact on race performance.

Whilst the heart rate and exercise intensity profiles provide key information on the physiological demands of the race, it does not give a temporal performance measure. Race regulations require the course to comprise one large loop (British

Cycling, 2010) rather than a series of smaller circuits (as in XCO and 24XCT races). This meant that although split times (and thus speed calculations) could be made at predetermined points along the course, a comparison (i.e. lap times) would not be appropriate as the nature of the terrain (and other variables), may affect the speed and not reflect relative performance. Temporal monitoring of a secondary performance variable such as power output would have added a valuable level of understanding to the performance dynamics of the participants as a stable heart rate does not necessarily equate to a consistent performance. This point should be of interest to future researchers using XCM populations, and was used to inform the protocol for Study Five.

Taken together these data provide useful information on exercise intensity and energy expenditure for coaches and athletes involved in ascertaining training and racing load, and also in the design of appropriate training and nutritional strategies for XCM racing. The remainder of the studies will focus on the physiology and bioenergetics of 24 h team mountain bike racing.

CHAPTER SIX

Study Three: Effects of exercising at different times of the day.

6.1 Introduction

Twenty four hour cross-country mountain bike racing requires the teams to compete throughout the day. Research has shown that some physiological variables are influenced by circadian rhythms (Table 2.6). It is plausible that these variations have the potential to influence mountain bike performance during a 24XCT race. This study was explorative; the purpose of which was to determine whether any physiological and performance factors relevant to 24XCT change with time of day. A secondary purpose was to determine whether a controlled laboratory setting could provide a suitable environment in which to examine time of day effect on physiological and performance factors relevant to 24XCT racing.

6.1.1 Research aim

The aim of this study was to investigate whether physiological and performance variables (relevant to 24XCT racing) vary at different times of the day when exercising at an intensity consistent with ultraendurance mountain biking.

6.2 Specific methods

6.2.1 Experimental design

A cross-sectional, laboratory-based research design was used in this study. Select physiological and performance variables were measured at different times of day whilst the participants were exercising at an intensity that was representative of ultraendurance cross-country racing.

6.2.2 Participants

Challenges were encountered when recruiting authentic volunteers for this study. Due to the protocol having a serious impact on the participants' time and effort with regard to attending the laboratory at differential time points throughout the day, an opportunistic sample was recruited. Six male and two female sports science students volunteered to participate in the study (age 22.1 ± 4.5 years; stature 1.76 ± 0.1; body mass 68.4 ± 11.9). All of the participants were actively involved in competitive university sport.

6.2.3 Protocol

The group order for testing was arranged in a Latin square design and is represented in Figure 6.1. The schedule for each group (n = 2) was such that each testing bout was separated by at least one day. During the 00:00 – 01:00 h four subjects were tested. The testing took place during October.

06:00 – 07:00	12:00 – 13:00	18:00 – 19:00	00:00 – 01:00
G1	G2	G3	G4
G4	G1	G2	G3
G3	G4	G1	G2
G2	G3	G4	G1

■ = groups not tested

Figure 6.1: Group order for the laboratory-based tests

6.2.3.1 Baseline measurements

Upon arrival to the laboratory the participants were seated for 30 min in ambient light conditions in order to ameliorate the effects of sleep inertia. Although sleep inertia was only expected in the early morning shift the procedure applied to all sessions for standardisation purposes. As suggested by Baxter and Reilly (1983), for the 06:00-07:00 h test participants woke at least one hour beforehand and only drank water prior to testing (~ 300 mL). After the seated period resting heart rate, blood pressure, intra-aural temperature and salivary cortisol concentrations were measured in accordance with protocols in Chapter Three.

6.2.3.2 Cycle protocol

Following a 5 min self-selected warm-up, each participant was required to cycle for 20 min on a Monarch 834E cycle ergometer (Monark Exercise AB, Vansbro, Sweden) at an intensity equivalent to 82% of their age predicted maximum heart rate based on the formula proposed by Tanaka *et al.* (2001) (Equation 6). The rationale for employing the target heart rate was that it was equivalent to the HR_{mean}/HR_{max} percentage reported in the previous study and was therefore representative of an ultraendurance cross-country race intensity. Table 6.1 details mean heart rate characteristics.

Table 6.1: Mean heart rate characteristics of participants

Variable	**Mean ± S.D.**
Predicted HR_{max} (beats·min^{-1})	193 ± 3
82% predicted HR_{max} (beats·min^{-1})	158 ± 3

The twenty minute exercise duration was employed in order to avoid fatiguing the participants (as they were not from a cycling background). The duration was determined during a pilot investigation. Cadence was spontaneously chosen by each participant throughout the test; participants were instructed to visually indicate to the experimenter whether they required less resistance (and therefore an increased cadence) or more resistance (and therefore a reduced cadence). The experimenter adjusted the cradle mass accordingly (in increments of 0.1 kg). At five minute intervals cadence, resistance, rating of perceived exertion and heart rate were recorded, and average values for the trial were generated. Power output was calculated using the following equation:

$$PO\ (W) = (rev \cdot min^{-1} \times m \cdot rev^{-1} \times kg\ resistance) \times 0.16345$$ **Equation 9**

Where: $m \cdot rev^{-1}$ = horizontal distance (m) per revolution of the flywheel, and 0.16345 is the conversion factor from $kg \cdot m \cdot min^{-1}$ to W.

(Brown *et al.*, 2006, p. 105)

For the duration of the test oxygen uptake was recorded using a MetaLyser 3B (Cortex, Leipzig, Germany) and mean values for the exercise bout were calculated. At a briefing session one week prior to the tests the participants were familiarised with the protocol.

Ambient light was the only form of illumination during the testing period and measured in lux using a Minilux P1 Photoelectric Photometer (Salford Electrical Instruments Ltd., Manchester, U.K.).

6.3 Statistical Analysis

All results are the pooled data for males and females and are presented as mean ± S.D. unless otherwise stated. Significance level was set at $p \leq 0.05$, and data were analysed using the Statistical Package for the Social Sciences (SPSS) software program (SPSS Inc., version 17.0, Chicago, Illinois). Due to unequal sample sizes in the midnight trial paired-sample t-tests were used. Missing values were excluded analysis by analysis with each t-test using all cases that had valid data for the tested variables (Field, 2006). For each variable six t-tests were required (Tables 6.2 to 6.8). Data for each variable were observations over time and as such the Bonferroni correction in significance level was not appropriate as it is highly conservative and may have missed any real differences (Bland and Altman, 1995). Pearson's Product Moment correlations were used to generate a correlation matrix for all of the measured variables.

6.4 Results

6.4.1 Heart rate

Figure 6.2 shows the mean exercise heart rate values at different times of day.

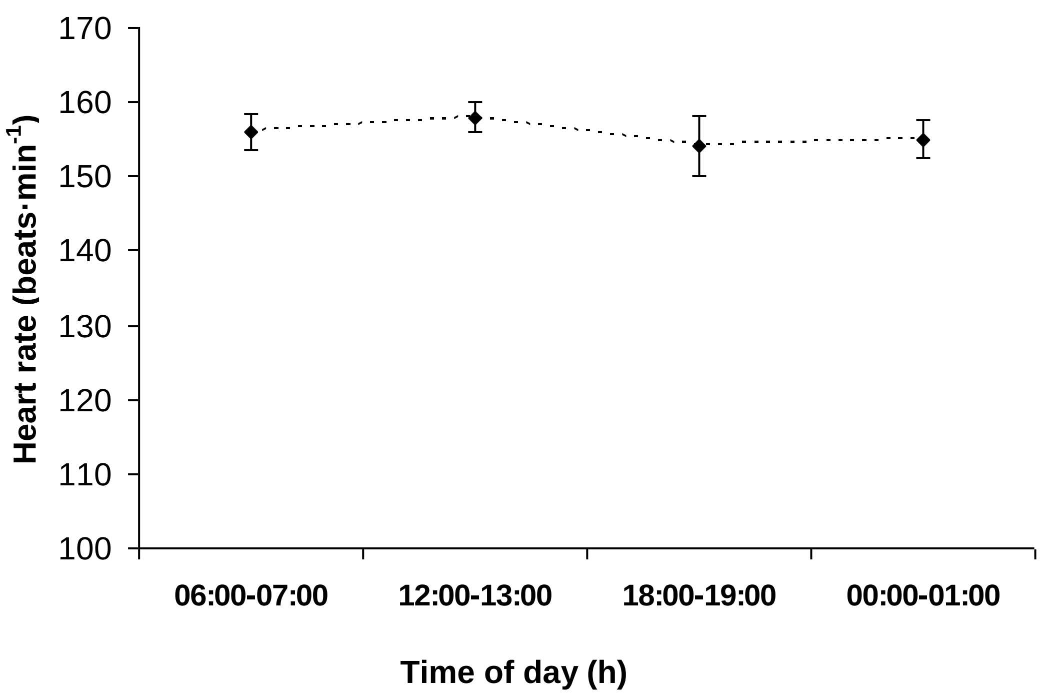


Figure 6.2: Mean exercise heart rate at different times of day. Note: the broken line is only intended to highlight the trend and not infer interpolation.

Table 6.2 shows the results of the t-tests for exercise heart rate.

Table 6.2: Statistical results for exercise heart rate at different times of day.

	12:00-13:00	18:00-19:00	00:00-01:00
06:00-07:00	$t_{(7)} = -2.48$, $p = 0.04$*, $d = 0.09$	$t_{(7)} = 1.14$, $p = 0.29$, $d = 0.6$	$t_{(3)} = 0.23$, $p = 0.83$, $d = 0.4$
12:00-13:00		$t_{(7)} = 3.13$, $p = 0.02$*, $d = 1.2$	$t_{(3)} = 1.76$, $p = 0.18$, $d = 1.3$
18:00-19:00			$t_{(3)} = -1.03$, $p = 0.38$, $d = 0.3$

* significant difference

6.4.2 Oxygen uptake

Figure 6.3 shows the mean relative oxygen uptake at different times of day.

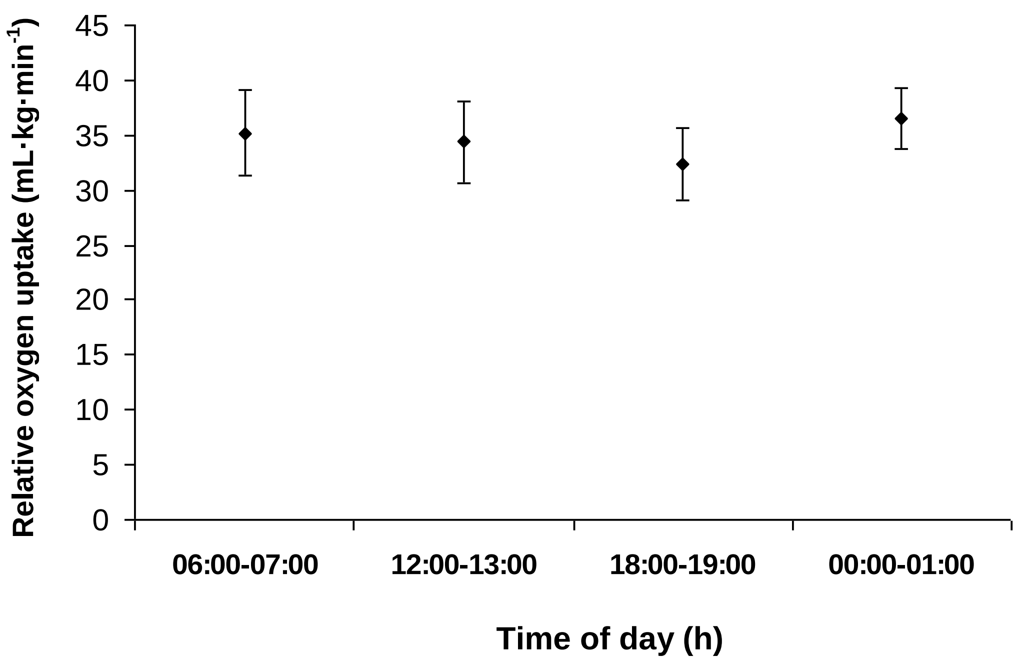


Figure 6.3: Mean relative oxygen uptake at different times of day.

Table 6.3 shows the results of the t-tests for oxygen uptake.

Table 6.3: Statistical results for oxygen uptake at different times of day.

	12:00-13:00	18:00-19:00	00:00-01:00
06:00-07:00	$t_{(7)}$ = 0.90, *p* = 0.40, *d* = 0.2	$t_{(7)}$ =1.85, *p* = 0.11, *d* = 0.8	$t_{(3)}$ = -2.19 *p* = 0.12, *d* = 0.4
12:00-13:00		$t_{(7)}$ = 1.35, *p* = 0.22, *d* = 0.6	$t_{(3)}$ = -4.19, *p* = 0.03*, *d* = 0.6
18:00-19:00			$t_{(3)}$ = -2.14, *p* = 0.12, *d* = 1.3

* significant difference

6.4.3 Salivary cortisol concentrations

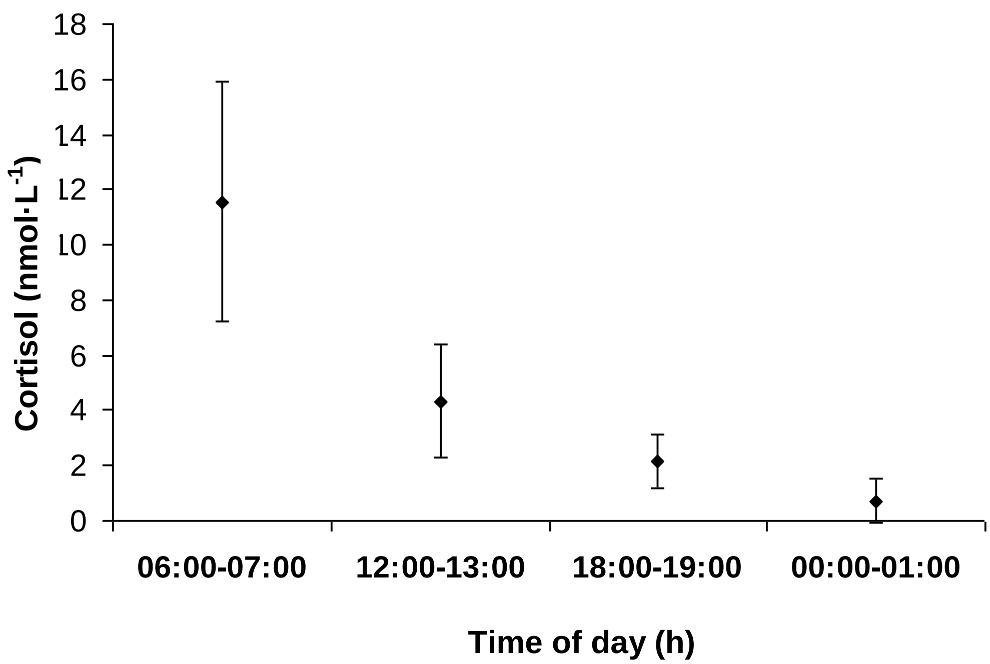


Figure 6.4: Mean resting salivary cortisol concentrations at different times of day.

Figure 6.4 shows the mean resting salivary cortisol concentrations at different times of day. Table 6.4 shows the results of the t-tests for salivary cortisol concentrations. Significant differences were observed for salivary cortisol concentrations between all of the trials.

Table 6.4: Statistical results for salivary cortisol concentrations at different times of day.

	12:00-13:00	18:00-19:00	00:00-01:00
06:00-07:00	$t_{(7)} = 4.96$, $p = 0.002$*, $d = 2.2$	$t_{(7)} = 7.04$, $p > 0.000$*, $d = 3.2$	$t_{(3)} = 6.14$, $p = 0.01$*, $d = 2.2$
12:00-13:00		$t_{(7)} = 4.41$, $p = 0.003$*, $d = 4.6$	$t_{(3)} = 3.46$, $p = 0.04$*, $d = 2.3$
18:00-19:00			$t_{(3)} = 5.04$, $p = 0.02$*, $d = 1.6$

* significant difference

6.4.4 Intra-aural temperature

Figure 6.5 shows mean resting intra-aural temperature at different times of day. The highest individual intra-aural temperature was recorded at 18:00 h. Table 6.5 shows the results of the t-tests for intra-aural temperature

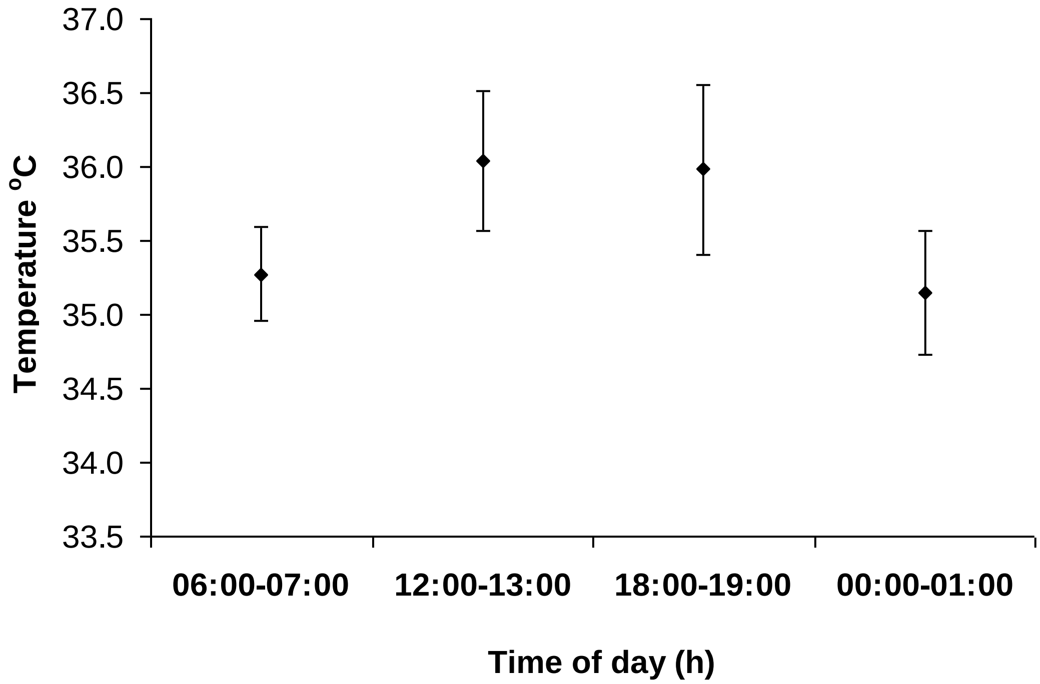


Figure 6.5: Mean resting intra-aural temperature at different times of day.

Table 6.5: Statistical results for intra aural temperature at different times of day.

	12:00-13:00	**18:00-19:00**	**00:00-01:00**
06:00-07:00	$t_{(7)}$ = -5.77, *p* = 0.001*, *d* = 1.9	$t_{(7)}$ = -4.37, *p* = 0.003*, *d* = 1.5	$t_{(3)}$ = 0.45, *p* = 0.68, *d* = 0.3
12:00-13:00		$t_{(7)}$ = 0.46, *p* = 0.66, *d* = 0.1	$t_{(3)}$ = 2.82, *p* = 0.07, *d* = 2.0
18:00-19:00			$t_{(3)}$ = 1.90, *p* = 0.15, *d* = 1.6

* significant difference

6.4.5 Power output

Figure 6.6 shows power output and exercise heart rate responses at different times of day.

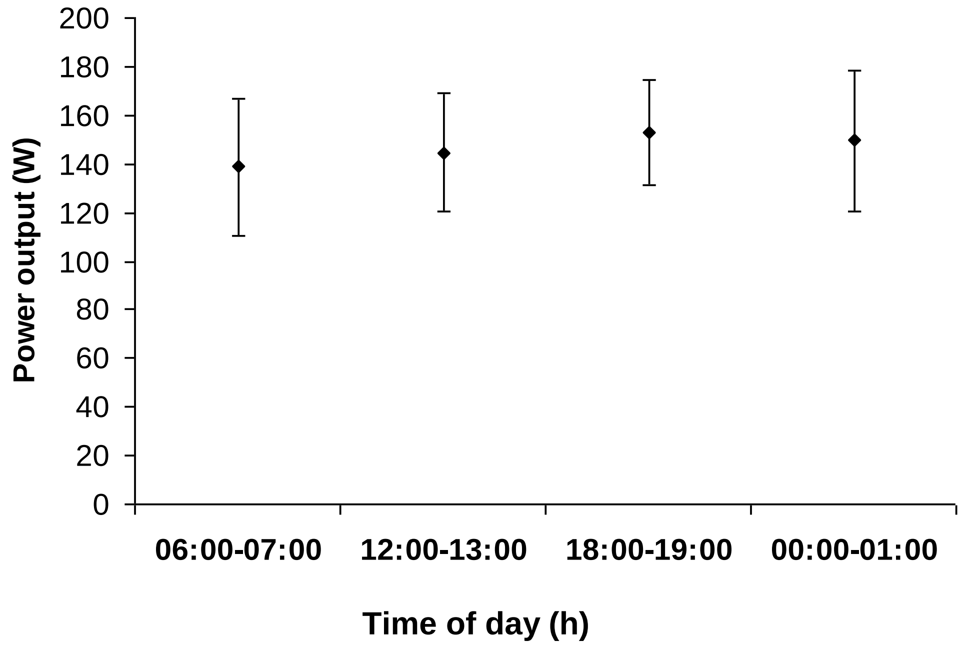


Figure 6.6: Mean power output at different times of day.

Table 6.6 shows the results of the t-tests for power output. Power output exhibits an amplitude of 4.4% above the 24 h mean at 06:00-07:00 h and a nadir amplitude of 5.3% below the 24 h mean at 18:00-19:00 h.

Table 6.6: Statistical results for power output at different times of day.

	12:00-13:00	18:00-19:00	00:00-01:00
06:00-07:00	$t_{(7)} = -1.34$, $p = 0.22$, $d = 0.2$	$t_{(7)} = -1.82$, $p = 0.11$, $d = 0.6$	$t_{(3)} = -0.73$, $p = 0.52$, $d = 0.4$
12:00-13:00		$t_{(7)} = -1.05$, $p = 0.327$, $d = 0.4$	$t_{(3)} = -0.22$, $p = 0.98$, $d = 0.2$
18:00-19:00			$t_{(3)} = 1.95$, $p = 0.15$, $d = 0.1$

6.4.6 Self-selected cadence

Figure 6.7 shows self-selected cadence at different times of day.

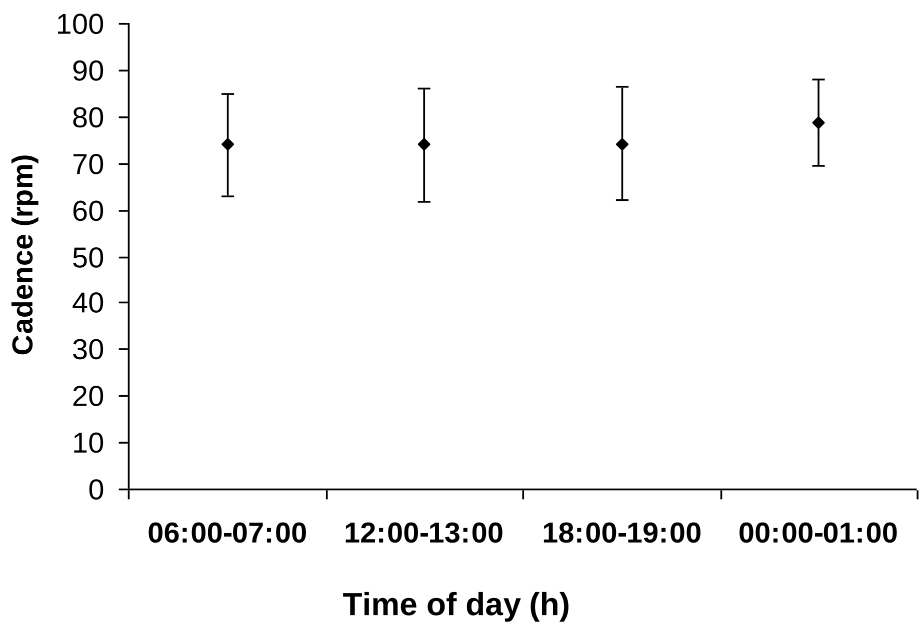


Figure 6.7: Mean self-selected cadence at different times of day.

Cadence increased by 6.8% above the 24 h mean in the 00:00-01:00 h shift. Table 6.7 shows the result of the t-tests for self-selected cadence. Cadence increased by 6.8% above the 24 h mean in the 00:00-01:00 h shift.

Table 6.7: Statistical results for self-selected cadence at different times of day

	12:00-13:00	18:00-19:00	00:00-01:00
06:00-07:00	$t_{(7)} = 0.02$, $p = 0.99$, $d > 0.0$	$t_{(7)} = -0.20$, $p = 0.85$, $d = 0.03$	$t_{(3)} = 0.13$, $p = 0.90$, $d = 0.5$
12:00-13:00		$t_{(7)} = -0.13$, $p = 0.90$, $d = 0.03$	$t_{(3)} = 2.22$, $p = 0.11$, $d = 0.5$
18:00-19:00			$t_{(3)} = -0.55$, $p = 0.62$, $d = 0.4$

6.4.7 Rating of perceived exertion

Figure 6.8 shows the ratings of perceived exertion at different times of day and Table 6.8 shows the results of the t-tests for RPE.

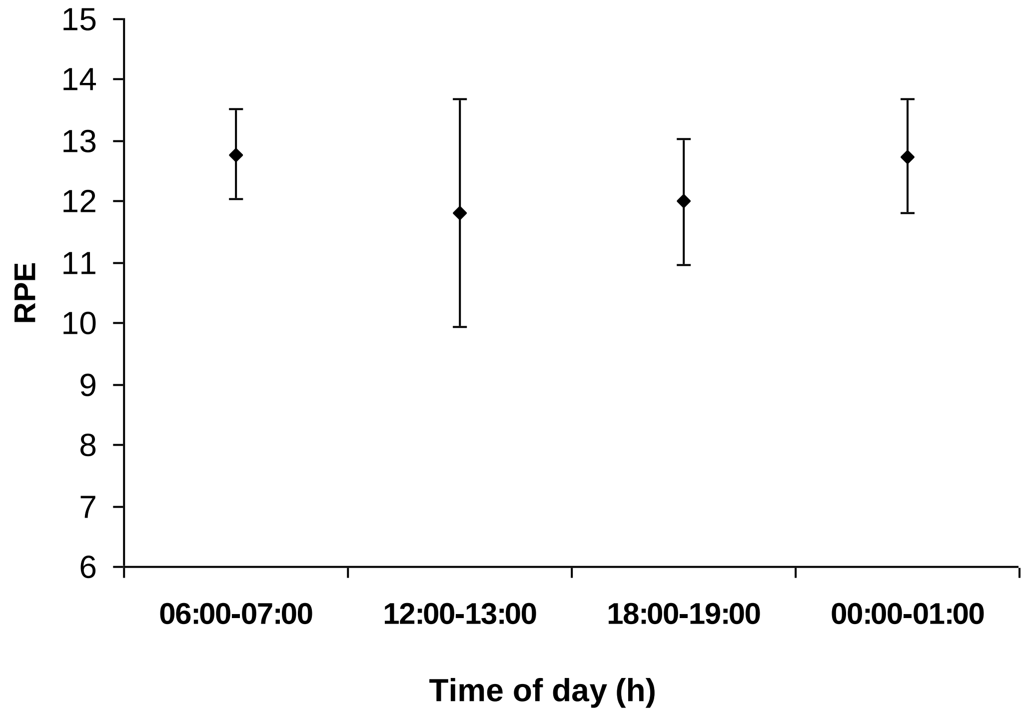


Figure 6.8: Rating of perceived exertion at different times of day.

Table 6.8: Statistical results for rating of perceived exertion at different times of day.

	12:00-13:00	**18:00-19:00**	**00:00-01:00**
06:00-07:00	$t_{(7)} = 1.80$, $p = 0.12$, $d = 0.7$	$t_{(7)} = 1.88$, $p = 0.10$, $d = 0.9$	$t_{(3)} = -1.36$, $p = 0.27$, $d = 0.3$
12:00-13:00		$t_{(7)} = -0.43$, $p = 0.68$, $d = 0.1$	$t_{(3)} = -1.87$, $p = 0.16$, $d = 0.6$
18:00-19:00			$t_{(3)} = -1.2$, $p = 0.32$, $d = 0.8$

6.4.8 Illumination levels

Table 6.9 shows the mean levels of illumination during the four times of day.

Table 6.9: Mean illumination levels (lux) during the testing periods.

	06:00:00	**12:00:00**	**18:00:00**	**00:00:00**
mean	24.1	311.4	0.4	0.0
S.D.	30.9	190.0	1.1	0.0

6.4.9 Correlates to performance

The correlation matrix reported significant correlations between cadence and power (p = 0.01, r = 0.47); RPE and illumination (p > 0.00, r =- 0.54); and RPE and power (p = 0.03, r = 0.42);

6.5 Discussion

The main aim of the study was to determine whether select physiological and performance factors changed with time of day when participants were exercising at an intensity that was representative of ultraendurance mountain bike racing. Significant differences (p < 0.05) were observed for several physiological responses (heart rate, oxygen uptake, salivary cortisol concentrations and intra-aural temperature) but not for performance variables (power output and self-selected cadence). On first appraisal this would suggest that the physiological variables were independent of performance variables, however the data require further scrutiny for two main reasons. Firstly, it may be that the participants were unaccustomed to the experiment and that a test-retest error (coupled with the low sample size during the midnight shift) might have reduced the statistical power and increased the likelihood of a type II error. Secondly, in several of the variables, patterns were observed which were accompanied by relatively large effect sizes. This may have been due to high inter-participant variation. As such, the findings will also be discussed descriptively.

6.5.1 Heart rate

The experimental design was such that no difference in heart rate was expected. However, significant differences were reported between 06:00-07:00 h and 12:00-13:00 h, and between 12:00-13:00 h and 18:00-19:00 h. The absolute differences in mean heart rates were 2 beats·min^{-1} for both comparisons (Figure 6.2). In real-terms the magnitude of this difference is small (~ 1.3%) when compared to the mean exercise heart rate and as such the exercise intensity across the trials can be regarded as relatively consistent.

6.5.2 Oxygen uptake

Horne and Pettit (1984) reported a lack of circadian rhythmicity in submaximal $\dot{V}O_2$ whereas in the present study a significant difference was observed between the values recorded at 12:00-13:00 h and those at 00:00-01:00 h. The magnitude of the difference was 2.1 $mL \cdot kg^{-1} \cdot min^{-1}$. Interestingly this significant difference was not accompanied by a significant difference in heart rate between these shifts, which is in contrast to the reported linear relationship shared between heart rate and oxygen consumption (Hiilloskorpi *et al.*, 1999; McArdle *et al.*, 2001; Ainslie *et al.*, 2003a). The exact reason for this contrasting result is unclear, however the reduced sample size in the midnight trial may have skewed the data.

6.5.3 Salivary cortisol concentrations

The salivary cortisol profile of the participants displays similar values to the free-cortisol cycle as reported by Edwards *et al*. (2001) and Popma *et al*. (2007). The cycle is characterised by a morning peak followed by a decline over the remainder of the day, with a trough at midnight. The results for cortisol indicate that the participants were normal with their phasing of circadian pattern, and that the pre-exercise protocol did not interfere with the natural rhythm. No correlation was reported between salivary cortisol concentrations and any of the other variables measured during the corresponding exercise bouts. This suggests that pre-exercise cortisol concentrations have little effect on performance. What would be of interest is to determine the dynamics of post-exercise cortisol concentrations. This was not undertaken in the present study, but was used to inform the protocol of Study Five.

6.5.4 Intra-aural temperature

Significant differences were observed for intra-aural temperature between the 06:00-07:00 h trial and both the 12:00-13:00 h and the 18:00-19:00 h trials. The magnitude of the differences were 0.7˚C in both comparisons. This nadir in body temperature during the early morning is consistent with previous research (Waterhouse *et al*., 2005; Atkinson *et al*., 2008), however the acrophase in the present study is relatively early when compared to those reported in the literature (Waterhouse *et al*., 2005; Atkinson *et al*., 2008). Although the participants were required to abstain from strenuous exercise 24 h prior to their testing sessions, the early acrophase may have been caused by activities of the participants preceding the test that were beyond the control of the experimenter. These activities may have increased metabolic heat production and masked the true circadian variation (Waterhouse *et al.*, 2005).

6.5.5 Self-selected cadence and power output

Moussay *et al.* (2002) reported a strong positive correlation between the circadian variations in oral temperature and self-selected cadence. This is in contrast to the present study where it was reported that during the 00:00-01:00 h shift intra-aural temperature was low yet cadence was at its greatest (though not significantly different). Notwithstanding the relatively low sample size in the midnight trial, the increase in cadence may not have been the result of a circadian rhythm in MST per se, but may have been influenced by a circadian rhythm in strength. As power output is a product of strength (torque) and speed (cadence), a reduction in strength can be compensated for by a concomitant increase in cadence in order to maintain the desired power output. Evidence of the power output and cadence relationship in the present study is supported by the significant positive correlation reported between these two variables. It has been shown that strength declines during the night (Gifford, 1987) so the observed increase in cadence may have been a compensatory measure. However, the nadir (though not significantly different) in power output during the 18:00-19:00 h trial suggests a reduction in torque during this period which is contrast to other research in the literature where an acrophase for power output, strength and torque have been reported (Gifford, 1987; Coldwells *et al.*, 1993; Callard *et al.*, 2000; Atkinson *et al.*, 2005). The reason for this discrepancy is unclear, and it is difficult to elucidate the exact cause from the available data. However, taken together, the data suggest that 24XCT competitors may produce peaks and troughs in power output at varying times during the race.

Although the participants were free to determine their own cadence, the experimental design may not have facilitated spontaneous self-selection. The relatively short duration of the exercise trial, coupled with participants' potential inertia to alter the resistance, may have meant that participants were prepared to endure a relatively strenuous cadence for the duration of the test. Whereas during a longer performance trial, such as a 24XCT race, participants are more likely to pace themselves and alter their cadence accordingly. Furthermore the protocol, by its very design, did not enable the participants to self-select their work-rate, which is in contrast to what happens during a 24XCT race. An alternative protocol such as working at a fixed power output lacks ecological validity, and a 20 min time-trial format would elicit a greater exercise intensity than that encountered during a 24XCT work-shift. This emphasises the lack of ecological validity when testing these variables in a laboratory and highlights the need for authentic subjects.

6.5.6 Rating of perceived exertion

The lack of change in perceived exertion across the trials suggest that the effects of time-of-day and illumination levels had little effect on this variable and that it does not influence submaximal cycling performance. This supports the findings of other research on light intensity and cycle ergometry (O'Brien and O'Connor, 2000; Ohkuma *et al.*, 2001). However, a significant negative correlation between RPE and illumination level was reported in the present study suggesting that during trials in the lighter conditions the participants perceived the same workload as requiring less effort. The correlations do not imply a causal nexus, and the limited range of ambient light in the present study may have blunted the potential effect of illumination on perceived exertion. The tests were carried out in October with maximal levels of illumination being ~ 310 lux, whereas the vast majority of 24XCT races are conducted during the summer months during which far greater illumination levels can be expected (30 000 + lux in direct sunlight). It may be that under these conditions illumination levels may have a more profound effect.

6.6 Conclusions

The main aim of the study was to determine whether any physiological and performance factors relevant to 24XCT changed with time of day when exercising at an intensity consistent with ultraendurance mountain biking.

The changes in cortisol concentrations were consistent with those previously reported (Edwards *et al*., 2001; Pompa *et al.*, 2007) as was the nadir in body temperature (Waterhouse *et al*., 2005; Atkinson *et al.*, 2008). Whereas the variation in oxygen uptake and the lack of significance in the performance variables were not consistent with previous studies (Table 2.6). Notwithstanding the limitations in methods as highlighted above, it may be that the performance variables are not affected by acute submaximal exercise bouts under natural light intensities at the four time points when participants are free to engage in their normal daily activities (i.e. sleeping, eating and drinking, working and resting). It may be that for short-duration exercise the human body has an acute response and can accommodate the stress without demonstrating any overt changes in the performance factors. In addition, variables that were omitted from the protocol may have a greater influence on 24XCT performance; these may include prolonged exercise bouts, sleep deprivation, serial fatigue, moving body mass against gravity, motivation, environmental factors, competition, and restricted food and fluid intake. These factors will be investigated in more detail in the following chapters. Furthermore the low opportunistic sample size may have blunted the sensitivity of the test to detect any circadian changes in the variables should any variations actually exist.

In conclusion, the laboratory protocol was not ecologically valid and that it is impracticable to simulate a 24XCT race in a laboratory and incorporate all of the relevant variables into the design. This underlines the need to test in the field during race conditions with competitive ultraendurance mountain bikers. The following chapter details the methods for field testing during a 24XCT race.

CHAPTER SEVEN

Field testing – general methods

7.1 Introduction

Hopkins *et al.* (1999) suggest that if a test of performance is to be of any use it should be analogous to the actual athletic event. Many laboratory protocols enable limiting physiological factors to be accurately measured, however they often have little relevance to sport (Krebs and Powers, 1989). Atkinson and Brunskill (2000) note that whilst simulated laboratory time-trials have been reported to be highly reliable for road cycling, they are valid only where there are no variations in external conditions (i.e. wind, hills, terrain, etc.) which, notwithstanding an enclosed velodrome, is an unrealistic scenario. Prins *et al.* (2007) reported a lack of relationship between a simulated laboratory mountain bike performance test and actual race performance. Furthermore, Hopkins *et al.* (1999) advise that a test should only be used if it is shown to be valid and more reliable than the actual event itself, and during which the participants are adhering to their normal training and nutritional practices. Failing these prerequisites they recommend that the 'event itself provides the only dependable estimate of performance' (Hopkins *et al*., 1999, p. 472). Myburgh (2003, p. 182) advises that 'when studying optimal training and performance it is probably better that researchers adapt their methods to suit the study of the relevant cohort'.

Nonetheless field testing is not without consequence; internal validity has the potential to be compromised at the expense of ecological validity. This dichotomy is often unavoidable, but the driving philosophy behind this thesis is for the outcomes to be applied, have ecological validity and be accessible in a currency that is relevant to coaches and athletes.

In light of this perspective, and taking into account the impracticality of replicating in a laboratory all of the variables associated with 24XCT racing, it was deemed necessary to test within the race. Mountain bike performance can be measured directly as race speed in a field setting. Race speed as a primary outcome variable has greater authenticity and relevance to competition performance than laboratory investigations of secondary predictors. However, as concluded in Study Two, ascertaining secondary performance variables during a race can also aid the understanding of the primary outcome.

An aim of this thesis was to develop a minimally invasive field-based protocol that did not interfere with the performance of the participants. The first part of this chapter addresses the rationale for selecting the power meter used to monitor the work done during the subsequent field testing. The second part of this chapter details the field methods that were common to studies Five and Six. Additional, specific methods are described in the relevant chapters.

7.2 Power Measurements

7.2.1 Overview of power meters

As a result of Study Two, directly measuring the power output of the participants was deemed an important factor in order to provide an insight into the temporal work rate. Choosing the most appropriate measuring device was therefore critical to the development of the methods.

In 1986 SRM (Schoberer Rad Messtechnik, Welldorf, Germany) produced the first commercially available portable cycling power meter. The SRM PowerMeter uses a specially engineered chainset with integral strain gauges. When the cranks are unloaded the strain gauges emit a constant electrical signal, however when a force is applied to the pedals, the strain gauges deform and emit a higher frequency signal which is proportional to the force applied (Wooles, 2007). Power output is subsequently calculated using the following equation:

$$P = T\omega = [(f_{loaded} - f_{zero\ offset})\ \nu 2\pi\ /\ F_{cal}\ 60] \qquad \textbf{Equation 10}$$

Where:

P = power (Watts)
T = torque (Nm)
ω = angular velocity (rad^{-1})
f_{loaded} = frequency output of PowerMeter when a known load is applied (Hz)
$f_{zero\ offset}$ = frequency output of PowerMeter when no load is applied (Hz)
ν = cadence (revolutions per minute)
F_{cal} = calibration factor, or "slope" of the PowerMeter (Hz/Nm)

(Wooles, 2007)

The manufacturer reports that the power measurement is reactionless and no energy is lost, and that the PowerMeter is temperature compensated and 100% linear. Several studies have found the SRM system to be valid and reliable (Jones and Passfield, 1998; Martin *et al.*, 1998; Lawton *et al.*, 1999; Balmer *et al*., 2000) and as such it is considered the criterion method for measuring the power output of cyclists. The SRM PowerMeter system is currently available in 18 different configurations based on cycling discipline, chainset / bottom bracket compatibility, and accuracy. The mountain bike specific chainset and the scientific version each have eight strain gauges with manufacturer's reported accuracies of ± 2% and ± 0.5% respectively. However, this method has limitations which are addressed later.

More recently other manufacturers have developed power meters including Powertap (CycleOps, Madison, USA) a wheel hub-based power meter; Polar S710 (Polar, Electro, Oy, Finland) a chain tension-based power meter; Quarq (SRAM, Illinois, U.S.A.) a chainset-based power meter, and Ergomo®Pro (SG Sensortechnik GmbH & Co, Mörfeldn-Walldolf, Germany) a bottom bracket-based power meter.

The Powertap has been shown to be valid and reliable during road cycling (Gardner *et al.*, 2004; Bertucci *et al.*, 2005). In separate studies Millet *et al.* (2003) and Hurst and Atkins (2006b) assessed the validity, reliability and agreement of the Polar S710 and found that power output measurements were affected by several variables including cadence, intensity and vibration during an intermittent protocol. As such the unit was not considered an appropriate tool for accurately measuring power output. Whilst the manufactures of the Quarq system claim an accuracy of ± 2%, there are no validation studies to date. A review of the Ergomo®Pro will subsequently be discussed. Interestingly no studies have investigated the off-road validity and reliability of any of the power meters.

7.2.2 Practical considerations of the power meters

When selecting the appropriate power meter for the current research a relevant concern was the mass of the individual units. Competitive ultraendurance mountain bikers and manufacturers strive to make their bicycles as light as possible; they go to great lengths to source reliable components that have a low mass as this reduces some of the retarding forces (Kirkland *et al.*, 2008). Small increases in mass adversely affect acceleration rate and climbing performance (Martin *et al*., 1998; Jeukendrup *et al*., 2000). Kirkland *et al*. (2008) and Duc *et al.* (2007) note that the Ergomo®Pro has a lower mass when compared to both the SRM PowerMeter and the Powertap and that the greater mass of the latter two could potentially limit their use. Table 7.1 highlights the additional mass added to the bicycle when using power meters.

Table 7.1: The additional mass encountered when using ambulatory ergometers

Power meter	Mass (g)*	Typical components power meter would replace	Mass (g)*	Additional mass (g)
Ergomo®Pro	270	Shimano XTR M952 bottom bracket	230	40
SRM MTB	1024	Shimano XTR M970 chainset/bottom bracket	747	277
PowerTap SL+ 2.4 MTB Disc Hub	680	Shimano XTR M975 Rear disc Hub	270	410
† SRAM Quarq S975 chainset	884	Shimano XTR M970 chainset/bottom bracket	747	137

* manufacturers' reported mass; † mountain bike specific version unavailable

From this perspective, the SRM, Powertap and Quarq would be less favoured by the participants compared to the Ergomo®Pro. Power meter compatibility with the favoured chainsets of the participants was also an important consideration (e.g. competitors routinely use Middleburn Duo[10] chainsets (Middleburn, Hampshire, U.K.) in order to minimise component mass; effectively ruling out the SRM and Quarq). These issues were particularly instrumental in the decision process as interference with the participants' preferred equipment choice may have jeopardized their compliance with the study and possibly their performance.

Furthermore, the data storage capacity of the handlebar-mounted computer units also had to be considered for logistical reasons when operating in a field-based

[10] These chainsets comprise only two chain rings, requiring a specific number of teeth to ensure optimal gear range. The SRM MTB is a triple chainset.

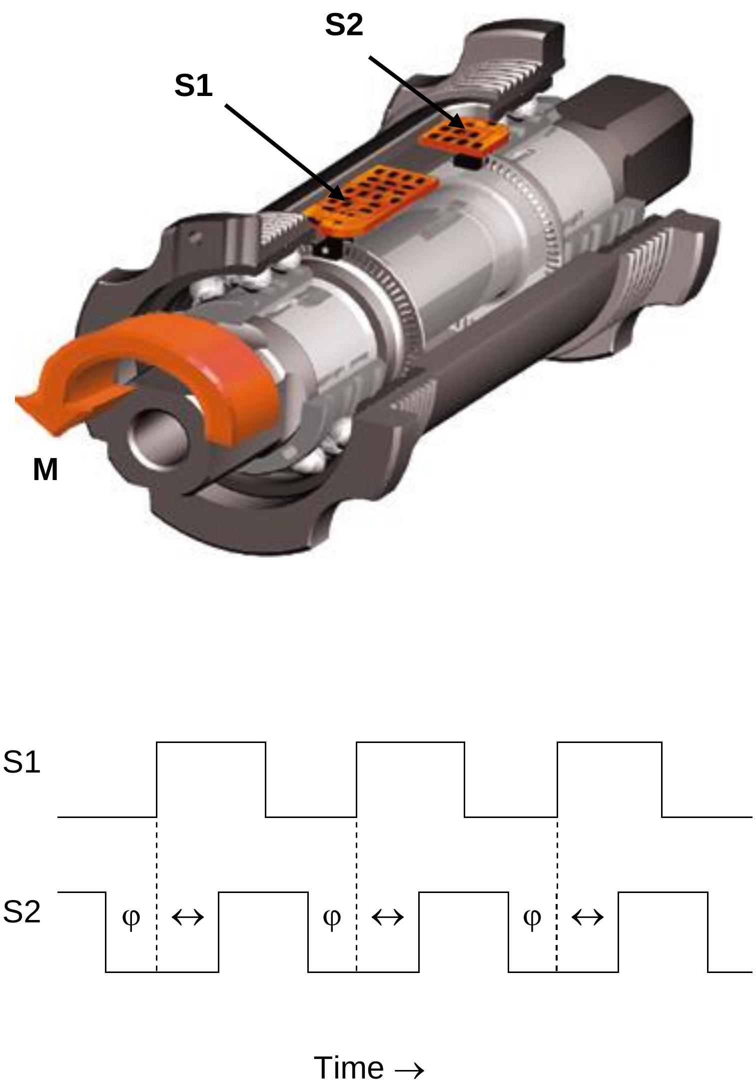
environment for 24 hours. When sampling data at 5 s intervals, the SRM PowerControl has a memory capacity of 18 h, whereas the Ergomo®Pro has a 60 h memory capacity. In light of the above factors, from a practical, logistical and anecdotal standpoint, the Ergomo®Pro was considered most appropriate.

7.2.3 Measuring principle of the Ergomo®Pro sensor

The Ergomo®Pro system consists of a bottom bracket axle sensor and a handlebar-mounted computer capable of displaying and storing data. The bottom bracket sensor employs two optoelectric sensors S1 and S2 that generate square wave signals that are in a phase relationship φ (Figure 7.1). The unit is based on the principle that when a torque is applied to the bottom bracket axle, the axle is twisted by an angle γ and the phase position φ is proportionally altered (Ergomo, 2007). The shifted phase position φ determines the torque (T) and power (P) is calculated using the equation:

$$P = T \times n$$ **Equation 11**

Where: n = cadence (Ergomo, 2007)



(Ergomo, 2007)

Figure 7.1: The measuring principle of the Ergomo®Pro

7.2.4 Validity and reliability of the Ergomo®Pro

The Ergomo®Pro stores 72 data points per crank revolution and has a manufacturer's reported accuracy of ± 0.5% (Ergomo, 2007) which is comparable to that of the SRM Science PowerMeter. However, a noteworthy point is that the sensor only measures the power output on the left-hand side of the axle, and that the recorded value is the power output measured by the sensor multiplied by two (Kirkland *et al*., 2008).

Clearly this principle is based on the assumption that there is bilateral symmetry in pedalling technique. When assessing the bilateral work contribution of nine cyclists using a Lode ergometer (Groningen, The Netherlands), Kirkland *et al.* (2008) reported a 48.9 ± 3.6% contribution from the left leg and 51.1 ± 3.6% from the right. In a validity and reliability study Kirkland *et al.* (2008) concluded that the Ergomo®Pro has acceptable accuracy under laboratory conditions. However, the accuracy of the unit has yet to be determined in a field setting. The following study investigated the agreement between SRM Powercranks and Ergomo®Pro whilst cross-country mountain biking.

7.3 Study four: Agreement between SRM Powercranks and Ergomo®Pro during cross-country mountain biking: a field study.

7.3.1 Methods

7.3.1.1 Experimental design

A field-based research design incorporating repeated trials on separate days was used in this study.

7.3.1.2 Participant information

One well-trained ultraendurance mountain biker volunteered to participate in the study (age 37 years; stature 1.76 m; body mass 70 kg; $\dot{V}O_{2peak}$ 58 $ml \cdot kg^{-1} \cdot min^{-1}$).

7.3.1.3 Instrumentation

As the validity of the SRM is well documented (Jones and Passfield, 1998; Martin *et al.*, 1998; Lawton *et al.*, 1999; Balmer *et al*., 2000), it was used as the criterion measure of power output in this study. The test bicycle, a Specialized S-Works Epic mountain bike, was fitted with an Ergomo®Pro bottom bracket power meter. Prior to installing the Ergomo®Pro, the bottom bracket shells of the test bicycle were re-threaded and re-faced by a skilled bicycle mechanic using a Bottom Bracket Facing Set - BFS-1 (Park Tools, USA). This was done in accordance with the manufacturer’s recommendations in order to ensure that the threads of the bottom bracket were optimally aligned and any bending stress during operation was avoided. The Ergomo®Pro bottom-bracket transmitter cable was interfaced with an Ergomo®Pro computer mounted on the left-hand side of the handlebar. An SRM Science PowerMeter (175 mm crank length, SRM, Jüllich, Germany) incorporating eight strain gauges was mounted onto the Ergomo®Pro bottom-bracket. A Powercontrol meter was mounted on the right-hand side of the handlebar and interfaced with the PowerMeter via a wired sensor attached to the bottom bracket shell, as per the manufacturer's guidelines. Figures 7.2 and 7.3 shows the bicycle and equipment configuration. Both power meters were set to sample data at 1 second intervals. Calibration certificates for the power meters can be found in Appendix I.

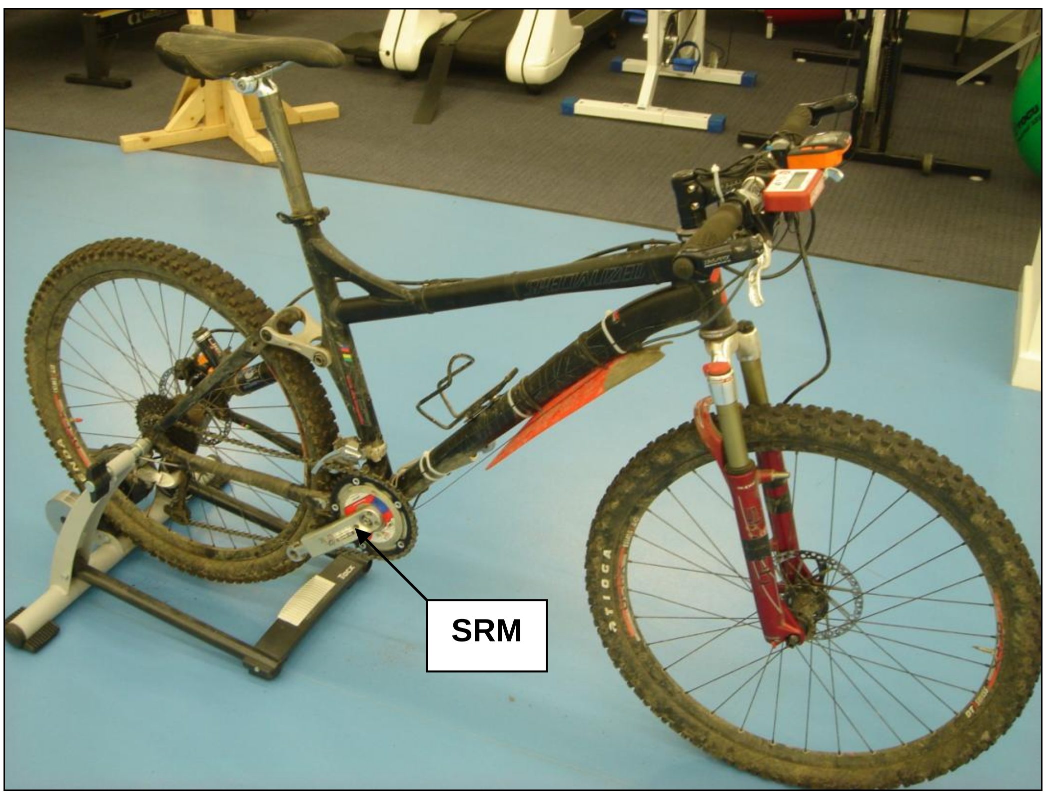


Figure 7.2: The mountain bike fitted with SRM and Ergomo®Pro power meters

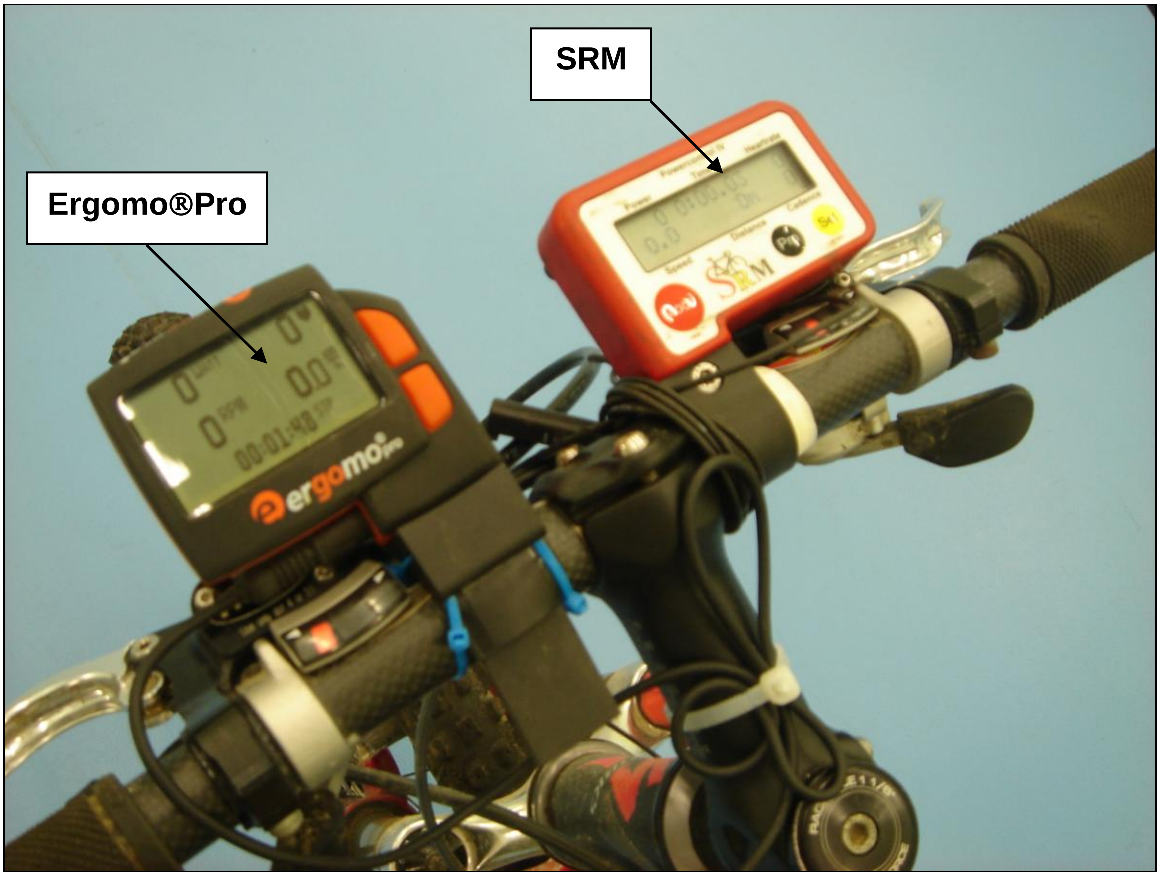


Figure 7.3: The handlebar-mounted display units of the power meters

7.3.1.4 The course

The data collection trials took place on a 5 km off-road circuit at Rivington Country Park, Lancashire, UK. The profile of the course is shown in Figure 7.4. The terrain was representative of a typical cross-country mountain bike course in accordance with UCI recommendations (UCI, 2006). Furthermore sections of the course have been previously used in the 2002 Commonwealth Games mountain bike competition. The total ascent per lap was 229 m.

Table 7.2: Environmental and course data for the agreement study

Variable	Value
Total vertical distance climbed (m)	231
Mean gradient (%)	4.6
Starting point from sea level (m)	150
Altitude range (m)	150 - 357
Temperature range (Celcius)	16 - 17
Precipitation	none

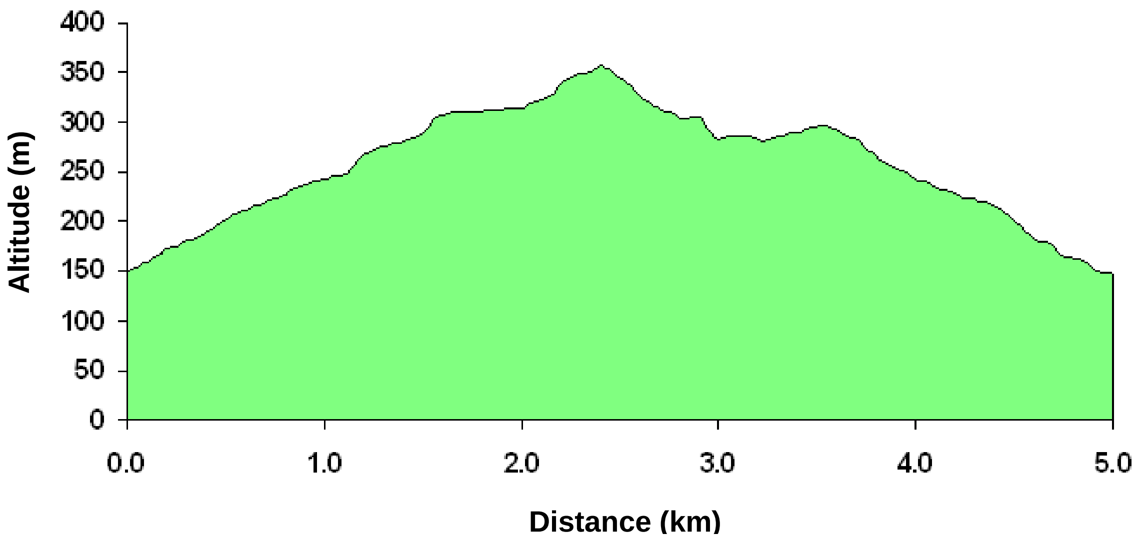


Figure 7.4: The profile of the test course

7.3.1.5 Test administration

Prior to testing, the offset procedures for SRM PowerMeter and the Ergomo®Pro were conducted in accordance with the respective manufacturers' guidelines. Following a self-paced 25 minute warm-up the participant completed three time-trial laps of the course (each time trial was separated by ten minutes active recovery) on four non-consecutive days, giving a total of 12 laps.

7.3.2 Statistical analysis

The differences between the power output measurements of the SRM and the Ergomo®Pro were compared using 95% limits of agreement (Bland and Altman, 1986; Atkinson and Nevill, 1998).

7.3.3 Results

7.3.3.1 Power

The data were analysed for heteroscedasticity by comparing the correlate of the mean and the absolute differences against the correlate of the $mean_{log}$ and absolute $difference_{log}$. The former correlation was not greater than the latter, indicating that the data were not heteroscedastic (Bussell, n.d.). As such absolute limits of agreement were used. Analysis of the absolute limits of agreement of the Ergomo®Pro for power output revealed a systematic bias (± random error) of 4.88 W (± 6.115, 95% limits of agreement = 10.995 - 1.235).

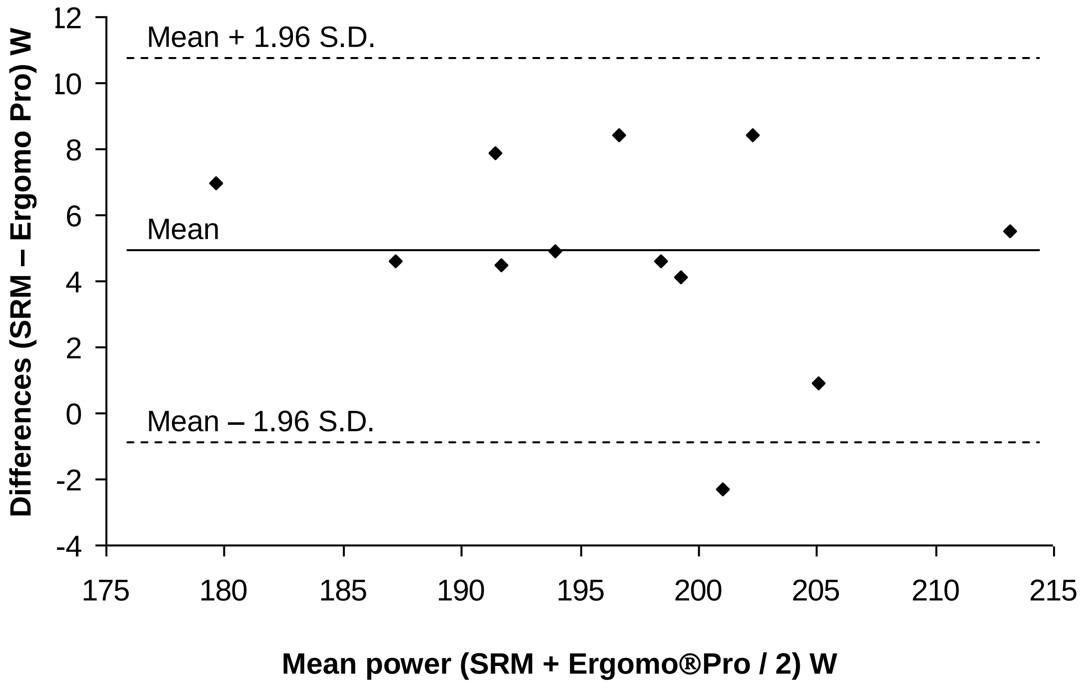


Figure 7.5: Bland-Altman plot of the differences between power output values recorded by the SRM and Ergomo®Pro power meters against mean power output .

Figure 7.5 shows the Bland-Altman plot of the differences between power output values recorded by the SRM and Ergomo®Pro power meters against mean power output. The line of equality and graphed raw power output data for the SRM and Ergomo®Pro for sample trials can be found in Appendix J.

7.3.3.2 Cadence

The data were analysed for heteroscedasticity by comparing the correlate of the mean and the differences against the correlate of the $mean_{log}$ and absolute $difference_{log}$. The former correlation was positive and greater than the latter, indicating that the data were heteroscedastic (Bussell, n.d.). As such ratio limits of agreement were used. Analysis of the ratio limits of agreement for cadence revealed a systematic bias (*/÷ random error) of 1.00 (*/÷ 1.059; 95% ratio limits of agreement = 0.94 – 1.059) indicating there is minimal difference between the two power meters with regard to cadence. Figure 7.7 shows a Bland-Altman plot of the differences between cadence values recorded by the SRM and Ergomo®Pro power meters against mean cadence.

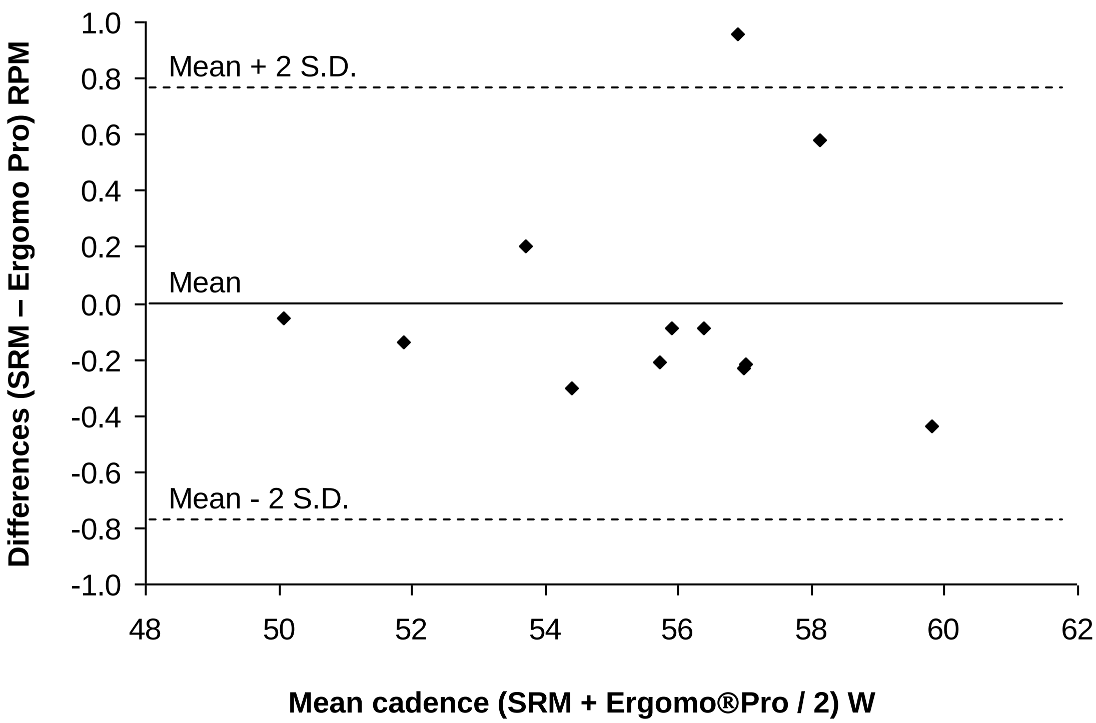


Figure 7.6: Bland-Altman plot of the differences between cadence values recorded by the SRM and Ergomo®Pro power meters against mean cadence.

7.3.4 Discussion

The aim of this study was to assess the agreement between the SRM PowerMeter and the Ergomo®Pro with a view to the latter being used as an appropriate tool to measure mean power output and cadence during a 24XCT mountain bike race. With regard to power output, the systematic bias and the random error represent 2.4 % and ± 3.1% of the grand mean of the sample respectively. These values are somewhat greater than the manufacturer's claimed accuracy of ± 0.5% (Ergomo, 2007). A most likely contributor to this error is the assumption of bilateral symmetry in pedalling technique. The analysis indicates that there is minimal bias for cadence. It should be noted that the limits of agreement are only estimates of the values that apply to the wider population, and that a different sample of power output data would give different limits (Bland and Altman, 1986). Furthermore, different Ergomo®Pro power meters and participants will give different limits of agreement.

To date no standard has been set as to what is acceptable for power output meters when using limits of agreement. However, Van Praagh *et al.* (1992) recommend that cycle ergometers should be within a 5% margin of error if they are to provide an accurate and reliable measurement of power output.

Taken together with the practical considerations alluded to previously, it was considered that the accuracy of the Ergomo®Pro was acceptable and that the unit was fit for purpose for measuring mean power output and cadence during a 24XCT mountain bike race.

7.4 General field methods

This section details the rationale and methods for testing during a 24 h team relay race. Field measurements were taken on one four-person team during the 2008 Bontrager Twentyfour12 endurance mountain bike race in Plympton, Plymouth. The methods described here form the basis of the testing for the remainder of the thesis. Specific methods will be addressed where appropriate.

7.4.1 Rationale for field methods

The protocol was designed to glean as much relevant information as possible whilst being minimally invasive and not impinging on the participants' performance in any way. Any disruption would have potentially altered the focus of the study from investigating a 24 h team *race* to that of studying a team *ride*. Clearly any hindrance in proceedings would have had a dramatic affect on the team's performance. Furthermore, the cooperation of the team members was imperative and as such the protocol needed to be as least disruptive to their race strategy as possible. The strategy chosen by this particular team was based on their previous race experience, and comprised changing team members every two laps (~90 min cycling, with ~270 min recovery).

7.4.2 Participants

7.4.2.1 Recruitment of participants

Participants were recruited opportunistically via the race organiser's promotional email newsletter and also via requests on relevant mountain bike Internet forums. Selection criteria were based on the previous three years' performance and the current year's (2008) intended race schedule. Five potential teams were approached and invited to be part of the study. Three teams expressed an interest, however due to geographical and timing restrictions (amongst other commitments) all of the riders from only one team could attend the pre-race laboratory testing within three weeks of the July 2008 race date.

7.4.2.2 Participant information

Four male participants volunteered for the study (age 36 ± 8.5 years; stature 1.77 ± 0.05 m; body mass 80.2 ± 3.1 kg). The participants were experienced competitive 24XCT mountain bikers. Table 8.1 shows the physiological characteristics of the participants. Based on their racing background and relative PPO data in Table 8.1, the participants were defined as well-trained according to the classification criteria for scientific cycling research proposed by Jeukendrup *et al*. (2000a). As such they were an ecologically valid cohort to study.

7.4.3 The 24XCT race

The event was chosen on merit as the course is highly regarded within the mountain bike fraternity. It is one of the three main prestigious 24 h races in the UK (alongside Original Source Mountain Mayhem and Endura Sleepless in the Saddle), and has been host to five rounds of the Cross Country Mountain Bike World Cup amongst other high-profile races. The course was 12.6 km and was entirely off-road. The race organisers provided medical support for all race entrants and participants provided their own bicycles (each participant chose to use a front suspension, hardtail mountain bike).

Due to the race being staged on a closed course with a circuit-based format (as opposed to a point-to-point), it was possible to have frequent access to the participants in order to perform the test procedures.

Table 7.2 shows environmental and course data for the race. Environmental data were collected via an Oregon Scientific Weather Station (Oregon Scientific Ltd., Berkshire, UK). Figure 7.7 shows the profile of the race course.

Table 7.3: Environmental and course data for the 24XCT race

Factor	Value
Start time	12.00 h
Lap distance (km)	12.6
Total vertical distance climbed per lap (m)	299
Mean gradient (%)	2.4
Starting point altitude from sea level (m)	55.8
Altitude range (m)	52.4 - 157
Temperature range (˚C)	8.6 – 20.8
Precipitation	none

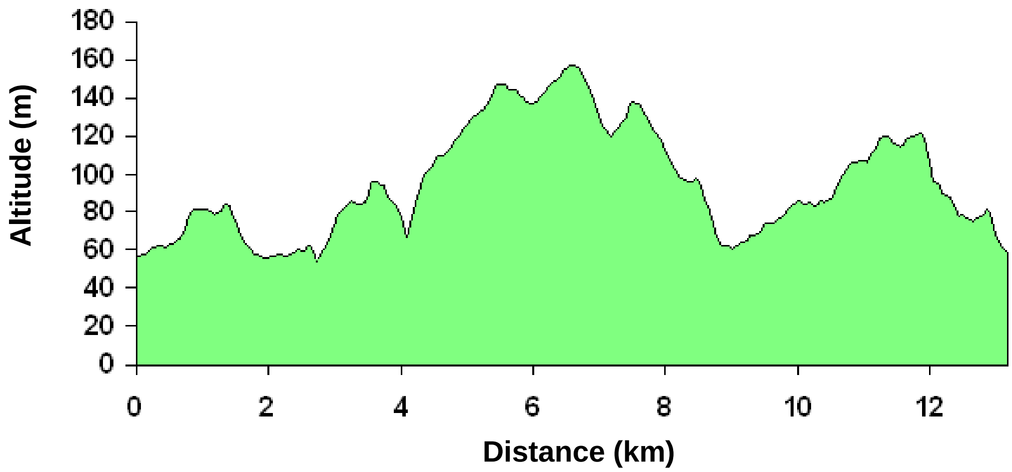


Figure 7.7: The profile of the 24XCT race course

Ambient light was measured in lux using a Minilux P1 Photoelectric Photometer (Salford Electrical Instruments Ltd., Manchester, U.K.). Figure 7.8 shows Illumination levels and ambient temperature during the race.

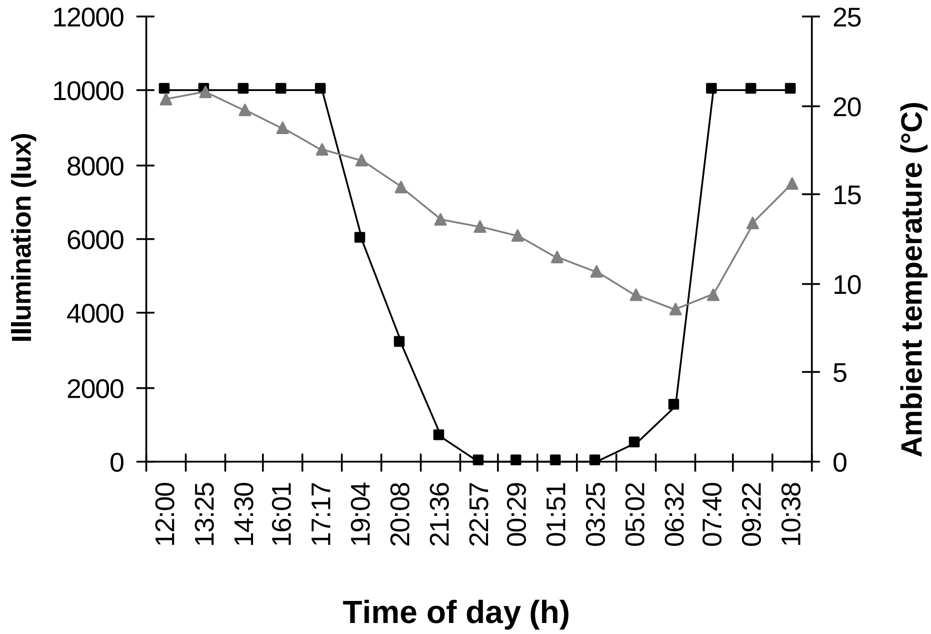


Figure 7.8: Illumination levels (■) and ambient temperature (▲) during the race. Maximum illumination measurements were limited to 10 000 lux.

7.4.4 Data collection

7.4.4.1 Field laboratory

All of the testing took place in a field laboratory situated next to the rider transition zone. The field laboratory comprised an enclosed trailer with electrical power supply (via a generator), work benches, freezer and specific bloods area (Figure 7.9). The field laboratory was situated less than 30 m from the transition area which facilitated an expedient transfer of the participants to the laboratory following their race shifts.

The race commenced at 12:00 h, and the format was for participant 1 to complete two laps of the course, then in the transition zone, pass a baton to participant 2 who would then complete two laps. After the completion of his shift,

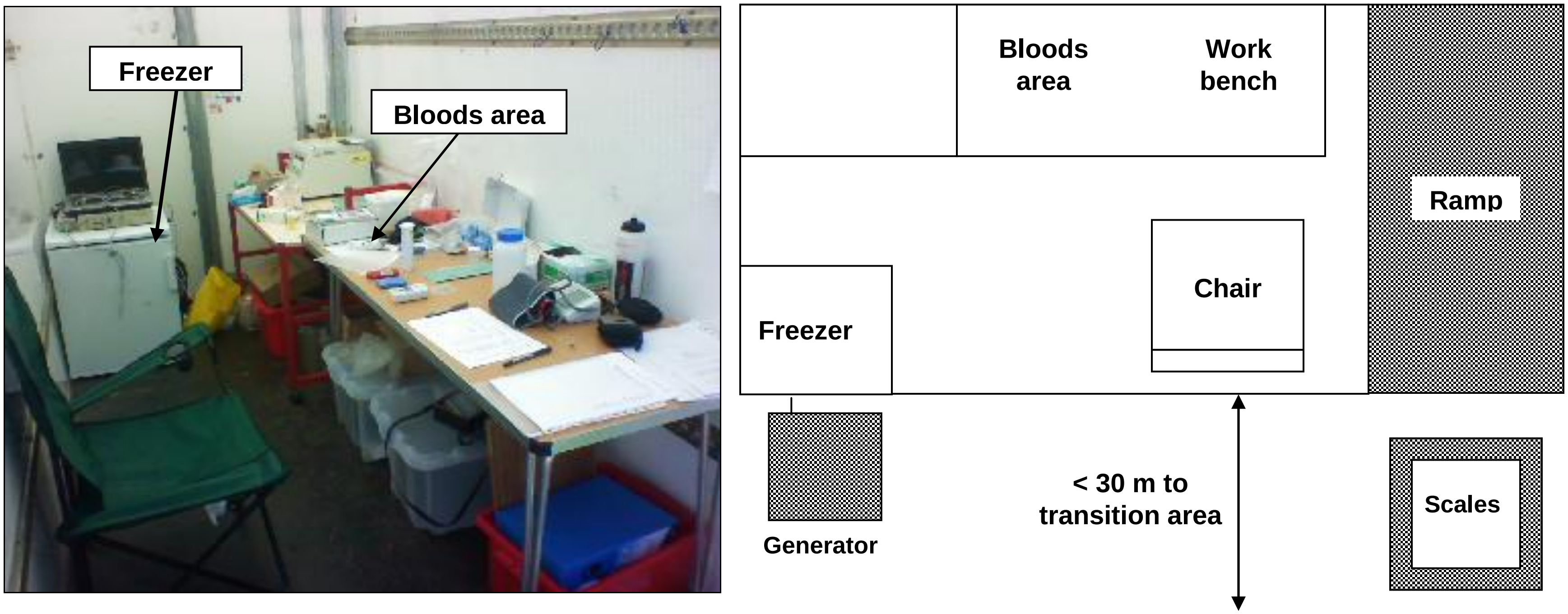


Figure 7.9: Inside (left) and floor plan (right) of the field laboratory.

Figure 7.10: A participant undergoing pre work-shift testing

participant 2 would then hand the baton to participant 3 who would then complete two laps and hand it on to participant 4. This process was repeated throughout the duration of the race. The winning team is deemed the one which completes the most laps in the 24 h period, however if a rider is still on the course when the 24 h time elapses he must complete the lap and it is included in the team's lap total. If different teams have a similar lap total then the higher placed team will be the one that has completed their laps in the least time. Participants were informally interviewed by telephone after the event to clarify aspects of their practices during the race.

Each participant was issued with a Motorola T5503 two-way radio (Motorola, Schaumburg, Illinois) and, at a pre-determined point on the course, the participants were instructed to radio through to the field laboratory. This was done in order to give advanced notice to the experimenter to begin the pre work-shift tests on the next participant and to prepare the laboratory for the post work-shift tests. The timing of the pre work-shift testing was conducted in accordance with how long the participant required to warm-up for the subsequent shift and were performed prior to the warm-up (typically 20-30 min prior to racing).

An assistant was sent to meet the incoming participant in the transition zone in order to ensure the Ergomo®Pro computer was coded to mark the end of the shift, and to administer a small amount of water in order to rinse the participant's mouth prior to salivary collection. Upon completion of each shift the incoming participant rode the short distance (<30 m) out of the transition area to the field laboratory where the testing commenced. Figure 7.11 details the protocol checklist for incoming and outgoing participants and details the order of the testing. Incoming participants were free to perform their cool-down routines after the testing protocol was conducted. In between work-shifts participants apportioned their time between activities for rest, sleep, food and fluid intake, and ablutions.

During the night-time work-shifts the participants used their own preferred illumination systems which in all cases comprised two handlebar mounted lights. Two participants used Blackburn X^6 systems (Blackburn, Santa Cruz, California) (mass = 874 g; manufacturer's reported illumination levels = 915 lux per light) and two used Light and Motion Solo Logic systems (Light and Motion, Monterey, California) (mass = 430 g; manufacturer's reported illumination levels = 675 lux per light).

7.4.4.2 Performance measurements

Power output, cadence and heart rate for each work-shift were recorded at 5 s intervals via an Ergomo®Pro (SG Sensortechnik GmbH & Co, Mörfeldn-Walldolf, Germany) bottom bracket power meter fitted to each subject's bicycle. Each unit was brand new and had been calibrated prior to use. The offset procedure was performed prior to each work shift. Official lap times from the race organisers (Appendix K) were used to calculate race speed.

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}} \qquad \textbf{Equation 12}$$

7.4.4.3 Physiological measurements

Blood lactate, blood pressure, salivary cortisol, and intra-aural temperature were measured in accordance with the methods described in Chapter Three. In addition to recording heart rate during the work-shift via the Ergomo®Pro, heart rate was also recorded continuously throughout the 24 h period via Polar heart rate monitors (Polar Electro, Oy, Finland). Polar coded chest transmitters were used and were worn in accordance with the manufacturer's guidelines.

Gross efficiency was calculated using the following equation:

$$\%\ \text{Gross efficiency} = \frac{\text{External power}}{\text{Metabolic work rate}} \times 100 \qquad \textbf{Equation 13}$$

Where: metabolic work rate = $\dot{V}O_2$ (absolute) x 348.8 (W per litre of O_2)

(Cooke, 2004)

7.4.4.4 Psychological measurements

Ratings of perceived exertion were recorded in accordance with the method in Chapter Three. The participants' positive and negative affect scale was measured via PANAS questionnaires (Watson *et al.*, 1988. Appendix B). The participants were instructed to circle the most appropriate answer on the Likert scale.

Outgoing participant	✓
Verbal confirmation mouth has been rinsed	☐
Record ambient temperature	☐
Record illumination level	☐
RPE	☐
Administer salivette	☐
Blood lactate	☐
Blood glucose	☐
Blood pressure and heart rate	☐
P.A.N.A.S.	☐
Intra-aural temp.	☐
Body mass	☐
Urine sample	☐
Collect salivette	☐
Post warm-up:	
Visual confirmation heart rate monitor belt is on	☐
Visual confirmation Ergomo has been coded	☐

Incoming participant:	✓
Incoming message received	☐
Assistant sent to meet rider	☐
Record ambient temperature	☐
Record illumination level	☐
Upon arrival:	
RPE	☐
Verbal confirmation Ergomo has been coded	☐
Verbal confirmation mouth has been rinsed	☐
Blood lactate	☐
Blood glucose	☐
Blood pressure and heart rate	☐
Administer salivette	☐
P.A.N.A.S.	☐
Intra-aural temp.	☐
Body mass	☐
Urine sample	☐
Collect salivette	☐
Visual confirmation Ergomo has been coded and record summary screen.	☐

Figure 7.11: Protocol check lists for outgoing and incoming participants

CHAPTER EIGHT

Study Five: Physiological and performance variables during an ultraendurance team relay mountain bike race

8.1 Introduction

In addition to the physical demands encountered during XCM racing as described in Study Two, competitors in 24XCT races have to deal with sleep deprivation, circadian rhythm disturbances, and changes in both ambient temperature and illumination levels. It is clear from the literature that athletic performance fluctuates over a nycthemeral period (Table 2.6), however data on 24XCT performance is scarce. This information is of importance to sport scientists, coaches and athletes involved in these events. Study Three highlighted the need to test these factors in a field setting. As such the purpose of this study was to characterise the bioenergetics and the physiological and performance variables during a 24 h ultraendurance mountain bike relay race.

8.1.1 Research aim

The aim of this study was to monitor the performance variables and physiological responses of the participants during the 24XCT race.

8.2 Preliminary laboratory testing

All preliminary laboratory testing was performed within three weeks of the start of the race. Anthropometric and physiological characteristics were measured in accordance with the methods detailed in Chapter Three.

8.3 Results

8.3.1 Anthropometric and physiological characteristics

Table 8.1 summarises the anthropometric and physiological characteristics of the participants.

Table 8.1: Anthropometric and physiological characteristics of four participants competing in a 24 h mountain bike relay race.

Variable	Mean ± S.D.
Body Fat (%)	10.7 ± 2.6
Muscle mass (kg)	45.3 ± 6.3
Absolute PPO (W)	422 ± 23.3
Relative PPO ($W \cdot kg^{-1}$)	5.3 ± 0.5
HR_{max} ($beats \cdot min^{-1}$)	185 ± 7
Absolute $\dot{V}O_{2peak}$ ($L \cdot min^{-1}$)	5.3 ± 0.8
Relative $\dot{V}O_{2peak}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	66.1 ± 9.6

8.3.2 Performance results

During the competition the team employed a two-laps-on (one complete work-shift), six-laps-off racing strategy. This resulted in a total of 18 work-shifts comprising 35 laps (Appendix K). Participants 1 and 2 completed five work-shifts (this included a one lap final work-shift for participant 1) and participants 3 and 4 completed four work-shifts. Only data for the first four work-shifts per participant were included in the analysis. Data for the fifth work-shifts for participants 1 and 2 can be found in Appendix L. Table 8.2 summarises the mean performance data for the participants during the 24XCT race.

Table 8.2: Mean work-shift performance data for a team of 4 competitors in a 24 h mountain bike relay race.

Variable	Mean ± S.D.
Overall standing	4^{th} place finishers
Speed ($km \cdot h^{-1}$)	18.3 ± 2.6
HR ($beats \cdot min^{-1}$)	157 ± 10
HR_{ave}/HR_{max} (%)	85 ± 3
Absolute power output (W)	219 ± 50.9
Relative power output ($W \cdot kg^{-1}$)	2.7 ± 0.7
Cadence (rpm)	64.1 ± 9.3
% $\dot{V}O_{2peak}$	75.7 ± 9.1

8.4 Data analysis

Due to the relay format of the race, only one team member was competing at any one time thus negating the ability to compare data for all participants concurrently. For analysis purposes a multiple case study design was employed. In addition, descriptive data were generated and a correlation matrix was used to compare physiological and performance variables using Pearson's Product Moment Correlations (Appendix M).

8.4.1 Rationale for not testing differences

To date the only comparable study has been by Laursen and co-workers (2003a). These authors measured selected physiological variables from four riders during a 24XCT race (which was subsequently reduced to 12 h due to inclement weather). They set a precedent by using a repeated measures ANOVA to analyse the data. However, the authors did not make it clear how the data met the criteria for such a statistical test. The assumptions for ANOVA are that the data should be normally distributed, the variances for each condition are similar and data should be at least on an interval scale (Field, 2006). It is doubtful that four observations can be reliably tested for normal distribution parameters (Siegel and Castellan, 1988; Fallowfield *et al.,* 2005). Indeed, in the present study many data sets had skewness and kurtosis ratios between -2 and +2 thus suggesting normality. However, this observation is more likely due to a statistical artefact rather than a normal distribution. Fallowfield *et al.* (2005) note that although ANOVA are relatively robust to violations, if such violations exist in every group the reliability of the test is compromised, thus questioning the use and prophetic power of the test. Furthermore, when using power output in the present study as an example, the inter participant difference was comparable to the between work-shift difference thus increasing the likelihood of a type II error. Wirnitzer and Kornexl (2008) collected data on five males and two females during an eight stage mountain bike race. They acknowledged the small sample size and used nonparametric tests (Friedman test and Wilcoxon paired tests) to test differences. However, nonparametric tests discard information in the data by reducing them to ranks, and are limited to one factor designs which are not suited for the pre and post work-shift analysis required for the present study. For information purposes, results of testing differences on data from the present study can be found in Appendix N.

8.4.2 Rationale for multiple case study design

The in-field methodological design was dictated by the team's race strategy and the competition regulations. Figure 8.1 provides a schematic temporal representation of the participants' work-shifts. To compare mean work-shift values for analysis is not without issue. It could be argued that, from a temporal and circadian perspective, participant 4's data from work-shift 1 is closer to participant 1's data from work-shift 2 than it is to participant 1's from work-shift 1 (shaded areas in Figure 8.1). However, in this example it would involve comparing participant 4's first work-shift with participant 1's second work-shift and not take into account serial fatigue effects.

Race shift	1				2				3				4			
Participants	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Timescale	~ 0-6h				~ 6-12h				~ 12-18h				~18-24h			

Figure 8.1: Schematic temporal representation of the participants' work-shifts

To avoid this issue, the most appropriate method of data analysis was deemed to be multiple case studies. Not employing statistical analysis may "go against the tide" of established practice, but in this case is wholly justifiable. This approach is commonplace in other branches of science where populations by definition are small (rare diseases, isolated psychological conditions, and animal populations at risk of extinction (Barlow and Hersen, 1984; Zhan and Ottenbacher, 2001)). When dealing with small-n samples from cycling and other ultraendurance sports, previous researchers have successfully employed case-study designs (Neumayr *et al.*, 2002; Bowen *et al*., 2006; Carpes *et al.*, 2007; Stewart and Stewart, 2007).

8.5 Findings

The findings are split into two sections. Firstly data are analysed on an individual basis where the nuances and specific traits of each participant are highlighted.

This is followed by a comparative analysis where common themes across participants are identified and analysed. These observations and how they potentially affected performance form the basis of the subsequent discussion.

8.5.1 Individual data

Table 8.3 shows descriptive anthropometric, physiological and work-shift information for each participant.

Table 8.3: Individual participant data

Participant	Age (y)	Mass (kg)	Stature (m)	$\dot{V}O_{2peak}$ (mL·kg^{-1}·min^{-1})	Work-shift start time (hh:mm:ss) 1	2	3	4
1	26	83.7	1.84	71.5	12:00:00	17:17:48	22:42:19	03:47:27
2	32	76.5	1.78	73.4	13:25:08	18:48:53	23:14:28	05:16:36
3	44	81.5	1.72	52.1	14:30:23	19:54:05	00:37:06	06:24:27
4	42	79.1	1.75	67.3	16:01:56	21:21:21	02:11:12	08:16:40

8.5.1.1 Participant 1

Participant 1 had been cycle racing for 12 years and was a former British Road Cycling team member. He was also a former cyclo-cross competitor. He had been competing in ultraendurance mountain biking for seven years. At the time of the study he was in the competition phase of his training macrocycle and had started the racing season in March of the same year. Table 8.4 shows the mean physiological and performance variables for participant 1 during the 24 h race.

Table 8.4: Mean physiological and performance variables for participant 1 during the 24 h race.

	Work-shift 1		Work-shift 2		Work-shift 3		Work-shift 4	
Speed (km·h^{-1})	17.8		15.0		16.4		16.6	
Power (W)	177		155		153		193	
HR (beats·min^{-1})	161		162		158		156	
Cadence (RPM)	70		55		68		69	
Efficiency (%)	11.3		9.8		10.0		13.0	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
RPE (arbitrary units)	9	17	9	18	13	19	12	16

Participant 1's data shows a reduction in speed, power output, cadence and gross efficiency during the second work-shift compared with the first. During the third work-shift speed, cadence and gross-efficiency increased, whereas power output remained constant and heart rate decreased. In the final work-shift there was a further increase in speed, power output and gross efficiency without an increase in heart rate. Participant 1 reported unusually high pre work-shift RPE values especially during the latter half of the race. The cause of this elevated perception of exertion is unclear. Of interest is the relatively low gross efficiency across work-shifts. This is addressed in detail in Chapter 8.6.1.5.

8.5.1.2 Participant 2

Participant 2 was a former nationally ranked elite XCO mountain biker who had been competing in cross-country racing for nine years, and specifically ultraendurance cross-country for four years. At the time of the study he was in the competition phase of his training macrocycle and had started the racing season in March of the same year. Table 8.5 shows the mean physiological and performance variables for participant 2 during the 24 h race.

Table 8.5: Physiological and performance variables for participant 2 during the race.

	Work-shift 1		Work-shift 2		Work-shift 3		Work-shift 4	
Speed (km·h^{-1})	23.2		23.6		18.4		22.3	
Power (W)	261		266		204		215	
HR (beats·min^{-1})	168		171		151		148	
Cadence (RPM)	76		78		68		72	
Efficiency (%)	21.6		21.3		20.2		22.4	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
RPE (arbitrary units)	6	17	6	18	6	19	7	19

For participant 2 the variables were relatively constant during the first half of the race. This was followed by a reduction in speed, power output, heart rate and cadence during the night-time shift. Heart rate then dropped further for the fourth work-shift whilst the other variables increased. His gross efficiency remained relatively constant for the first two work-shifts, and then decreased during the third followed by a peak during the fourth.

8.5.1.3 Participant 3

Participant 3 had been competing in cycle racing for 22 years and specifically in ultraendurance mountain biking for the last four. At the time of the study he was in the competition phase of his training macrocycle and had started the racing season in May of the same year. Table 8.6 shows the mean physiological and performance variables for participant 3 during the 24 h race.

Table 8.6: Physiological and performance variables for participant 3 during the race.

	Work-shift 1		Work-shift 2		Work-shift 3		Work-shift 4	
Speed (km·h^{-1})	16.6		17.3		16.2		14.8	
Power (W)	217		210		183		163	
HR (beats·min^{-1})	169		165		149		135	
Cadence (RPM)	56		57		50		47	
Efficiency (%)	16.3		16.2		15.6		15.4	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
RPE (arbitrary units)	7	16	7	18	8	17	9	19

For participant 3 speed, power output, heart rate, cadence and efficiency were relatively consistent during work-shifts 1 and 2. There was a progressive decrease in these variables during the second half of the race. His profile was consistent with a down-regulation of performance due to fatigue during the second half of the race. The aetiology of this is unclear from the data presented in Table 8.6, however it is possible that glycogen depletion was a contributing factor and will be addressed in greater detail in the following chapter.

8.5.1.4 Participant 4

Participant 4 had been competing in XCO for 18 years, and specifically ultraendurance mountain biking for eight years. At the time of the study he was in the competition phase of his training macrocycle and had started the racing season in March of the same year. Table 8.7 shows the mean physiological and performance variables for participant 4 during the 24 h race.

Table 8.7: Physiological and performance variables for participant 4 during the race.

	Work-shift 1		Work-shift 2		Work-shift 3		Work-shift 4	
Speed (km·h^{-1})	19.9		18.7		15.7		19.8	
Power (W)	313		275		230		296	
HR (beats·min^{-1})	171		159		141		155	
Cadence (RPM)	70		62		58		70	
Efficiency (%)	21.3		20.9		21.3		23.4	
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
RPE (arbitrary units)	7	16	7	16	7	17	7	18

The data for participant 4 revealed a nadir for speed, power, cadence, and heart rate during work-shift 3. His speed and cadence returned to initial levels in the final work-shift and his heart rate increased slightly. His gross efficiency was relatively stable across the first three work-shifts and then peaked during final work-shift.

8.5.2 Comparative analysis

Figure 8.2 provides a graphical comparison of speed, power output, heart rate and gross efficiency for each participant for each work-shift. It highlights common themes shared by the participants.

8.5.2.1 Speed, power output and cadence

Race speed was variable between participants and also between work-shifts. This variation could be due to a myriad of physiological, environmental, nutritional, technical and psychological factors. With the exception of participant 3, a commonality of the participants was an increase in speed, power output and cadence during the final work-shift compared with the penultimate one.

8.5.2.2 Heart rate and gross efficiency

For all of the participants mean heart rates were lower in the third work-shift compared to those in the second. With the exception of participant 4, mean heart rates subsequently dropped to their lowest values in the final work-shift. Unfortunately, the continuous measurement of heart rate for the entire 24 h period was problematic. During the sleeping period 50% of the participants had some data loss, thus recovery heart rates cannot be compared.

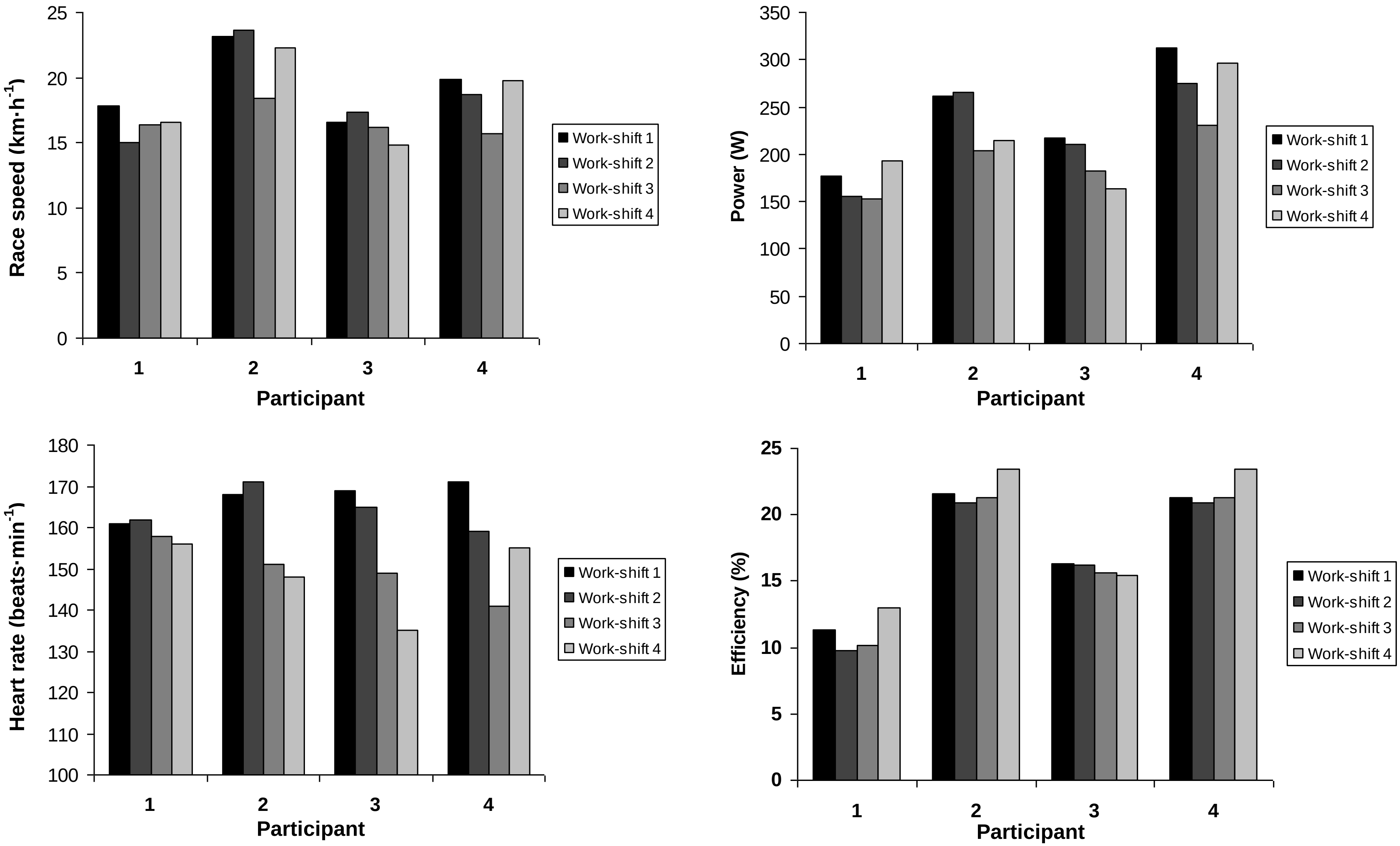


Figure 8.2: Comparison of performance and physiological variables by work-shift

Gross efficiency was significantly correlated to race speed (*r* = 0.64, *p* = 0.01). For all participants it was less than the 24.4 to 28.8% range Lucía *et al.* (2002b) reported for well-trained competition road cyclists. The most likely explanation for the attenuated value is the increased energy cost of mountain biking due to the bicycle design and the terrain as reviewed in Chapter 2.3.2.6. Gross efficiency values oscillated slightly during work-shifts 1 to 3, then (with the exception of participant 3) they increased with the participants recording their greatest values in the fourth work-shift.

8.5.2.3 Blood lactate

As was expected post work-shift blood lactate concentrations were elevated compared to pre work-shift values indicating an anaerobic contribution to the energy provision. Of interest is the common attenuation of blood lactate concentrations post work-shift 3 (Figure 8.3). This issue will be discussed later in the chapter.

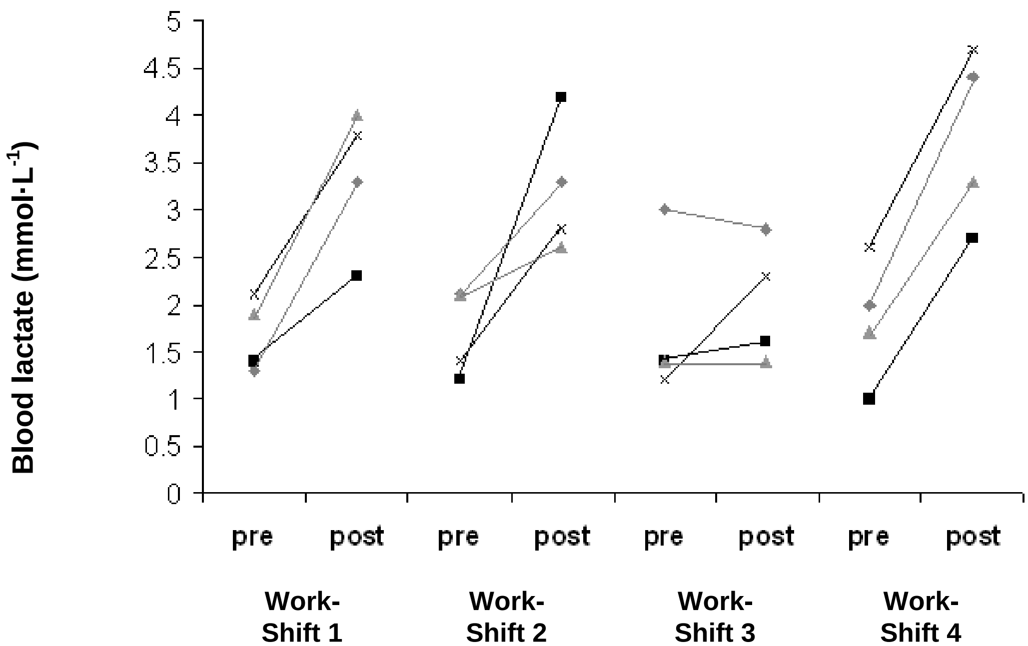


Figure 8.3: Blood lactate concentrations for participants 1 (♦), 2 (■), 3 (▲) and 4 (x) pre and post each work-shift.

8.5.2.4 Salivary cortisol

Pre work-shift salivary cortisol concentrations for all participants were consistent with normal circadian values reported in the literature (Kudielka *et al.*, 2007; Salimetrics, 2010) and those reported in Study Three for sports science students. As expected post work-shift concentrations were elevated, however work-shift 4 showed a blunted response (Figure 8.4). In this work-shift the pre salivary cortisol concentrations for participant 4 were elevated and opposed the trend of the other participants. It may have been that this sample was contaminated with food which may have introduced error into the data (Salimetrics, 2010).

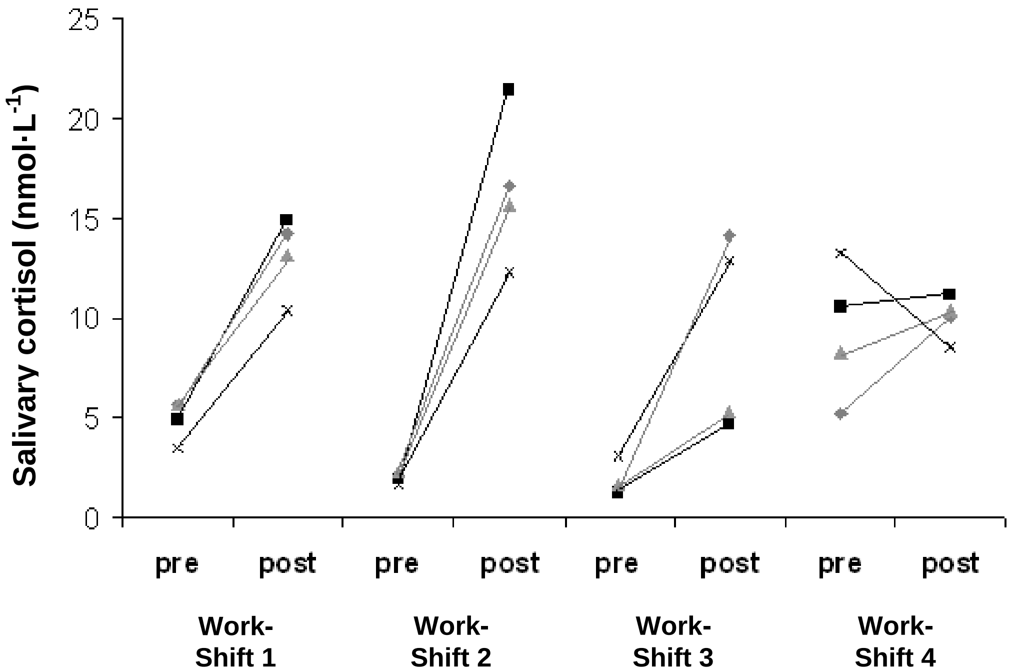


Figure 8.4: Salivary cortisol concentrations for participants 1 (♦), 2 (■), 3 (▲) and 4 (x) pre and post each work-shift.

8.5.2.5 Intra-aural temperature

For all of the participants intra-aural temperature was maintained within relatively tight tolerances (Figure 8.5). Participant 1's post work-shift temperature consistently increased, whereas the opposite was true for participant 2. No observable patterns were evident across the participants for time of day. The data for participant 4 during work-shift 2 is lower than all the other recordings. This may be due to measurement error. Although the intra-aural method has been shown to be valid and reliable (Sato *et al.*, 1996; Smith and Fehling, 1996; Newsham *et al.*, 2002; Edwards *et al.*, 2007), Atkinson *et al.* (2005) reported a possible cause of error if sweat enters the external auditory meatus. This is supported by Newsham *et al.* (2002) who reported a weak correlation between tympanic temperature methods and rectal temperature during recovery.

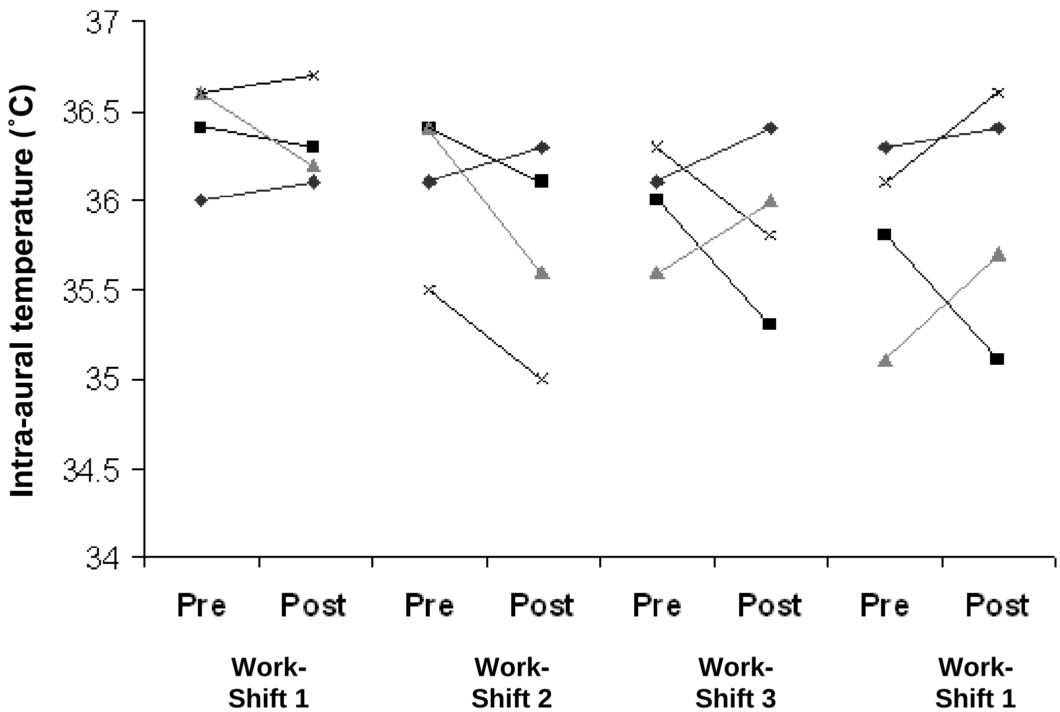


Figure 8.5: Intra-aural temperature for participants 1 (♦), 2 (■), 3 (▲) and 4 (x) pre and post each work-shift.

8.5.2.6 Anthropometric and physiological correlates to performance

Correlates to speed were reported for cadence (r = 0.82, p = 0.00); power (r = 0.66; p = 0.01); gross efficiency (r = 0.64, p = 0.01) body mass (r = -0.62, p = 0.01) and relative peak power output as determined from laboratory tests (r = 0.81, p = 0.00). Furthermore no correlation was reported for heart rate and power output. Figure 8.6 shows the dissociation between heart rate, which was relatively constant, and power output which was stochastic.

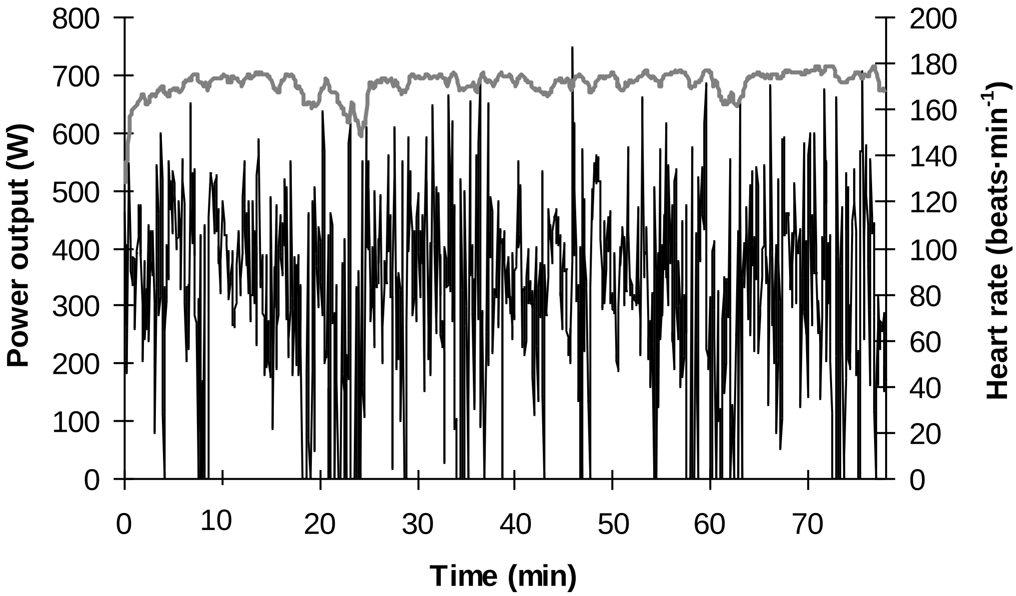


Figure 8.6: A representative plot of heart rate (–) and power output (–) for one participant for one work-shift during the race.

8.5.2.7 Positive and negative affect scales (PANAS)

Figure 8.7 shows the orthogonal positive and negative scores for the participants over the time course of the race. Whilst a detailed analysis of the participants' mood is beyond the remit of this thesis, it can be seen that the positive scale fluctuates during the race and that participant 3's values steadily decline mirroring his reduction in race performance.

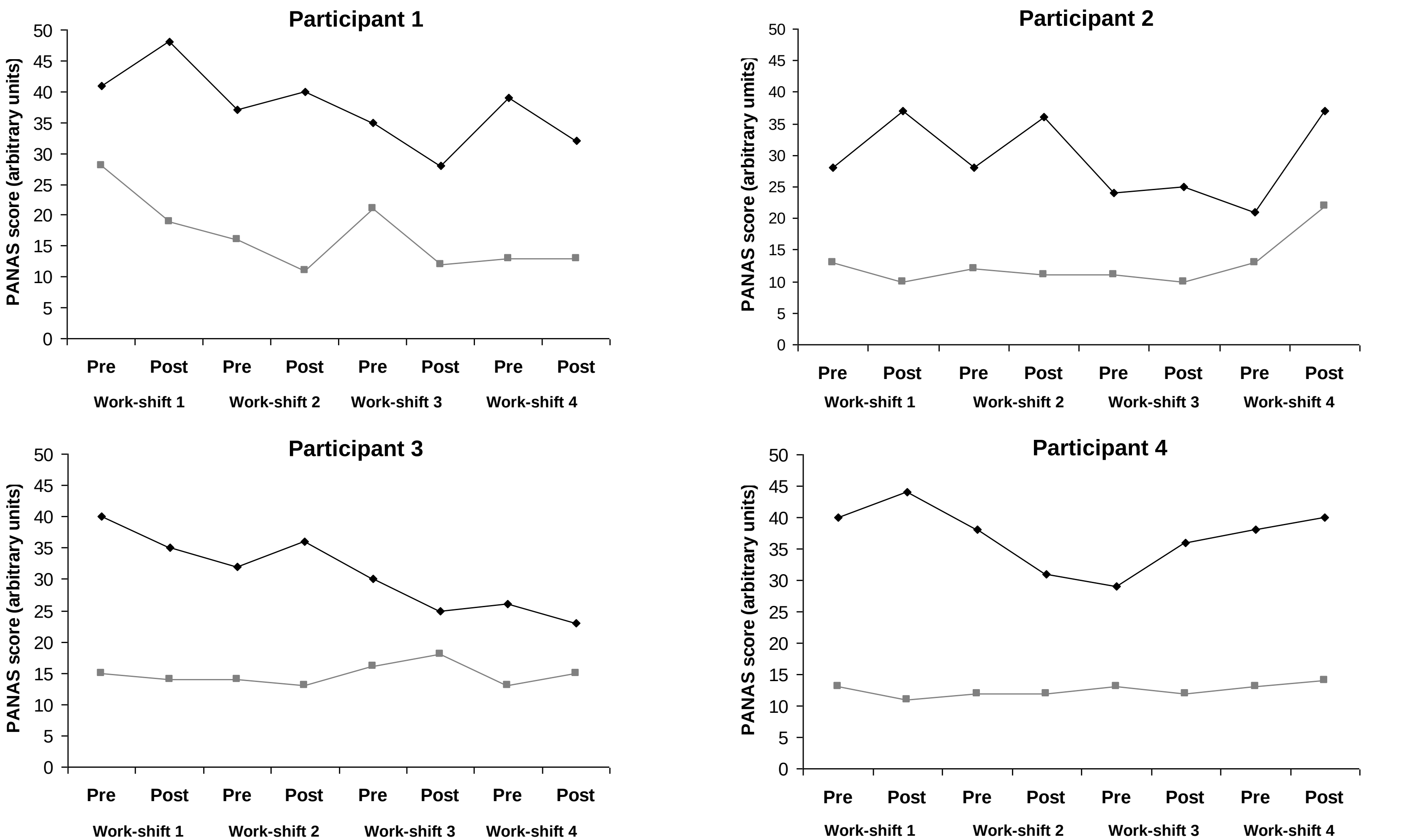


Figure 8.7: Positive (♦) and Negative (■) Affect Scale (PANAS) pre and post work-shifts for each participant.

8.6 Discussion

The aim of this study was to describe and analyse key physiological and performance variables during a 24 h ultraendurance mountain bike relay race. The team's overall standing at the end of the race was 4th place out of a field of 42. They were 5 min 34 s ahead of the 5th place finishers (who had also completed the same number of laps), and two laps short of 3rd place (Appendix K). Their advantage over the next placed team equated to an average of just 19 s per lap. This reinforces the importance of having non-invasive testing methods that do not affect the team's performance. The general classification result confirms the calibre of the participants and the authenticity of the data with regard to representing well-trained 24XCT performance.

8.6.1 Performance and influencing variables

Race speed is the primary outcome variable in 24XCT mountain biking as it relates directly to the distance covered within the set timeframe (Equation 13). The main finding from the present study was the intra and inter participant variance in speed over the course of the race.

The strong positive correlation between race speed and normalised peak power output as determined in the laboratory is consistent with the findings of other research on XCO racing (Lee *et al.*, 2002; Impellizzeri *et al.*, 2005; Gregory *et al.*, 2007; Prins *et al.*, 2007; Costa *et al.*, 2008). However, it is in contrast to the lack of relationship reported for XCM racing in Study Two. Interestingly the mean course gradients and the cumulative vertical distance climbed in both the XCM race and the present 24XCT race were similar. Thus the disadvantages of raising inert body mass against gravity were comparable in both studies. A plausible explanation for the conflicting findings may be explained by the different formats of the two races. Although the XCM and 24XCT disciplines are both ultraendurance mountain bike competitions, the former is continuous whereas the latter is discontinuous. The 24XCT races are more intense (as determined by percentage of HR_{max} and $\dot{V}O_{2peak}$) and in essence are like a series of four XCO races. In addition it may be due to the technical demands of the race. Competitors and coaches generally acknowledge that 24XCT races are more technical than XCM competitions (personal communication with competitors) and require more frequent acceleration and deceleration. A reduced inert body mass would therefore be an advantage during 24XCT racing. However, this has not been tested directly in this study and would therefore benefit from future research attention.

Of specific interest is the upturn in performance during the last work-shift. There are several plausible explanations for this observation which are discussed below.

8.6.1.1 Pacing strategies and race performance

The 24XCT racing format is unique in that competitors aim to cover the greatest distance within a set timeframe, whereas most laboratory-based pacing strategies have focussed on time-to-exhaustion exercise or fixed-distance trials (Laursen *et al.*, 2003b; Atkinson *et al.*, 2005). As such comparable data on fixed timeframe competition are scarce.

The distribution of mean power output across work-shifts, and the temporal speed profile of the participants throughout the event would suggest that a catastrophic failure of a peripheral system (to the point where the participants were exhausted and could not continue) did not occur. Rather the findings are in accordance with the complex systems model (Noakes and St Clair Gibson, 2004) and indicate that the participants' performances were teleoanticipatory insofar as they employed pacing strategies throughout the race. This model would suggest that the participants consciously or unconsciously regulated their metabolism without fatiguing any one peripheral system whilst leaving enough physical reserve capacity to deal with any unforeseen circumstances. As the endpoint of the event became closer and the probability and severity of an unforeseen circumstance was reduced, less reserve capacity would have been needed during work-shift 4 and the pacing "algorithm" could allow for a greater effort. Although this model supports the observation of an increase in power output (external work) during the final work-shift, it does not fully account for the attenuated heart rate (internal work). Whilst this latter point will be analysed further in this discussion, the lack of catastrophic fatigue for any participant coupled with the upturn in performance provides sufficient support for the view that a pacing strategy was employed. Although catastrophic fatigue[11] did not occur, participant 3's profile is consistent with that of down-regulation by a central governor. His positive affect scores steadily reduced, which may be linked to attenuated glycogen stores. This issue will be addressed in the following chapter.

8.6.1.2 Circadian variations and race performance

The circadian variations in the physiological variables (Figure 8.2) that contribute to performance may account for the attenuation in speed during the third work-shift compared to the fourth. There was a general reduction in power output during the third work-shift which was also accompanied by an attenuated cadence. Both of these variables were significantly positively correlated with race speed. This reduction in pedalling frequency is in accordance with the findings of Moussay *et al.* (2002) who reported a reduction in body temperature, MST and pedal frequency during a similar time of day in a group of highly trained cyclists. The data are in contrast to the findings reported in Study Three for sports science students, where a peak in cadence was observed at 12:00-01:00 h. This latter point supports the need for ecological validity and appropriate subject selection when designing testing protocols for ultraendurance mountain bike racing.

Power output is a product of torque applied at the pedals and cadence (Equation 11). A reduction in the latter will contribute to a reduction in power output for a

[11] The point when the participant is exhausted and cannot continue

constant torque. Although not measured directly in this study, a circadian reduction in torque generation during the third work-shift would also contribute to the observed reduction in power output. Callard *et al.* (2000) reported a circadian reduction in torque during the early morning which would support this concept. Furthermore Atkinson *et al.* (2005) found that 16.1 km time trial performance to be worse in the early morning (07:30 h) than in the early evening (17:30 h). Whether the time of day variation in power output in the present study was due to endogenous circadian rhythms or some other external factor remains unresolved.

8.6.1.3 Perceived exertion, mood and race performance

A more simple explanation for the difference in speed between work-shifts 3 and 4 may be that the participants were not exerting themselves as much during the penultimate work-shift, thus allowing for sufficient recovery for an upturn in performance during the final work-shift. Supporting this concept are the blunted blood lactate concentrations observed for all participants post work-shift 3. These values for this work-shift stand out markedly compared to the profiles of the other three work-shifts (Figure 8.3). A biochemical interpretation of this phenomenon would be that exercise intensity was reduced and less anaerobic energy contribution occurred.

However, this is in opposition to the participants' post work-shift ratings of perceived exertion, which in general rose gradually across the time course of the race. This discrepancy between the perception of effort and the biochemical measures of metabolism supports the findings of Green *et al.* (2003). They reported that during 60 min constant workload ergometry blood lactate dissociated from RPE. This is further substantiated in the present study by the strong correlation between pre work-shift blood lactate concentrations and RPE, and the subsequent lack of correlation in post work-shift values. The data suggest that the participants perceived the third work-shift to require as much exertion as the other work-shifts, despite the metabolic strain, myocardial load and riding performances being reduced. Furthermore, in the present study, RPE was not correlated to heart rate values, which again concurs with Green *et al.* (2003) in that heart rate is not thought to be a key factor in RPE. In addition a negative correlation was reported between pre work-shift RPE and mean power output for the subsequent work-shift, with no correlation for post work-shift RPE and power output being reported. This would suggest that the participants' perception beforehand influenced the subsequent effort during the work-shift. Again this highlights a dissociation between the perceived and the actual demands of the task. Martin and Gaddis (1981) reported that self-chosen work rate in subjects was reduced and RPE was higher for the same workload following sleep deprivation. Whilst this would account for the reduction in performance during work-shift 3, it would not explain the subsequent improvement in performance during work-shift 4 despite increasing sleep loss. From this data it would seem that a single variable is not responsible for RPE, and that fatigue is a complex sensory perception rather than a physical phenomenon (Robertson and Noble, 1997).

A similar response was observed by Laursen *et al.* (2003b) who reported an increase in final trial performance during a series of time-to-exhaustion tests. They suggested it may have been due to the psychological boost of knowing it was the “final test”. Moreover, Hickey *et al.* (1992) observed similar results for repeated trials despite a lack of difference in physiological variables, and concluded that awareness of the “last task” somehow influenced performance time. This may explain the observation in the present study, as the increased speed in work-shift 4 was not accompanied by an increase in heart rate compared to work-shift 3 and no correlation was reported between the two variables.

Mood and cognitive function have been reported to follow circadian patterns with reductions occurring in the early morning (Edwards *et al.*, 2007). However, there is scant evidence directly linking mood and perception to physical performance. The PANAS results in Figure 8.7 show that the positive and negative scales for each participant oscillated over the duration of the race. Whilst it was beyond the remit of this thesis to address the relationship between mood, perception and performance, it highlights that these factors fluctuate throughout the event, and that this is an area that warrants further investigation.

8.6.1.4 Illumination levels and race performance

An obvious explanation for the reduction in speed during the third work-shift compared to the fourth is that the lack of illumination impaired visual acuity (Maas *et al.*, 1974). Although the participants were equipped with sophisticated lighting systems and were well-versed in racing at night, the artificial illumination levels were not comparable to those recorded during the daytime. In addition, during this work-shift the participants had to carry the additional mass of the lighting units around the course. Performance improved in the following work-shift during which illumination increased, and the mass of the lighting systems was removed.

The subsequent increase in performance with the return of daylight is in agreement with the reports of Lloyd *et al.* (1977) and Linderman *et al.* (2003). Linderman and co-workers (2003) also noted that this coincided with subjects reporting a euphoric feeling and an increase in vigour. However, the authors did not confirm the link between mood states and performance. Indeed, establishing a link between paper and pencil tests of mood and physical performance has yet to be achieved. Despite the lack of causality, Maas *et al.* (1974) found that increased illumination levels decreased subjects' perceptions of fatigue. However, O'Brien and O'Connor (2000) and Ohkuma *et al.* (2001) reported that illumination levels had no effect on power output during cycling ergometry. It should be noted that in these latter experiments illumination ranges were 1411 - 6434 lux and 50 - 500 lux respectively, whereas in the present study illumination during the final work-shifts ranged from 500 - 10 000+ lux which may have had a more profound effect. Furthermore, the former experiments were performed on stationary ergometers and the subjects did not have to negotiate technical terrain where visual acuity plays a critical role. Interestingly, in the present study race speed was not significantly correlated to illumination level, however this may be due to the maximum range of the photometer being limited to 10 000 lux and the participants' variance in speed reducing the sensitivity of the correlation.

An increase in visual acuity may have contributed to an improvement in bike handling skills and led to the increase in gross efficiency observed during the last work-shift.

8.6.1.5 Gross efficiency and race performance

Gross efficiency was significantly correlated to race speed. Linderman *et al.* (2003) reported an increase in speed during the latter half of a circuit-based 12 h XCM race. They hypothesised that the increased illumination may have improved the riders' efficiency. However this was speculation as they did not measure either variable. In the present study the increase in visual acuity during the final work-shift would not solely account for the participants recording their highest levels of gross efficiency for the entire race; insofar as the first work-shift had a comparable illumination level.

It may simply be that during the fourth work-shift the competitors were more evenly spread around the course compared with the first, during which there was bunching of riders due to the mass start. A more evenly distributed field enables riders to select the best, and most efficient, racing line and choose an exercise intensity which is not, to some extent, dictated by others (Overend, 1999).

A further plausible explanation for the increase in gross efficiency is that the six antecedent laps each participant completed prior to the final work-shift enabled them to become familiar with the course. The participants commented that they ‘knew what gear to be in’, ‘knew the racing line’, ‘when to brake’ and ‘where to carry speed through corners’ during the final work-shift compared to the previous three (post-race personal communication with the participants). A key point here is that although the participants had pre-ridden the course as part of their preparation procedures, they had only done so a maximum of two times. Furthermore these preparatory laps had been performed at sub-race pace (personal communication with the participants). Because of this the participants will have used different gear ratios and approached sections of the course at reduced speeds. This approach is not atypical and coaches and riders often show concern about expending energy prior to a race. This knowledge has great applied relevance to the athletes and coaches. If an increase in course familiarity leads to an increase in gross efficiency and race speed it would be advisable for competitors to become familiar with the course in order to begin the race with maximum gross efficiency. The optimal number of preparation laps has yet to be established.

Gross efficiency is external power as a percentage of metabolic work rate (Equation 13). A true measurement of external power is therefore fundamental in ascertaining valid gross efficiency values. Whilst power meters are an accurate reflection of external power during road cycling and laboratory-based ergometry work, during cross-country mountain biking this premise may not necessarily hold true under certain conditions. For example, during a “rhythm” section of trail a competitor may choose one of two options. A rider with limited skill may pedal through the section, and in doing so register a high external power output value (as measured by the power meter) and a high metabolic work rate (as determined by heart rate). Alternatively an adroit competitor may use a technique called “pumping” to traverse the rhythm section. Pumping is an advanced skill during which the rider “weights” and “un-weights” the bicycle via powerful shifts in body position (British Cycling, 2010). This entire process is completed with the crank arms in a horizontal position. In this example cadence and therefore power output are both recorded as zero by the power meter despite considerable metabolic work being done (as determined by heart rate). A skilful rider can actually accelerate through a rhythm section using the pumping technique (British Cycling, 2010). The rider in the first example would therefore have a greater gross efficiency, as determined by Equation 13, than the rider in second example. Moreover, in the second example if the rider’s skill was to deteriorate due to fatigue, the rider would have to pedal through the section and would paradoxically register an increase in gross efficiency despite a reduction in performance. It is therefore recommended that gross efficiency is interpreted on an individual basis in conjunction with race speed, as an increase in gross efficiency that is accompanied with a decrease in speed may indicate a breakdown in skill. Due to skill playing a considerable role in cross-country mountain biking, inter-participant comparisons of power output and gross efficiency are inconclusive as determinants of performance. Furthermore if a rider dismounts and runs though a short technical section, or a steep climb, the work done would not be recorded by the power meter. This highlights a limitation of power meters as a measure of work done during certain situations in cross-country mountain biking. These issues go some way to explaining Participant 1's comparatively reduced power output and gross efficiency. He was a former cyclo cross competitor (which is an off-road cycling discipline where dismounting and running are core skills) and may have employed these skills during the 24XCT race.

8.6.1.6 Sleep deprivation and race performance

As the race progressed the participants would have been subject to an increased homeostatic drive to sleep as a function of time spent awake. During the night they would have experienced a further increased drive for sleep as a result of the endogenous circadian pressure (Doran *et al.*, 2001; Van Dongen and Dinges, 2005). Throughout work-shift 3 both systems would have been in phase exerting a heightened "pressure" for sleep. During the final work-shift the circadian pressure for sleep would have been attenuated, whilst the homeostatic drive would have increased. Whether this would exert a greater or lesser pressure for sleep is unclear, however Meney *et al.* (1998) reported a recovery in mood states during the day following a single night of sleep deprivation. Doran *et al.* (2001) found vigilance tasks to be better in the daytime compared to the night time following sleep deprivation. This suggests that the removal of the circadian pressure for sleep would improve mood despite an ever increasing homeostatic pressure for sleep. This may account for the increase in performance during the fourth work-shift in the present study.

The increase in speed at the end of the race would indicate that sleep deprivation did not have an adverse effect on the participants' performance, which is in accordance with the putative view in the literature (Martin, 1981; Martin and Gaddis, 1981; Martin and Haney, 1982; Horne and Pettitt, 1984; Angus *et al.*, 1985; Takeuchi *et al.*, 1985; Martin *et al.*, 1986; Meney *et al.*, 1998; Nidl *et al.*, 2002). In addition participants were able to nap in between work-shifts which has been shown to ameliorate the effects of sleep deprivation (Van Dongen and Dinges, 2005). It may also have been that sleep deprivation did affect performance, but any reductions were masked by improvements in other variables, for instance improvements in gross efficiency.

The exact reasons for the upturn in performance during the final work-shift remain unclear, however it is probable that it was a complex interaction of all or some of the variables highlighted above. As such future research is required to fully elucidate the cause(s).

8.6.2 Anthropometric and physiological characteristics

When normalised to body mass, the anthropometric and physiological characteristics of the participants are similar to those reported for the XCM athletes in Studies One and Two. They are also consistent with those of other ultraendurance athletes reported in the literature (Colombani *et al.*, 2002; Kimber *et al.*, 2002; Bowen *et al*., 2006; Knechtle *et al.*, 2009). This is unsurprising as it is not uncommon for ultraendurance mountain bikers to compete in both XCM and 24XCT races during the competitive season. Once again the mean age of the participants is greater than those reported for XCO racers highlighted in Table 2.1, but comparable with other ultraendurance research and those reported in Studies One and Two. This trend is consistent across ultraendurance sports and the underpinning reasons warrant further investigation (Zalcman *et al.*, 2007).

8.6.3 Heart rate

The main finding regarding mean heart rate was that there was a reduction during the second half of the race, resulting in a decline in exercise intensity as determined by percentage of maximum heart rate. This was unexpected in light of the upturn in race-speed in the final quartile, and is inconsistent with a rise as a result of cardiovascular drift as reported in previous research (Neumayr *et al.*, 2004; O'Toole *et al.*, 1998; Boulay *et al*., 1997). A key cause of cardiovascular drift is a reduction in plasma volume. The lack of progressive dehydration in the participants (detailed in the next chapter) during the race in conjunction with an increase in performance and a decrease in heart rate would indicate that cardiovascular drift was not an issue. In accordance with the present study, Linderman *et al.* (2003) reported a declining heart rate during the latter half of a 12 h XCM which was accompanied by an increase in race speed. However, the authors could not account for this observation.

Coyle and Montain (1992) noted that heart rates are elevated when exercise is performed in the heat. During the 24XCT race the ambient temperature was greatest at the start and subsequently dropped during the night shifts (Figure 7.8). This reduction in temperature may have contributed to the progressive reduction in exercise heart rate observed for the participants (Tables 8.4 to 8.7) and is supported by the significant correlation between these variables (Appendix M). However, this association does not hold true during the final workshifts during which ambient temperature increased and heart rates further decreased. This suggests that other factors also contributed to the reduction in heart rate.

Neumayr *et al.* (2004) reported a gradual decline in heart rate for ten elite road cyclists during a 525 km race, however this was accompanied by a reduction in performance. The authors suggested it was the result of down-regulation in order to protect the heart. Impellizzeri *et al*. (2002) also reported a significant decrease in heart rate in successive laps accompanied by a significant increase in lap time for XCO racing, but did not account for this observation. It may be that in the present study there was a change in substrate to favour fat oxidation. However it would be expected that this would be accompanied by a commensurate decrease in performance, which is incongruent with the observed increase in speed. A plausible explanation may be that the increase in efficiency was sufficient to more than offset any reduction due to a change in substrate. However this was not confirmed.

Mean exercise intensity as determined by the ratio of mean race heart rate to maximum heart rate was slightly higher than that reported for the XCM race detailed in Study Two. This was expected, because although the cumulative race duration was analogous (~6 h) the XCM was a constant form of exercise whereas the 24XCT was discontinuous. The recovery periods allowed for more intense race intervals which is supported by the participants exercising at a higher percentage of $\dot{V}O_{2peak}$ compared to those competing in the XCM race. This is in accordance with the inverse relationship observed between exercise intensity and duration (Stroud, 1998; Padilla *et al.*, 2000). In contrast, the duration of the 24XCT work-shifts are shorter than XCO races, yet the exercise intensity is less than those reported in the literature for XCO competitions (Impellizzeri *et al*., 2002; Lee *et al*., 2002; Stapelfeldt *et al*., 2004; Costa and De-Oliveira, 2008). This again would confirm that the participants were employing pacing strategies by taking into account the multiple work-shifts and the overall end-point of exercise rather than just a sole work-shift. The mean speed in the present study was approximately 1.8 $km \cdot h^{-1}$ faster than in the XCM race, which is in line with the observation that the HR_{ave}/HR_{max} value and the percentage $\dot{V}O_{2peak}$ were higher in the present study.

8.6.4 Intra-aural temperature

Circadian rhythms in body temperature have been associated with rhythms in physical performance (Reilly *et al.*, 1997). Atkinson *et al.* (2005) reported a circadian rhythm in core temperature to persist following a warm-up. In the present study it is probable that this rhythm was masked by the metabolic heat production resulting from the work-shifts and the high throughput of foodstuffs. This explains the lack of correlation between intra-aural temperature and any performance variables. In addition, four data points throughout the day may not be a sensitive enough measure to detect subtle sinusoidal circadian rhythms (Atkinson and Reilly, 1996). As expected there was a slight increase in intra-aural temperature post work-shifts, however, what was not expected was an equal number of decreases. This may reflect individual responses to the exercise or could be attributed to possible measurement error due to sweat entering the external auditory meatus.

8.6.5 Salivary cortisol

The pre work-shift cortisol levels demonstrate a near-normal circadian profile, with a peak in the early morning and a trough at night (Figure 8.4). This is consistent with values previously reported in the literature (Edwards *et al*., 2001; Kudielka *et al*., 2007; Popma *et al*., 2007) and with research showing that cortisol secretion maintains its rhythmicity during up to 80 h of sleep deprivation (Martin *et al.*, 1986). The persistence of this trend despite racing indicates that the circadian rhythm was robust in this cohort. Cortisol has multiple functions across multiple systems and, independent of circadian variation, is released in response to short-term demands of psychological and physiological stress, and low levels of glycogen (Loebel and Kraemer, 1998; Dickerson and Kemeny, 2004). The normal cortisol concentrations observed before each work-shift would suggest that the participants did not perceive the pre-shift period as a psychological stress. This is plausible as the participants were well versed in this type of racing and aside from the initial mass start, the transfer of the riders to demarcate a new work-shift was a relatively low-key affair. A further factor that may have resulted in normal pre-cortisol concentrations was the timing of sampling. Samples were taken in the field laboratory 20-30 min before the start of the shift and may have been too early to account for any state anxiety the participants may have subsequently experienced in the transition zone. In addition cortisol is known to be secreted episodically (approximately every 20 min) (Hellman *et al.*, 1970) and thus the timing of the sample may have affected the amount of cortisol that was detected.

Elevated post work-shift salivary cortisol concentrations were expected as it is well documented that exercise increases cortisol release, and that it has permissive effects on other physiological functions. Critical levels of cortisol are necessary for catecholamines to have an effect on the cardiovascular system such as vasoconstriction for blood shunting, and tachycardia (Dickerson and Kemeny, 2004). In the present study circulating catecholamine levels, vasoconstriction and vasodilatation were not determined so this cannot be confirmed. However, it is reasonable to assume that these physiological functions occurred and that the elevated cortisol levels contributed to this. The positive correlation between post work-shift salivary cortisol and work-shift heart rate lends further support to this concept. Furthermore, an elevated heart rate would indicate increased exercise stress. The influence of glycogen depletion on cortisol levels are discussed in detail in the following chapter.

Following heavy resistance exercise, elevated cortisol concentrations have been shown to reflect tissue remodelling and inflammatory responses (Kraemer *et al*., 1996) with chronic elevated levels being linked to overtraining (Samilios *et al.*, 2003). The return to normal circadian concentrations during the recovery periods would indicate that the work-shifts were not putting the participants in an overreaching condition, or that participants were in an overtrained condition prior to the race (Lucía *et al.,* 2001b). Indeed following exercise hyper-cortisol concentrations normally return to basal levels within two hours (McArdle *et al.*, 2001). This was observed in the present study and can, in part, be explained by the participants being experienced in 24XCT racing, and the exercise being submaximal.

The reasons for the common blunted salivary cortisol response in work-shift 4 are unclear. Several plausible explanations may account for this. It may be that knowing the end of the race was imminent reduced anxiety within the participants. However, as psychological stress is only one precursor to cortisol production, it would still be expected that the physiological load and the reduction of glycogen levels would continue to promote cortisol secretion (Ainslie *et al.*, 2003b). It may be that repeated exposure to acute stress throughout the day attenuates cortisol release, or that the secretion process itself becomes fatigued. Repeated bouts of strenuous exercise may also affect levels of other hormones, such as adrenocorticotropic hormone (ACTH) and catecholamines which influence cortisol release. Research in the literature focuses mainly on chronic exposure to stress, and data regarding repeated acute stress on cortisol secretion are scarce. Limited research has shown that a single bout of exercise can suppress night-time cortisol secretion (Hackney *et al.*, 1989; Kern *et al.*, 1995). Hackney and Viru (1999) found that night-time cortisol release was attenuated following two 60 min exercise bouts at 65% $\dot{V}O_{2max}$ undertaken at 07:00 and 17:15 h. The researchers did not offer a physiological mechanism to explain this, but they hypothesised that it may be due to reduced catecholamine release. To the author's best knowledge no other studies have investigated cortisol response to serial bouts of strenuous exercise (~76% $\dot{V}O_{2peak}$) throughout a nycthemeral period. Taken together it would appear that repeated exercise has some form of blunting effect on cortisol release. It is impossible to interpret the cause of this based on the available data. Typically, a blunted cortisol response when exposed to a stressor is indicative that the individual is not coping with the stressful situation. However, this is generally observed during chronic exposure to stress such as post traumatic stress disorder. Data on acute exposure to stress during ultraendurance exercise is scant and therefore warrants further attention.

8.7 Conclusions

A strength of the study design was that it had great ecological validity and the data are authentic to 24 h ultraendurance mountain bike racing. The multiple case-study approach allowed for the richness and nuances of the data to be analysed, which may otherwise have been lost if testing of differences had been used (Appendix N). It was found that mean work-shift speed varies over the course of the race and increased towards the end. These data suggest that pacing strategies, in line with the complex systems model, were employed. Speed was shown to correlate with mean work-shift cadence and power output with each of these variables fluctuating throughout the course of the race.

Furthermore, race speed was correlated with relative PPO as determined in the laboratory. A noteworthy issue which has great applied relevance to competitors is that efficiency increased in the last work-shift, and was significantly correlated with performance. A probable contributing factor was that the participants became increasingly familiar with the course at race-speed. This latter point has practical implications for the optimal preparation tactics of the athletes. This aspect will be discussed further in Chapter 10. In addition to the factors discussed above, it is necessary to investigate the role that nutrition had on 24XCT performance. As such the following chapter addresses the nutritional requirements of 24XCT racing.

CHAPTER NINE

Study Six: Nutritional requirements and dynamics during an ultraendurance team relay mountain bike race

9.1 Introduction

As exercise duration increases, the physiological laboratory measurements usually associated with endurance performance become less relevant. Limiting factors for such performance include the rate of substrate provision, finite gastric emptying rates, fluid imbalances, and thermal regulation (Kreider, 1991; Laursen and Rhodes, 2001; Colombani *et al*., 2002). The majority of nutritional recommendations for endurance events are derived from controlled laboratory settings, however relatively little is known about the energy and fluid intake dynamics that occur during ultraendurance races (Kruseman *et al.*, 2005; Knechtle *et al.*, 2009). The methodological difficulties of measuring these variables during a mountain bike race may explain the paucity of associated research (Stroud, 1998; Kimber *et al.*, 2002; Cramp *et al.*, 2004). Determining the energy balance and hydration dynamics during the 24XCT competition will help inform athletes and their coaches when planning nutritional strategies for future competitions. This chapter will analyse the nutritional practices of a team of four competitors during a 24XCT race.

9.1.1 Research aim

The nutritional literature indicates that ultraendurance competitors will not be able to match energy intake to energy expenditure. It is also reported that ad libitum fluid intake will not replace all of the body water lost through sweat, though this will not necessarily result in a state of dehydration or a reduction of performance. The aims of this study were to i) determine whether there was a difference between the energy intake and the energy expenditure of the participants, ii) monitor their hydration status during the 24 h race period, and iii) determine the energy cost ($kJ \cdot min^{-1}$) during the work-shifts.

9.2 Specific methods

9.2.1 Experimental design

This study was undertaken during the same race as Study Five. It adopted a field-based, multiple case-study research design. Similar descriptive case-study methods have been used by other researchers to determine nutritional intakes of other ultraendurance athletes (Lindeman, 1991; Clark *et al.*, 1992; Bowen *et al.*, 2006; Knechtle *et al.*, 2009).

9.2.2 Participants

Four male participants volunteered for the study (age 36 ± 8.5 years; stature 1.77 ± 0.05 m; body mass 80.2 ± 3.1 kg). They were the same individuals as those in Study Five. Table 8.1 highlights the participants' characteristics.

9.2.3 Instrumentation

9.2.3.1 Nutrition diary

Each participant completed a 24 h diary for the duration of the race and were instructed to record the content, volume and timing of all solids and liquids consumed. The participants each had their own assistant to support them throughout the race, and in most cases these assistants prepared the food and scribed the information. Participants were allowed free access to food which was consumed ad libitum. In practice, the participants brought their own food and drink caches to the race and had a predetermined nutritional strategy (based on their preferred taste, sponsorship and past experience). This improved the accuracy of the diaries, however some food items were purchased from the race venue. It was requested that they submitted all food packaging where possible. Each participant was issued with a 750 mL graduated, cycle-specific water bottle (Science in Sport, Blackburn, UK) which was used to determine the volume of fluids they consumed. The diaries were analysed for macro nutrient content using a combination of nutritional information from the food packaging and WinDiets software (WinDiets Research, Robert Gordon University, Scotland). No attempt was made to advise the participants on their nutritional practices.

9.2.3.2 Urine analysis

Participants were issued with a graduated beaker and instructed to record the volume and timing of urine voided throughout the 24 h period. An Osmocheck refractometer (Vitech Scientific Ltd, West Sussex, U.K.) was used to provide an indicative reading of urine osmolality (U_{osm}) pre and post each work-shift. The Osmocheck is a thermally compensated, digital hand-held refractometer that is calibrated from 0 to 1500 $mOsmol \cdot kg^{-1}H_20$ with a manufacturer's reported measurement accuracy of ± 20 $mOsmol \cdot kg^{-1}H_20$ (Vitech, n.d.). The unit measures the refractive index of the urine which is directly related to specific gravity (the mass concentration of urinary solutes). It calculates osmolality (the molecular concentration) based on the empirical relationship between specific gravity and osmolality (Vitech, n.d.; Lord, 1999). The manufacturer reports a correlation coefficient of 0.99[12] (Vitech, n.d). Urine osmolality was measured in accordance with the manufacturer's guidelines; prior to each measurement the zero-setting procedure was performed, and the prism of the refractometer was cleaned and calibrated against distilled water. Pre and post each work-shift participants were instructed to collect a sample of mid-stream urine in a small beaker. Using a Pasteur pipette 0.3 mL of urine was placed onto the prism surface of the Osmocheck and a reading was taken. Lord (1999) notes that the

[12] Care should be exercised when interpreting correlation coefficients as they are not necessarily a true reflection of agreement between two measurements.

relationship between specific gravity and osmolality may vary if glucose and protein are present in the urine. Medi-Test Combi-8 (Macherey-Nagel, Düren, Germany) reagent strips were used to assess the urine for the presence of glucose and protein. A reagent strip was briefly dipped into the beaker of urine and any excess urine was removed. A reading was taken after 45 seconds by comparing to a colour chart (Macherey-Nagel, Düren, Germany). The remaining urine in the beaker was included in the participant's voided urine total.

9.2.3.3 Sweat loss

Sweat loss and percentage changes in body mass for each participant for each work-shift were calculated using the following equations adapted from Cox *et al.* (2002):

$$SL = [(BM_{pre} - BM_{post}) - (UO + FO)] + (FLC + FC) \qquad \textbf{Equation 14}$$

$$\%\ change = \frac{(BM_{post} - BM_{pre}) \times 100}{BM_{pre}} \qquad \textbf{Equation 15}$$

Where:

SL = sweat loss (mL); BM = body mass (g); UO = urine output (g); FO[13] = faecal output (g); FLC = fluid consumed (g); FC = food consumed (g). Assuming 1g = 1 mL. No correction was made for respiratory water loss or metabolic fluid changes.

Acute serial changes in body mass have been shown to be acceptable markers of body fluid status in the field (Armstrong, 2005) and have been used in previous

[13] None of the participants reported urine or faecal output during their work-shifts effectively rendering UO and FO as zero. Recovery sweat loss was not calculated due to the difficulties determining FO in the field.

research on cross-country mountain biking (Linderman *et al.*, 2003; Wingo *et al*, 2004; Rose and Peters, 2008; Knechtle and Rosemann, 2009).

9.2.3.4 Blood glucose concentrations

Pre and post each work-shift, a 5 µL finger-prick blood sample was taken from the participant's left index finger and analysed for glucose concentrations using a Medisense Precision QID blood glucose meter (Abbott Laboratories Ltd, Berkshire, U.K.). Solnica and Naskalski (2005) reported good agreement between the Precision QID and reference laboratory measures over a blood glucose range of 0.9 to 11.0 $mmol \cdot L^{-1}$. Capillary blood was applied to a test strip (Medisense glucose test strip, Abbott Laboratories Ltd, Berkshire, U.K) and measured in $mmol \cdot L^{-1}$. Prior to testing, the Medisense Precision QID meter was calibrated in accordance with the manufacturer's guidelines.

9.3 Data analysis

For analysis purposes a multiple case-study design was employed. Descriptive data were generated and a correlation matrix was used to compare nutritional, physiological and performance variables using Pearson's Product Moment correlations (Appendix M). For information purposes the results of testing differences can be found in Appendices N and O.

9.4 Findings

The findings are split into two sections. Firstly data are analysed on an individual basis where the nuances and specific traits of each participant are highlighted. This is followed by a comparative analysis where common themes across participants are identified and analysed. These observations and how they potentially affected performance form the basis of the subsequent discussion.

9.4.1 Individual analysis

The energy intakes of the four participants during the 24XCT race are detailed in Table 9.1.

Table 9.1: Dietary intakes of four participants during the 24 h mountain bike team relay

	TEE	Energy intake		CHO			Protein			Fat	
Participant	**MJ**	**MJ**	**$kJ \cdot kg^{-1}$**	**g**	**$g \cdot kg^{-1}$**	**%E**	**g**	**$g \cdot kg^{-1}$**	**%E**	**g**	**%E**
1	38.3	16.4	196	732	8.7	75	180	2.1	18	28	7
2	23.8	20.5	267	975	12.7	80	106	1.4	9	58	12
3	31.0	17.2	211	522	6.4	51	171	2.1	17	143	32
4	28.4	15.2	192	649	8.2	71	88	1.1	10	57	19
Mean	**30.4**	**17.3**	**216**	**719**	**9.0**	**69**	**136**	**1.7**	**13**	**76**	**18**
S.D.	**6.1**	**2.2**	**34**	**191**	**2.7**	**12.7**	**45.9**	**0.5**	**5.0**	**48.7**	**10.9**

TEE = total energy expenditure; **CHO** = carbohydrate; **%E** = percentage of energy intake

9.4.4.1 Participant 1

Table 9.2 summarises the carbohydrate intake and fluid dynamics for participant 1 during the race.

Table 9.2: Carbohydrate intake, fluid intake, sweat loss and urine voided during the event for participant 1

	Pre work shift	Work shift 1	Rec. period	Work shift 2	Rec. period	Work shift 3	Rec. period	Work shift 4	Rec. period
CHO intake (g)	N/A	74*	87	30	259	22†	115	22†	123
Fluid intake (mL)	N/A	750	600	750	1450	250	1100	300	750
Sweat loss (mL)	N/A	750	N/A	950	N/A	300	N/A	300	N/A
Urine voided (mL)	N/A	0	380	0	360	0	250	0	160

Rec. = Recovery; * = CHO powder; † = CHO gel (total gel mass 50 g)

The macronutrient content of participant 1's diet concurred with the recommended composition for endurance athletes, with 75% of the energy consumed being derived from carbohydrates (Walberg-Ranking, 1995; Raforth, 1998; Eberle, 2000; Manore and Thompson, 2000). However, his total energy intake accounted for only 43% of the energy he expended, indicating that endogenous fuel stores contributed considerably to his energy expenditure. His in-race feeding was only at a near-optimal level in the first work-shift, and was considerably reduced during the subsequent shifts. Participant 1 did not take advantage of the recovery periods and only on the second one did he meet the recommended 200 g threshold of carbohydrate ingestion (Neufer *et al.*, 1987; Coyle and Montain, 1992). Participant 1 consumed 5.95 L of fluid over the 24 h period, and with the exception of work-shift 2, his ad libitum drinking closely matched his sweat loss.

9.4.1.2 Participant 2

Table 9.3 summarises the carbohydrate intake and fluid dynamics for participant 2 during the race.

Table 9.3: Carbohydrate intake, fluid intake, sweat loss and urine voided during the event for participant 2.

	Pre work shift	Work shift 1	Rec. period	Work shift 2	Rec. period	Work shift 3	Rec. period	Work shift 4	Rec. period
CHO intake (g)	47	63*	213	0	269	62*	137	0	185
Fluid intake (mL)	500	750	2250	0	1250	750	500	0	1450
Sweat loss (mL)	N/A	850	N/A	100	N/A	650	N/A	100	N/A
Urine voided (mL)	0	0	550	0	650	0	600	0	200

Rec. = Recovery; * = CHO powder

Participant 2's nutritional practices were the most favourable out of the team. Eighty percent of his energy consumed was derived from carbohydrate, and his energy intake accounted for 86% of the total energy he expended. His recovery carbohydrate intake was at optimal levels for all intervals apart from the night time, during which he spent most of the time asleep. Participant 2's work-shift hydration and carbohydrate replacement strategy was binary in approach; he either chose to take a bottle of carbohydrate beverage and consumed all of the contents, or did not take one and his fluid and carbohydrate consumption was zero. He later confirmed he was placing more reliance on the recovery intervals for his nutrition than during the work-shifts (personal communication with participant). This participant consumed the most fluid and had a total fluid consumption of 7.45 L.

9.4.1.3 Participant 3

Table 9.4 summarises the carbohydrate intake and fluid dynamics for participant 3 during the race.

Table 9.4: Carbohydrate intake, fluid intake, sweat loss and urine voided during the event for participant 3.

	Pre work shift	Work shift 1	Rec. period	Work shift 2	Rec. period	Work shift 3	Rec. period	Work shift 4	Rec. period
CHO intake (g)	28	0	244	0	73	27*	0	96†	54
Fluid intake (mL)	500	750	1400	750	200	500	0	750	500
Sweat loss (mL)	N/A	1000	N/A	1150	N/A	810	N/A	700	N/A
Urine voided (mL)	500	0	175	0	700	0	450	0	0

Rec. = Recovery; * = CHO derived from food (food mass = 110 g); † = CHO derived from gel (22 g total gel mass 50 g) and powder (74 g)

Participants 3's nutritional strategy was somewhat erratic. He opted not to consume exogenous carbohydrates during the first two work-shifts, preferring instead to rely on the recovery periods (personal communication with participant). His carbohydrate consumption during the first recovery period was greater than the recommended 200 g threshold, however during subsequent recovery periods his carbohydrate consumption was considerably attenuated, with none being consumed during the night-shift. Participant 3 complained of nausea and not wanting to consume commercially manufactured carbohydrate bars, gels and powders during the second half of the race. Instead he opted to consume ‘real food’ (personal communication with participant). His energy intake accounted for 55% of the energy he expended, with carbohydrates contributing to only 51% of the energy he consumed. This was the lowest percentage energy contribution from carbohydrates reported for the team. Participant 3 had the greatest loss of fluids due to sweat, and although he maintained a steady fluid intake during the work-shifts, he failed to successfully address the balance whilst racing. Furthermore his recovery hydration was the lowest value of the team. His total fluid consumption amounted to 5.35 L. However, this did not result in progressive dehydration as determined by acute change in body mass or urinary osmolality.

9.4.1.4 Participant 4

Participant 4’s energy consumption contributed to 54% of his energy expenditure, with 71% of the energy consumed derived from carbohydrates. His in-race carbohydrate delivery was near-optimal during work-shifts 2 and 3. However, his carbohydrate consumption during work-shifts 1 and 4, and also during the recovery intervals, was somewhat below recommended levels. His in-race hydration strategy generally matched his fluid loss through sweat. Participant 4’s total fluid consumption was 6.6 L.

Table 9.5 summarises the carbohydrate intake and fluid dynamics for participant 4 during the race.

Table 9.5: Carbohydrate intake, fluid intake, sweat loss and urine voided during the event for participant 4.

	Pre work shift	Work shift 1	Rec. period	Work shift 2	Rec. period	Work shift 3	Rec. period	Work shift 4	Rec. period
CHO intake (g)	74	38*	139	76*	153	76*	93	0	N/A
Fluid intake (mL)	1500	750	950	750	750	750	400	750	N/A
Sweat loss (mL)	N/A	900	N/A	750	N/A	750	N/A	750	N/A
Urine voided (mL)	900	0	780	0	200	0	275	0	N/A

Rec. = Recovery; * = CHO powder

9.4.2 Comparative analysis

9.4.2.1 Individual practices and energy dynamics

There were two main themes regarding the participants' nutritional strategies. Firstly, it was evident that nutritional practices are specific to the individual and vary considerably. This is congruent with the putative view in the literature (Saris *et al.*, 1989; Clark *et al.*, 1992; Gabel *et al.*, 1995; Garcia-Roves *et al.*, 1998; Cramp *et al.*, 2004; Zalcman *et al.*, 2007). Secondly, all participants failed to match energy consumption with energy expenditure. Indeed, on average, energy consumption equated to only 57% of energy expenditure. This is in accordance

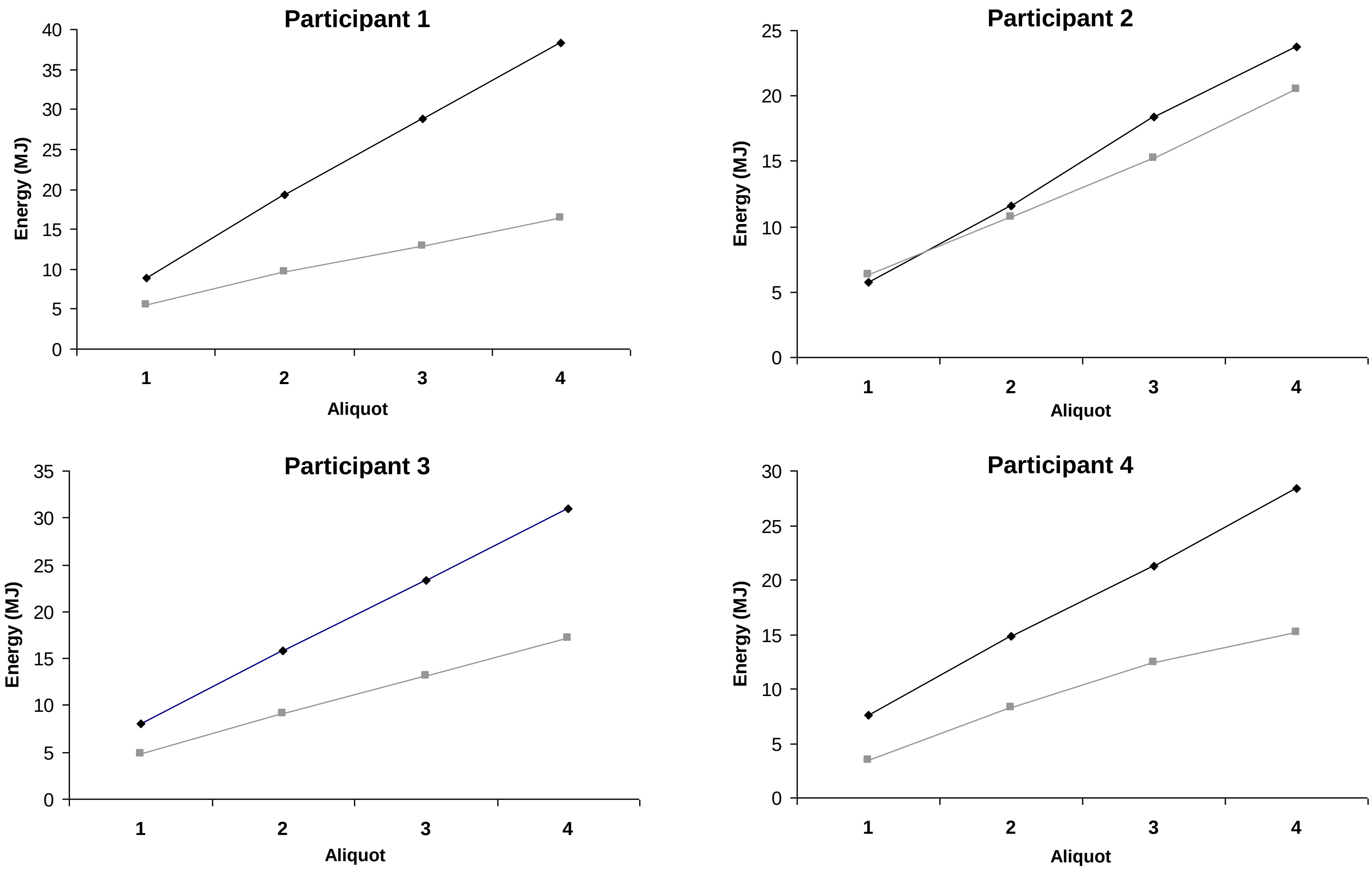


Figure 9.1 Cumulative energy expenditure (♦) and consumption (■) during the race.
Each aliquot relates to the period of time that includes a work-shift and associated recovery period.

with other research on ultraendurance competitions where exogenous energy contributions have accounted for only 40 to 54% of the energy expended (White *et al.*, 1984; Colombani *et al.* 2002; Kimber *et al.* 2002). Figure 9.1 shows the cumulative energy consumption versus the cumulative energy expenditure for each participant during the race. None of the participants matched their energy consumption with their expenditure, leading to an inexorable bifurcation between the two as the race progressed. The mean rate of energy expenditure during the work-shifts was estimated to be 74.5 ± 10.9 $kJ \cdot min^{-1}$ (17.8 ± 2.6 $kcal \cdot min^{-1}$).

9.4.2.2 Blood glucose

The blood glucose concentrations of the participants were maintained within normal ranges as reported in the literature (Ainslie *et al.*, 2003b). There was a common attenuation in blood glucose during the final work-shift (Figure 9.2), although no participants became hypoglycaemic (equivalent to blood glucose concentrations less than 3 $mmol \cdot L^{-1}$ (Ainslie *et al.*, 2003b)). A pattern is evident for post-shift blood glucose concentrations to be slightly elevated compared to pre-shift levels. This may simply be an artefact of the participants consuming a carbohydrate beverage shortly before completing the work-shift and reporting to the field laboratory.

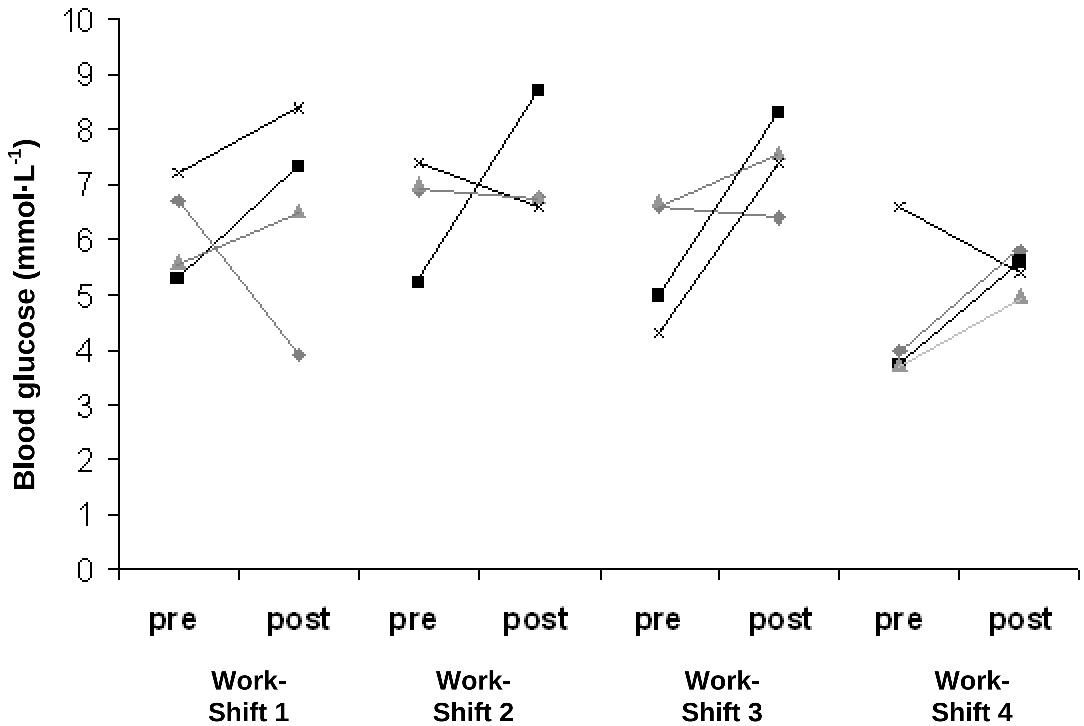


Figure 9.2: Blood glucose concentrations for participants 1 (♦), 2 (■), 3 (▲) and 4 (x) pre and post each work-shift.

9.4.2.3 Fluid intake and urine osmolality

Although the participants' fluid intake practices and their sweat loss varied during the course of the event, none of the sweat losses amounted to the 2% body mass loss associated with excessive dehydration (Sawka *et al.*, 2007; Rose and Peters, 2008). Urine osmolality concentrations greater than 1200 mOsmol·kg^{-1}H_2O are consistent with severe dehydration (Smith, 2006). It is evident from Figure 9.3 that the participants' pre work-shift urine osmolality concentrations were relatively elevated before the first work-shift, and would suggest that the participants did not start the race in an optimally hydrated condition. However, throughout the race they generally did not record concentrations greater than 1000 mOsmol·kg^{-1}H_2O. Taken together, the pre and post body mass measurements and urine osmolality data indicate that the participants maintained (or improved) their hydration status during the competition. Pre work-shift urinary osmolality concentrations were significantly negatively correlated (p = 0.05; r = -0.48) with race speed, however this does not necessarily imply causality.

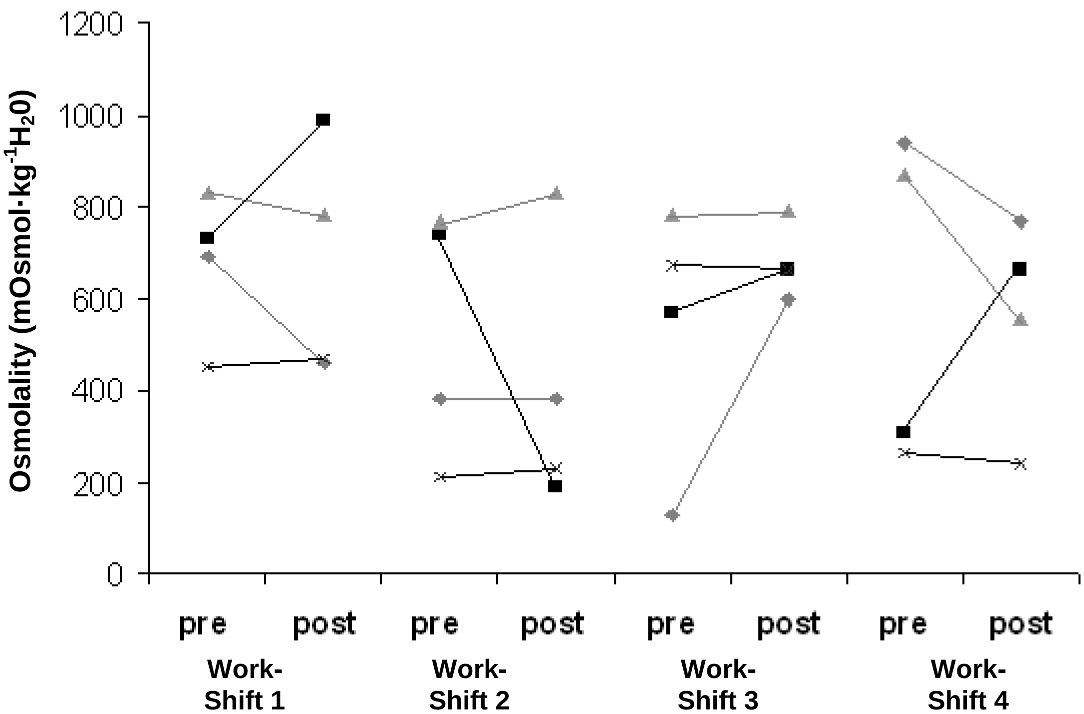


Figure 9.3: Urine osmolality for participants 1 (♦), 2 (■), 3 (▲) and 4 (x) pre and post each work-shift.

9.5 Discussion

This was the first study of its kind to simultaneously investigate the energy balance, hydration status and performance of 24XCT mountain bikers during an entire 24 h race. In addition the rate of energy expenditure ($kJ \cdot min^{-1}$), and the temporal patterns of the carbohydrate and fluid consumption during the race were determined.

The validity of the nutrient intake data depended on how accurately the participants recorded their food and fluid consumption. Due to the participants' pre-planned food caches, the limited consumption of addition foods and drinks, and the real-time updating of the diaries (rather than recall), data were considered an accurate representation of actual food and fluid consumed during the 24 h period.

9.5.1 Energy balance

The rate of energy expenditure whilst racing was estimated to be 74.5 ± 10.9 $kJ \cdot min^{-1}$ (17.8 ± 2.6 $kcal \cdot min^{-1}$). At the time of writing, this is the first study to ascertain the energy cost of 24XCT mountain bike racing. The observation from Study 5 that mean work-shift heart rate did not increase over the duration of the race, coupled with the participants not becoming increasingly dehydrated, would indicate that cardiovascular drift was minimised. This in turn would suggest that the heart rate and $\dot{V}O_2$ relationship was robust and the data were a valid estimation of energy expenditure. The high daily energy expenditures of the participants are congruent with other studies using doubly labelled water to determine values for amateur runners in the Marathon de Sables (Stroud, 1998), national cross-country skiers (Sjodin *et al.*, 1994) and professional cyclists (Westerterp *et al*., 1986). The values are also similar to the extrapolated estimates (from 12 h data) for 24XCT proposed by Laursen *et al.* (2003a). They predicted it would be approximately 33.6 MJ.

Of importance was the finding that energy intake only accounted for between 43 and 86% of energy expenditure. This large discrepancy in energy balance is in accordance with the other research in the literature reporting that during prolonged exercise athletes are unable to match their energy intake with their high energy expenditure (Kreider, 1991; Burke, 2002; Colombani *et al*., 2002; Kimber *et al.*, 2002; Kruseman *et al.*, 2005; Stewart and Stewart, 2007).

The intra-participant work demand per shift was relatively constant (i.e. completing two laps), and the energy consumption was consistently less. This lead to an increasing gulf between the two as the race progressed. The energy intake may have been limited by the maximal rate of the participants' energy delivery systems, or because they did not employ optimal nutritional practices. The latter is most plausible as the participants' carbohydrate intake was routinely less than the optimal levels. This concurs with the findings of Stewart and Stewart (2007), and suggests that the participants were unable to successfully self-regulate their energy intake to match their expenditure.

Linderman *et al.* (2003) reported that during a 12h XC race subjects were able to achieve the optimal rate of carbohydrate intake of 1 $g \cdot min^{-1}$. However, the researchers did not determine the energy expenditure of the riders so it was unclear whether the subjects balanced energy consumption with expenditure. Laursen *et al.* (2003a) reported a decline in energy intake during 12 h of ultraendurance team relay mountain bike racing. Kimber *et al.* (2002) also reported optimal carbohydrate ingestion rates during a triathlon, however the energy consumption of the athletes was only 40% of the energy they expended. It seems inevitable therefore that during an ultraendurance mountain bike race energy expenditure will outstrip energy consumption and endogenous stores will be required to redress the energy deficit.

The wide range of energy consumption between participants indicates the personal nature of nutritional practices, and is in accordance with research for ultraendurance sports (Clark *et al.*, 1992; Garcia-Roves *et al.*, 1998; Saris *et al.*, 1989; Laursen *et al*., 2003a; Linderman *et al*., 2003). Other studies have proposed several reasons for this inter-subject variation including food and flavour fatigue, a limited digestive capacity and the practical difficulty of consuming the required energy (Kreider, 1991; Burke, 2002; Stewart and Stewart, 2007). It is probable that a combination of these factors contributed to the deficit in the present study.

All of the participants showed poor nutritional knowledge insofar as they erroneously thought they could address the energy deficit during the recovery periods. In addition participant 3 felt nauseous which reduced his willingness to consume food. This may have been due to food or flavour fatigue, gut ischaemia, or because he did not drink enough fluids. A further factor that may have influenced the participants' intake is the reported circadian variation in gut motility. Goo *et al.* (1987) found a circadian variation in gastric emptying to exist with rates being lowest at 20:00 h compared to 08:00 h.

9.5.2 Carbohydrate intake

The total energy expended during the race period was greater than the daily-threshold above which athletes will typically have to consume and digest foodstuffs whilst competing (Brouns *et al.*, 1989a; Brouns *et al.*, 1989b; Linderman *et al*., 2003; Stewart and Stewart, 2007). This was the case in the present study and all riders opted to consume exogenous carbohydrate at some point whilst racing. Nonetheless, all but participant 1 chose not to consume exogenous carbohydrate during at least one work-shift; preferring instead to refuel during the recovery period. The participants' subjective reasons for this included the practical difficulty of consuming foodstuffs whilst racing; wanting to avoid gastrointestinal distress; not 'feeling the need for feeding' during the relatively short work-shifts; being able to 'make up for it' during the recovery intervals; and wanting to 'focus on the racing' (post-race personal communication with the participants). This strategy is similar to that adopted during contemporary road cycling where aggressive racing is prevalent and in-race refuelling is compromised (Garcia-Roves *et al.*, 1998).

The average percentage of $\dot{V}O_{2peak}$ attained during the race was 76% suggesting that carbohydrate contributed significantly to the energy provision (Thomas *et al*., 1991; Cramp *et al.*, 2004). During the majority of the work-shifts, participants opted to consume exogenous energy primarily in the form of carbohydrate beverages, or gels (Science In Sport (S.I.S.), Blackburn, UK; Torq, Shropshire, UK). Carbohydrate intake was positively correlated with fluid intake which is not surprising as carbohydrate beverages were a major source of fluid consumption. With the exception of participant 3 during work-shift 3, the beverages and gels provided the sole means of exogenous energy supply whilst racing. Furthermore, the participants only took a single bottle (750 mL) with them during the work-shifts in order to minimise the mass they would have to carry. This meant that the maximum amount of carbohydrate they could consume via the beverage was capped by the optimal concentration (~75 g) (Coyle and Montain, 1992).

The delivery of carbohydrate was somewhat less than the consumption rates recommended in the scientific literature in order to maintain blood glucose concentrations (Coyle and Montain, 1992; Walberg-Rankin, 1995; Jeukendrup *et al.*, 2000; Stewart and Stewart, 2007). They were within the attenuated ranges Garcia Roves *et al.* (1998) reported for professional road cyclists, and similar to those for ultraendurance mountain runners (Kruseman *et al.*, 2005). In general, the composition of the carbohydrate beverages were in accordance with previously published research, yet the rate of delivery was somewhat less than the recommended 15 $ml \cdot kg \cdot h^{-1}$ (Coyle *et al.*, 1992; Maughan and Noakes, 1991; Abbiss and Laursen, 2005).

The 24XCT format enables riders to consume food and drink within the timeframe of the race, without necessarily having to consume during a work-shift. In theory this practice should produce the desired results. Neufer *et al.* (1987) and Coyle and Montain (1992) reported that a threshold of 200 g of carbohydrates should be consumed within four hours of the beginning of the exercise in order to benefit from an optimal ergogenic effect. Although the recovery window between the work-shifts was of a comparable duration, the 200 g threshold was rarely achieved by the participants. During the second half of the race, carbohydrate ingestion during the recovery intervals was less than that of the first half for all participants. These results are in accordance with the findings of Linderman and co-workers (2003) who reported a decline in caloric consumption over the course of a 12 h mountain bike marathon. They found that some subjects reported feeling nauseous and bloated during the event, which they suggested might be due to attenuated blood flow to the gut as a result of blood shunting to the working skeletal muscles. This offers a plausible explanation for the observations in the present study.

The carbohydrate consumption rates in the Linderman *et al.* (2003) study were approximately threefold those in the present study. This may be explained by the race format and riders' nutritional strategies. In the Linderman *et al.* (2003) study the race was continuous without prolonged breaks for refuelling, so riders had to consume foodstuffs whilst racing. They had to consume carbohydrate more consistently throughout the race whereas in the present study feeding was discontinuous. It would seem that the over reliance on the recovery periods for carbohydrate supplementation in the present study was not an optimal nutritional strategy.

9.5.3 Blood glucose concentrations

There were no differences in blood glucose concentrations pre and post each shift, which is in accordance with the findings of Linderman *et al*. (2003), however there was a shared attenuation in blood glucose concentrations for work-shift 4. The below-recommended carbohydrate intake and high energy expenditure, would indicate that there was a progressive depletion of the participants' glycogen stores throughout the 24 h race period. In the last work-shift blood glucose concentrations could not be maintained compared to the first three. This may be accounted for by fasting whilst asleep during the night time recovery period. Nilsson and Hultman (1973) found that hepatic glycogen can be considerably reduced as a result of an overnight fast. Pertinent to this discussion is the release of cortisol in response to low glycogen levels (Loebel and Kraemer, 1998). The maintenance of blood glucose concentrations for work-shifts 1 to 3 despite insufficient exogenous carbohydrate, coupled with the elevated cortisol concentrations suggests glycogenolysis occurred. Ainslie *et al.* (2003b) reported significantly higher levels of cortisol during prolonged hill walking when subjects were fed a low energy diet compared to a high energy one. During prolonged exercise cortisol secretion also promotes triglyceride breakdown in adipose tissue to glycerol and fatty acids for use as an energy substrate (McArdle *et al*., 2001). This would account, at least in part, for the increased post work-shift cortisol concentrations for work-shifts 1 to 3. The blunted cortisol response during work-shift 4, due to the reasons proposed in the previous chapter, may be linked to the lower blood glucose concentrations observed in the last work-shift. It may be that the lack of cortisol secretion reduced glycogenolysis, however this is speculative and requires further research.

9.5.4 Hydration

The difference between mean pre and post-race body mass (0.1 ± 0.15%) was considerably lower than the 2% threshold regarded as excessive dehydration (Sawka *et al.*, 2007; Rose and Peters, 2008). Although compartmental shifts cannot be accounted for, this would indicate that dehydration did not occur. As there were no traces of glucose or protein in any of the urine samples, it was taken that the refractometer measurements were accurate values (Lord, 1999). This is in contrast to the findings of Linderman *et al*. (2003) who reported that subjects lost nearly 4% of their bodyweight during a 12 h XCM race. The difference in the race format between the continuous XCM and the discontinuous 24XCT may explain these conflicting results. It would suggest that the recovery periods during the 24XCT race were used effectively for hydration by the participants in the present study.

Differences in fluid consumption over time were observed, with work-shifts 3 and 4 being less than that of the first one. This may be due to environmental conditions; the first work-shifts occurred during the hottest period of the day (18.7 to 20.4ºC; 12:00:00 to 17:17:48) and work-shifts 3 and 4 spanned cooler segments (8.6 to 15.6ºC; 22:57:06 to 12:00:00). This suggests that the spontaneous fluid ingestion of the participants was partly influenced by ambient temperature and / or their sweat rates, and concurs with the findings of Schenk *et al.* (2010) for mountain bike stage racing. This is further supported by the significant positive correlation between ambient temperature and sweat loss reported in the present study.

Fluid consumption rates were similar to those reported in the literature for XCSR racing (Rose and Peters, 2008; Wirnitzer and Kornexl, 2008; Schenk *et al.*, 2010), but less than those reported by Laursen *et al.* (2003a) for 24XCT. In the present study fluid intake was capped at 750 mL per work-shift because the participants opted to take only one bottle in order to minimise carrying additional mass (personal communication with participants). On two occasions participant 2 opted not to take any fluid in order to make further mass savings. During each work-shift participant 4 consumed the entire contents of the bottle indicating that the limiting factor for fluid intake during the work-shifts was the availability of fluid rather than thirst.

Participant 3 (during work-shifts 1 and 2) and participant 4 (during work-shift 4) opted to consume plain water rather than a carbohydrate beverage. During ultraendurance races this practice is not unique, Knechtle *et al.* (2009) noted that for competitors in the Race Across America (RAAM) their main beverage was pure water. Similarly Onywera *et al.* (2004) and Gabel *et al.* (1995) reported that ultraendurance cyclists and Kenyan distance runners respectively prefer plain water. More recently Cruz *et al.* (2009) found that plain water was a popular mode of hydration during mountain biking. Whilst maintaining hydration status, this practice will have contributed to the reduced energy consumption in the present study.

Intra-aural temperature was relatively stable throughout the race. The participants demonstrated that they were able to successfully thermoregulate despite the range of environmental temperatures and the metabolic heat produced as a result of the exercise bouts. Taken together these results suggest that the participants' ad libitum fluid consumption was sufficient to maintain their hydration status and is in accordance with other research in the literature (Casa, 2004a; Noakes, 2007; Rose and Peters, 2008).

9.5.5 Nutrition and performance

No previous research has simultaneously investigated the temporal nutritional practices and performances of competitors during a 24 h ultraendurance mountain bike race. The present study enabled this to be achieved. Although the analysis is associative and not causal, it provides an interesting insight into these parameters during the race.

Laursen and Rhodes (2001) suggest that the ultraendurance threshold is a theoretical exercise intensity that maintains a constant energy contribution from carbohydrate and fat throughout the race resulting in optimal performance. Therefore a reduction in carbohydrate availability would result in an attenuated exercise intensity that would fall below the optimal UET.

Participant 3's performance profile was consistent with that of a down-regulation of exercise intensity over time. His carbohydrate consumption was the lowest of the team and his energy intake accounted for 55% of the energy he expended. Utter and co-workers (1999) reported significantly higher ratings of perceived exertion for subjects performing 2.5 h of exercise during a placebo trial compared with a carbohydrate supplemented one despite no differences in post-exercise blood lactate concentration. They suggested that substrate availability played a mediating role in perceived exertion. This would provide a plausible explanation for participant 3's performance. His RPE response rose slightly throughout the course of the event, despite his performance and heart rate being reduced. This demonstrates a dissociation between RPE and cardiovascular load, and is further supported by a lack of correlation between post work-shift RPE and heart rate. Furthermore his positive affect scale responses steadily declined throughout the race.

In contrast participant 2's race profile was consistent with a sound pacing strategy. His energy intake accounted for 86% of the energy he expended, and his carbohydrate consumption was the greatest out of the team. He also reported a RPE drift throughout the race; however his race-speed increased towards the end and it was accompanied by an increase in his positive affect scale response. It is impossible to precisely separate these associations, but they would suggest that an interaction between nutrition and perceived exertion plays a role in mediating exercise performance. This area presents a complex but interesting challenge for future research.

9.6 Conclusions

The aim of this study was to investigate the energy balance and hydration status of participants during a 24 h cross-country competition. It was the first study of its kind to successfully achieve this. The participants were unable to match their energy intake with their energy expenditure and it was estimated that endogenous fuel stores supplied between 14 and 57% of the energy expended. The participants also failed to optimally use the recovery periods between race-shifts. These periods have the potential to ameliorate the negative energy balance, and the data suggest they should be used in conjunction with in-race feeding to reduce the energy deficit. Moreover all of the participants failed to meet current sports nutritional recommendations for energy and carbohydrate intake. This may in part be due to poor nutritional practices, but it may also be that published recommendations cannot be achieved in field conditions and that more realistic guidelines are required. This latter point highlights the need for a better understanding of ultraendurance mountain bike competitors and the in-race nutritional and physiological demands placed upon them.

Nonetheless the energy consumption of the participants in the study was sufficient to fuel the race before reaching exhaustion from substrate depletion. The participants' ad libitum drinking was sufficient to maintain adequate hydration status. These results provide new information regarding the energy dynamics of 24XCT racing and can be useful for coaches and athletes preparing nutritional strategies for such events. In addition it provides novel information on the competitors' responses to 24 h relay races which can help organisers develop guidelines for such events, and assist health professionals involved with supporting the athletes.

9.7 Summary of the 24XCT race

Although the participants had a successful race in terms of their overall classification, the evolution of their preparation and team strategy were not optimal. It is clear from the previous two studies that sports science has a role to play in researching optimal strategies and informing the coaching process. The following chapter proposes a model that identifies the factors that affect ultraendurance mountain bike performance.

CHAPTER TEN

Summary of work

10.1 Synthesis of conclusions

The previous studies in this thesis have demonstrated that ultraendurance cross-country mountain biking comprises many influencing variables that potentially affect performance. They have also demonstrated that it is inaccurate to suggest that factors affecting performance in ultraendurance XC mountain biking are the same as those for XCO mountain biking. Atkinson *et al.* (2003a) produced a comprehensive model of the factors that influence race velocity in road cycling. A model specific to ultraendurance mountain biking has yet to be determined. This chapter synthesises the results and conclusions from the preceding studies and, combined with research in the literature, proposes a model for ultraendurance mountain biking. In addition, original contributions to knowledge are highlighted, the limitations of the thesis are discussed and recommendations are made for future research.

10.1.1 Factors affecting performance

As previously established, success in ultraendurance mountain biking is dependent upon riding the bicycle at the fastest possible speed over the duration of the event. This forms the primary outcome in the proposed model with all other

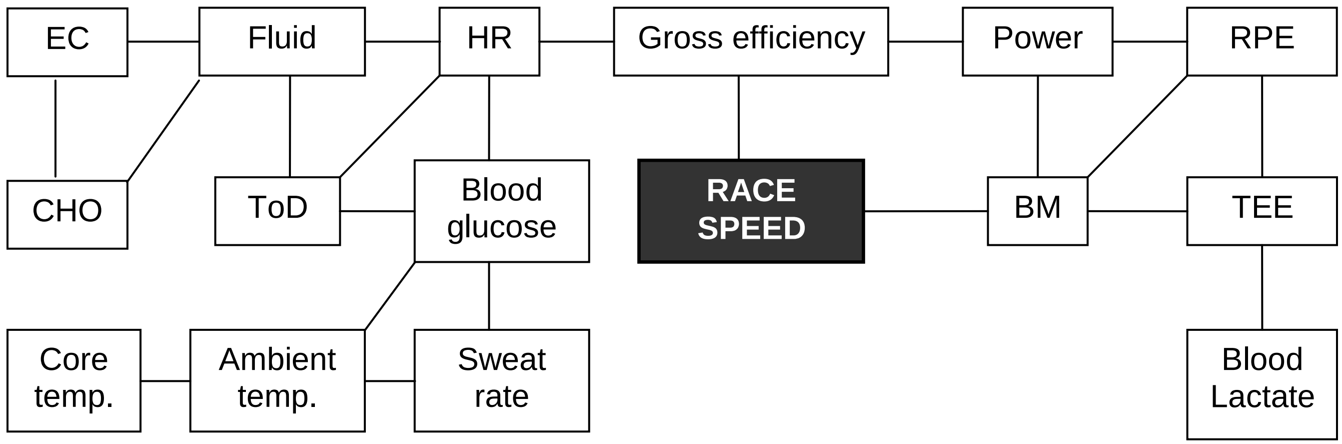


Figure 10.1: Schematic showing the influencing factors affecting the 24XCT performance. It is based on the variables measured in Studies 5 and 6 and the correlation matrix in Appendix M. Although each line represents a significant relationship a causal nexus cannot be assumed. EC = energy consumed; CHO = carbohydrate intake; HR = heart rate; RPE = rating of perceived exertion; ToD = time of day; BM = body mass; TEE = total energy expended; and temp. = temperature.

factors being subservient to it. Figure 10.1 shows the associations between the variables measured during studies Five and Six and the correlation matrix in Appendix M. It shows that race speed is associated with a plethora of factors. These direct influences, in conjunction with consideration of published research, were used to construct an integrated model of the factors that affect competitive ultraendurance mountain bike performance. The components of the model are detailed below.

10.2 Constructing the model

10.2.1 Anthropometric and physiological factors applied to the model

This thesis has shown that ultraendurance mountain bike performance cannot be predicted from anthropometric and physiological factors alone. However, a prerequisite level of physical fitness was established. A relatively high level of aerobic capacity, and an ability to work at a high percentage of it for prolonged periods, was demonstrated by all of the participants (70-76% $\dot{V}O_{2peak}$ for a continuous or cumulative 6 h). A lean body type (% body fat 10.7 ± 2.6) was characteristic of the ultraendurance mountain bikers and when normalised to body mass they had similar peak power outputs to XCO riders and other competitive road cyclists reported in the literature. Furthermore PPO was reported to correlate with 24XCT race speed. Figure 10.2 identifies the anthropometric and physiological factors that contribute to the model.

Physiological factors
• Anthropometric characteristics • Inherent physiological characteristics • Training status • Gross efficiency

Figure 10.2: Physiological factors applied to ultraendurance mountain biking.

Race speed during the 24XCT was also positively correlated with gross efficiency. The relationship between gross efficiency and other physiological variables is evident in Equation 14, and is determined by the amount of power that can be produced in relation to the metabolic work rate. This is dependent on, and will affect factors other than physiological ones. For example a more efficient rider will accrue less metabolic heat (Noakes, 2000a), which in turn will attenuate the physiological heat loss mechanisms and fluid replacement strategies. How the power generated translates into speed will depend upon the rider's skill set and technique when traversing the course (pedalling technique, bike handling skills, selecting the correct gear, and choosing the correct racing line) and the efficiency of the equipment (use of suspension systems, mass of the bicycle, illumination equipment etc.). These aspects are dependent upon parameters outside of the physiological domain. As such, the physiological factors do not fully explain the differences in race speed, and further influencing factors need to be applied to the model.

10.2.2 Nutritional factors applied to the model

The nutritional aspects of 24XCT racing were addressed in Study Six and in the main are also applicable to XCM racing within the proposed model. The data from Study Six, coupled with research in the literature, indicate that energy consumption during an ultraendurance race does not match energy expenditure. Strategies to enhance energy intake and glycogen resynthesis will clearly be beneficial to the physiological systems represented in Figure 10.2, and will also influence teleoanticipation and pacing strategies. Similarly the physiological factors, such as gross efficiency, will in turn influence the nutritional requirements. Study Six showed that the issues surrounding optimal nutrition during ultraendurance mountain biking are complex, and that successful strategies should include a pre, during and post work-shift approach. The nutritional factors that contribute to the model are represented in Figure 10.3.

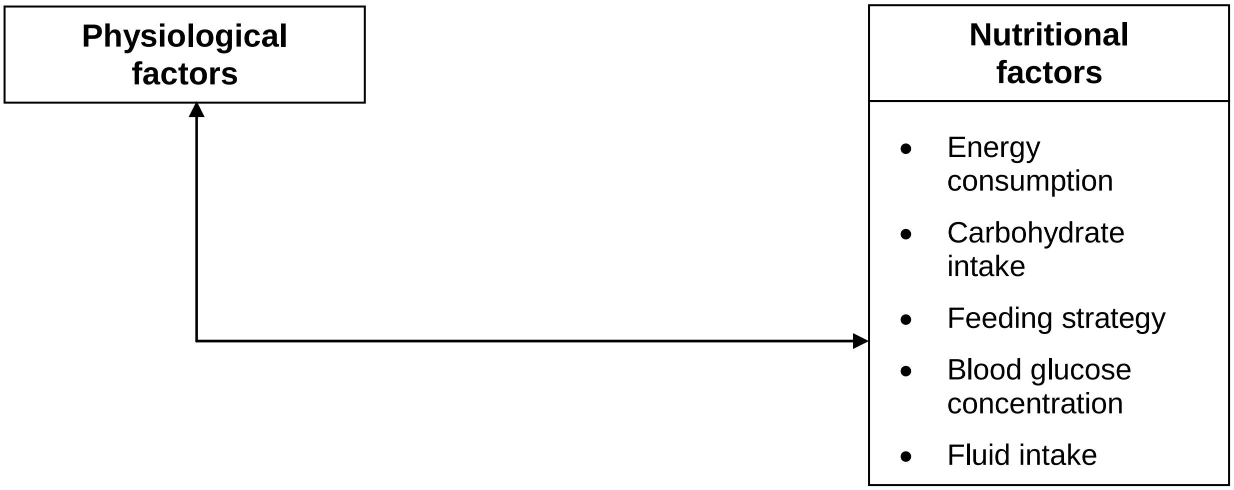


Figure 10.3: Physiological and nutritional factors applied to ultraendurance mountain biking

10.2.3 Technical and tactical factors applied to the model

The predetermined and real-time tactical factors, in addition to pacing strategies and technical ability, play pivotal roles within the proposed model. In the XCM race a constant HR_{ave}/HR_{max} suggested that an “internal work” pacing strategy was employed by the participants. Factors that influence this include training status, exercise duration, course profile, ambient temperature, the availability of foods and fluids, and other exogenous and endogenous factors. The pace a rider initiates will influence the physiological responses to the exercise, which in turn will influence real-time alterations in pacing in accordance with the complex systems model. The two-laps-on, six-laps-off race strategy employed by the participants during the 24XCT race has a “knock-on” effect to the other factors in the model. Whilst this strategy is common amongst 24 h teams, others employ a one-lap-on, three-laps-off strategy. This would have different ramifications for the other “boxes” in the model. Furthermore, how adroit a rider is will influence how efficient he is at traversing the terrain, which in turn will influence both the physiological responses and the nutritional requirements. The pivotal role of technical and tactical factors is represented by reciprocal arrows in Figure 10.4.

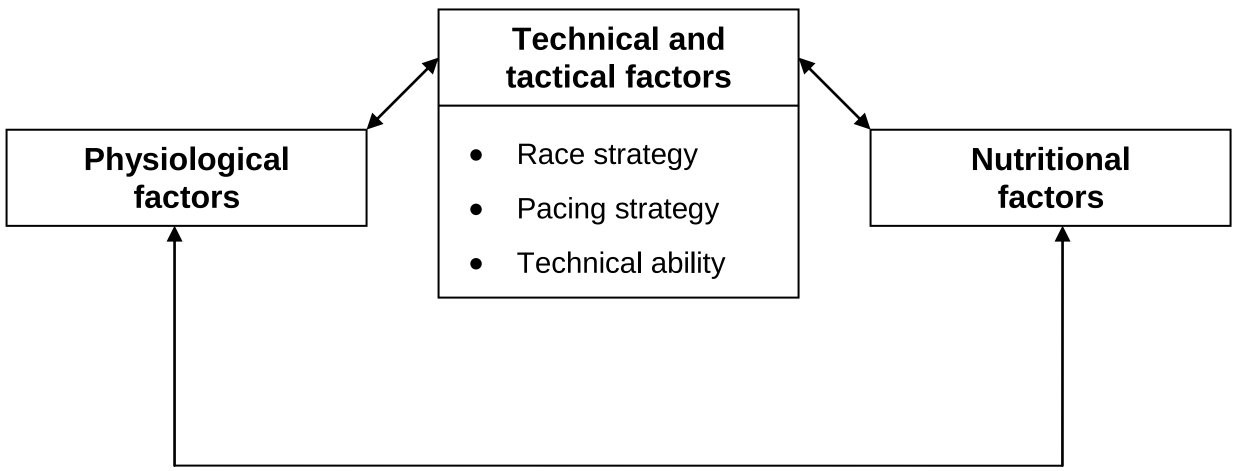


Figure 10.4: Physiological, nutritional, and technical and tactical factors applied to ultraendurance mountain biking

10.2.4 Environmental and circadian factors applied to the model

Ultraendurance mountain bike competitions take place in a variety of environmental conditions. Most courses are in mountainous areas where weather and terrain are variable. The protracted nature of ultraendurance events makes it almost inevitable that fluctuations in environmental conditions of some sort will be encountered. The ambient temperature range during the 24XCT race was substantial (8.6 – 20.8˚C) and, coupled with the metabolic heat production as a result of the work-shifts, placed a demand on the thermoregulatory systems of the participants. Successful thermoregulation, in part, requires adequate hydration, thus highlighting the integrative links between the physiological, environmental and nutritional factors within the model.

Competitors also have to deal with the demands of the physical environment. Data from studies Two and Five coupled with XCO data in literature show that shorter duration, steeper gradient courses have an effect on exercise intensity and place an increased load on the cardiovascular system. It was noted in Chapter Two that resistive forces oppose speed, and that changes in course gradient or environmental factors such as wind speed will affect race performance and allied physiological responses. These links between the environment and the physiological factors are shown in Figure 10.5.

In addition, the participants in the 24XCT race encountered circadian variations. Despite the potential masking effects of exercise and serial fatigue, a trend for a reduction in several of the measured physiological variables in the 24XCT race was evident during the night-time. Whether this was an endogenous circadian influence, the effects of illumination, sleep deprivation or a product of the three remains unresolved. Hormonal rhymicity was also found to be disrupted during the 24XCT race. The exact causes of this were not identified, but may have been due to low blood glucose concentrations, reduced glycogen stores, exercise stress, sleep deprivation and psychological stress. Taken together, these environmental and circadian factors were shown to influence other factors within the model, and are collectively represented in Figure 10.5.

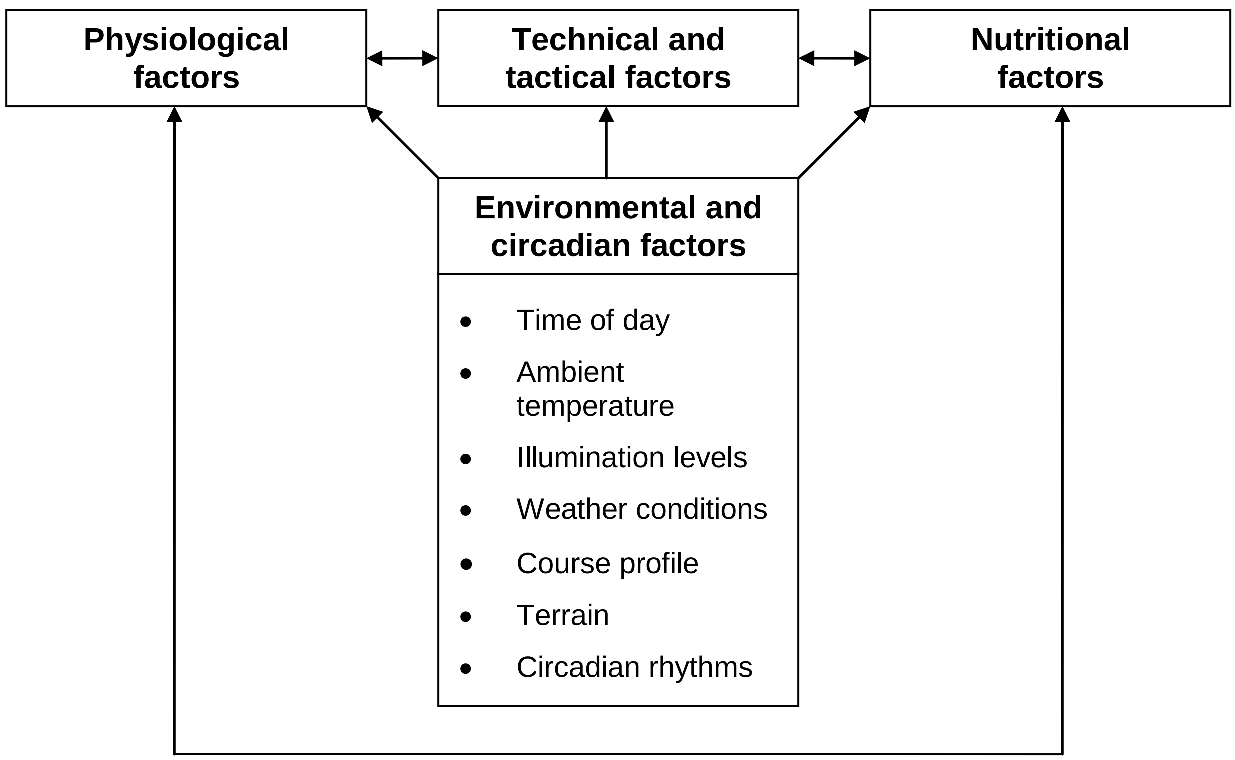


Figure 10.5: Physiological, nutritional, technical and tactical, and environmental and circadian factors applied to ultraendurance mountain biking

10.2.5 Putting it all together

Figure 10.6 is the proposed integrated model of factors that influence ultraendurance mountain bike performance in line with variables covered in this thesis. In the model speed is the primary performance variable and is situated at the apex. The domains that underpin this are physiological factors, technical and tactical factors, and nutritional factors. These domains do not operate in isolation; rather they have been shown to be integrated and inter-dependent. These domains are further influenced by the sub domain that includes environmental and circadian factors.

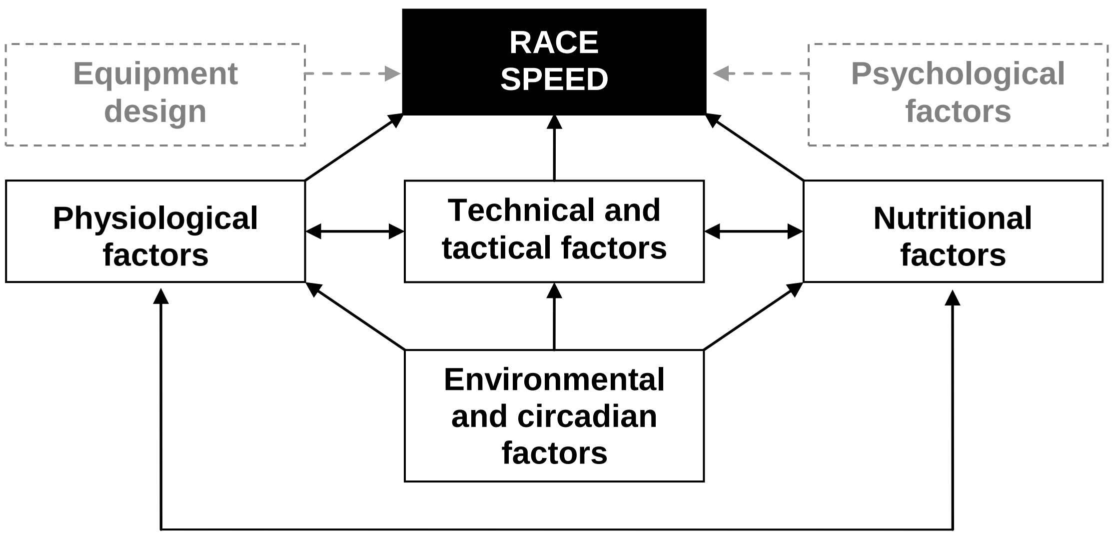


Figure 10.6: Integrated model showing the various factors that influence competitive ultraendurance mountain bike performance.

Two aspects of the model whose influences on performance were beyond the remit of this thesis are equipment design and psychological factors. There is a growing body of research addressing the energy cost of equipment design, in particular suspension units. They have been briefly reviewed in Chapter Two; some studies have reported no affect of suspension units on oxygen consumption (Seifert *et al.*, 1997; MacRae *et al.*, 2000; Neilens and LeJeune, 2001), and others have (Metcalfe, 2002; Titlestad *et al.*, 2006). However none of this research has addressed these issues in a race setting, and it is an important direction for future research. The impact of 24XCT on the perception of exertion and mood were acknowledged in Study Five, and changes in the PANAS and RPE scales were observed. It was found that the positive affects of the participants fluctuated throughout the race and that RPE dissociated from race speed and blood lactate concentrations. However, the impact of these psychological dynamics on performance were beyond the scope of this thesis and warrant further investigation. These two components of the model are represented as greyed text in Figure 10.6, and future researchers may wish to pursue these areas.

10.3 Practical implications

The concept of practical application of findings is central to the philosophy of this thesis. Below is an outline of how sports scientists, coaches and athletes can use this new information when planning and preparing for competition in ultraendurance mountain bike races. In addition this information is of great practical importance to race organisers and health professionals involved with supporting the athletes.

10.3.1 Power output vs. heart rate as a measure of exercise intensity

It was clear from the literature that there is much debate about which is the most appropriate tool for quantifying exercise intensity during cycling competitions and training. It is a pertinent issue as it is a fundamental component of training alongside duration and frequency. The merits and shortcomings of power output and heart rate as gauges of exercise intensity were reviewed in detail in Chapter Two. It was reported in Study Five that there was a lack of relationship between these two variables by work-shift. Figure 8.6 provided an obvious account of the lack of temporal association of these variables within a work-shift, with power output displaying an oscillatory profile and heart rate a relatively constant one. This is in agreement with the putative consensus in the scientific literature (Jeukendrup and Van Diemen, 1998; Atkinson and Brunskill, 2000; Hurst and Atkins, 2006a) and supports the view that the cardiovascular system lags behind metabolism at a cellular level (Stapelfeldt *et al*., 2004). In a real time perspective heart rate and power output are not expected to correlate with race speed (Jeukendrup and Van Diemen, 1998). The simple observation that speed decreases on climbs yet heart rate and power output are elevated confirms this, rendering neither as real-time predictors of the primary outcome variable. However, when mean heart rate and power output were compared to mean speed across work-shifts a significant positive correlation was observed for power output but not for heart rate. Although a significant correlation does not imply causality, it would suggest that all things being equal a greater mean power output per lap would result in an increased lap speed. However, as detailed in Chapter 8, the skill of a rider can dramatically affect this relationship. In terms of muscular work done (external work), power output is a direct measure. In ultraendurance mountain biking the competitors have to deal with additional stressors across multiple systems (Figure 10.6) not least of which is that encountered by the cardiovascular system. In terms of overall exercise induced stress (internal work), heart rate is the appropriate measure.

The efficacy of heart rate and power output as tools for measuring exercise intensity is an interesting paradox that researchers are still attempting to resolve. Based on the findings of this thesis, it is proposed that the coach and the athlete need to be clear from the outset whether monitoring work done, or measuring overall exercise-induced stress, is the most important. Power output may best represent the former and heart rate may best reflect the latter. It is proposed that overall exercise-induced stress is more pertinent to ultraendurance mountain biking than it is to XCO racing. The complex systems and teleoanticipatory mechanisms require afferent feedback from endogenous somatosensors. To race or train at a given power output regardless of heart rate implies a conscious overriding of these myocardial afferent signals and subsequent teleoanticipatory “black box” calculations. This in turn may lead to a rise in heart rate during prolonged exercise in line with the findings of O’Toole *et al.* (1998). Noakes *et al.* (2001) suggests that the limiting factor in endurance work is coronary blood flow and not oxygen availability at the muscles and that there are protective control mechanisms that prevent myocardial ischaemia. Under a progressively increasing heart rate he suggests that a neural mechanism terminates exercise before the heart reaches a state of myocardial anaerobiosis, citing evidence that progressive myocardial ischaemia does not occur during maximal exercise in healthy athletes. The result would be in line with a linear model of fatigue in that fatigue would be observed to be catastrophic. It is therefore proposed that, where possible, both power output and heart rate are monitored. In this proposition power output would be used to provide valuable secondary data regarding mechanical work done during training and racing. However, heart rate data would provide feedback on whole-body stress and act as an overriding governor to ensure performance and health are not compromised, and that teleoanticipatory afferent feedback is not consciously overridden and linear fatigue is avoided.

10.3.2 Energy expenditure and nutritional strategies

Establishing the energy cost of the two types of ultraendurance mountain biking is of great practical value to competitors. This knowledge is a key aspect when addressing the energy balance during a race and can be used to inform post race and post work-shift nutritional strategies to maximise recovery. The finding in Study Six that the energy consumption of the participants equated to less than 60% of the energy expended provides essential information for devising nutritional strategies to minimise such a deficit. Study Six also provided information on the practical importance of in-race feeding as well as during the recovery shift in order to address the energy shortfall. It is recommended that competitors view their nutritional strategies for the race holistically and aim to maximise their energy consumption throughout the entire 24 h period and not just episodically during the recovery periods as this was shown to be insufficient.

In a wider context, being able to establish an energy cost of an activity is also of practical relevance to those individuals and health care professionals involved in weight-loss and weight management programmes.

10.3.3 Familiarisation and efficiency

Of great practical relevance to competitive ultraendurance mountain bikers was the observation that the participants' efficiency improved during the final work-shift, which was crucially accompanied by an increase in race speed (with the exception of participant 3). Whilst the exact cause of this remains elusive, it appears that familiarisation resulting from riding the course at a pace analogous to racing is an important contributing factor. A subjective explanation for this was accounted for by the participants' observations that by the last work-shift they knew which racing lines to take and which gears to select. Extrapolating this leads to the supposition that if the participants had this knowledge from the outset they would have been more efficient and have ridden faster from the outset. This has important ramifications for the preparation of riders. Although in the 24XCT study, the participants pre-rode the course, they did so only twice and not at race pace. Clearly this was not sufficient and they were still familiarising themselves with the course as the race progressed. In this instance it took the participants six laps to become accustomed to the course. Their pre-race preparation is not atypical and it is commonplace for competitors to want to refrain from exerting themselves too much prior to the race. It is a recommendation of this thesis that competitors pre-ride the course several times at race-pace. This would have to be performed in the days prior to the event in order to avoid serial fatigue. This approach is not applicable to XCM where the course is point-to-point and the logistics of continually pre-riding is prohibitive. In addition the recall of course information and the physiological strain of this approach would be arduous. However the entire course need not be ridden. For example non-technical fireroad climbs would not benefit from pre riding whereas technical sections would. The most efficient use of a riders' pre-race time and energy may be to identify these key sections and pre-ride them at race-pace. These observations remain to be proven, and provide an exciting and challenging area for future research.

10.3.4 Establishing the feasibility and agreement of a bottom-bracket based power meter

Establishing the feasibility and agreement of a bottom-bracket based power meter during cross-country mountain biking is of great relevance to sports scientists, coaches and athletes as it provides a further measure of power output in the field. The minimal additional mass compared to other power meters, should increase riders' willingness to use them. This will enable coaches and sports scientists to: i) monitor exercise intensity in terms of external work done, ii) monitor changes in power output as a result of training, iii) provide a motivational tool for training, iv) establish normative values for research purposes, and v) monitor progress following injury or a layoff from training.

10.3.5 A blueprint protocol for future sports science research

It has been highlighted throughout this thesis that there is a need for authentic data collected during ultraendurance mountain bike races. Such field-based data in conjunction with controlled laboratory based research will help aid the understanding of the sport. It is hoped that the methods described in this thesis will provide a blueprint for future research protocols.

10.4 Limitations of the thesis

10.4.1 Internal and ecological validity

The main strengths of this thesis also contributed to its potential weaknesses. A trade-off often exists between internal and ecological validity. It was central to the philosophy of this thesis that data collection was in an applied setting. In maximising ecological validity and authenticity of data, internal validity was challenged insofar as a single variable could not be identified as the sole factor that impacted on the dependent variable. However, from the outset the research was deductive in nature and as such this was expected. One implication of this was, rather than identifying sole cause-and-effect variables, further lines of inquiry for future research were generated.

10.4.2 Sample size

To maintain high levels of ecological validity authentic participants were required. Compared to other cycling disciplines, the population of ultraendurance mountain bikers is relatively small. Recruiting high-level, compliant participants is difficult due to the limited population. However it is no solution to simply increase the size of the population by broadly defining the category. This meant that in the 24XCT study a multiple case-study approach was employed rather than traditional inferential statistics. As such the findings cannot be generalised to the wider population, however this was never the aspiration.

10.4.3 Frequency, duration and the testing environment

In order for sinusoidal rhythms to be detected, at least six testing sessions are required (Atkinson and Reilly, 1996). However, based on the typical 24XCT race strategy of 2-laps-on (~90 mins), six-laps-off (~270 mins) each rider will only be able to be tested four times during the 24 h race period. This was the case in the studies Five and Six and therefore the frequency of the sampling may not have been sensitive enough to detect subtle changes. More data points would theoretically be possible when testing a team with a one lap on, three laps off strategy. However, with this protocol less time will be available to collect data and the participants may be less compliant due to the limited recovery period.

In order to minimise the invasiveness of the protocol and maintain the compliance of the participants, the duration of the testing sessions were constrained to 20-30 mins. This meant that the number of variables that could be measured were limited and selected on relevance and practicability. For example, during the 24XCT race it was originally proposed that blood triglyceride concentrations would be measured in order to give a more detailed understanding of substrate dynamics. This required a 100 μL blood sample which proved problematic to achieve via a fingerprick capillary blood sample and not practical via a cannula. As such this and other variables were omitted from the field-testing protocol that would otherwise have been measured in the laboratory.

10.4.4 Estimation of energy expenditure

Due to the nature of mountain bike racing energy expenditure cannot be measured directly. As such the determination of energy expenditure was estimated indirectly and was dependent upon the integrity of the HR–$\dot{V}O_2$ relationship. The robustness of this association is well documented and is detailed in Chapter 2.3.2. Furthermore an assumption was made that 20.2 kJ are liberated for every litre of oxygen consumed. This method is widely used in sports science research and is an accepted practice for estimating energy expenditure in an applied setting (Mastroianni *et al.*, 2000; McArdle *et al.*, 2001; Laursen *et al.*, 2003a). Whilst every practicable measure was taken to ensure the accuracy of the data, it is nonetheless a potential source of error. Clearly any elevation in heart rate not directly associated with metabolism (e.g. isometric muscular contraction, cardiovascular drift, psychological factors, and caffeine ingestion (O'Toole *et al.*, 1998; Stapelfeldt *et al*., 2004)) will artificially elevate the subsequent estimated energy expenditure (Ainslie *et al.*, 2003a). In addition the resting energy expenditure was estimated from an established equation (Harris and Benedict, 1919) and not measured directly. Future researchers may wish to use these methods in combination with the other methods of estimating energy expenditure (e.g. doubly labelled water) in order to improve the accuracy, and assess the efficacy of the heart rate method in a field setting.

10.4.5 Incremental test protocol

The incremental test protocol detailed in Chapter 3.3.1 was use to determine the following physiological factors of the participants: peak aerobic power, calibration of $\dot{V}O_2$ – HR curve, and lactate response. The protocol for this test included a 30 W increase every two minutes as recommended by Cooke (2004) to determine aerobic power. Cooke (2004) also notes that $\dot{V}O_2$ at LT is independent of the rate of increase of exercise intensity. This latter point is supported by Yoshida (1984) who reported no difference in $\dot{V}O_2$ at LT when protocols of 25 W every minute or 25 W every four minutes were used. Similar protocols were employed by Green *et al.* (2003) and Prins *et al.* (2007) when determining maximal aerobic power and reference blood lactate concentrations (2 mmol and 4 mmol respectively). Although some researchers have employed reduced work stage durations of 30 seconds (Lausen *et al.*, 2003a) and one minute (Impellizzeri *et al.*, 2005a) several others have used longer durations of three minutes (Carpes *et al.*, 2003; Costa and De-Oliveira, 2008), four minutes (Baron, 2001; Impellizzeri *et al.*, 2002), and five minutes (Lee *et al.*, 2002; Cramp *et al.*, 2004; Gregory *et al.*, 2007). These protracted protocols have been employed in order to facilitate the occurrence of a plateau in oxygen uptake in accordance with $\dot{V}O_2$ maximum test termination criteria as recommended by the British Association of Sport and Exercise Sciences (BASES). On reflection this may be the reason why peak aerobic capacity and not maximal aerobic capacity was attained by the participants in this thesis. Furthermore if power output at LT is required three minute work stages are recommended (Cooke, 2004). Despite the wide range in work stage durations in the literature, it would therefore be prudent to employ longer duration work stages than those detailed in Chapter 3.3.1 when data pertaining to the above variables are required. It is therefore recommended that future research in this area should employ work stages of at least four minutes duration.

10.5 Original contributions to knowledge

Due to the dearth of research in this area, this thesis has contributed substantially to the understanding of the physiology and bioenergetics of ultraendurance mountain bike racing. The original contributions to knowledge of the research are outlined below.

10.5.1 Physiological contributions

In studies One and Five anthropometric and physiological data for XCM and 24XCT competitors were generated. It was also established that competitive XCM and 24XCT ultraendurance mountain bikers differ anthropometrically and physiologically from competitive XCO mountain bikers. This database of information is important to coaches and sports scientists when assessing the physiological characteristics of riders.

Furthermore, for the first time the energy demands of XCM and 24XCT mountain bike racing were established and estimated to be 59.9 kJ and 74.5 kJ respectively. This provides valuable information for coaches and sports scientists with regard to designing training programmes and nutritional strategies in order to optimise performance.

A relevant guideline for gauging exercise intensity during ultraendurance mountain bike racing and training was recommended. This method includes an integrative HR_{ave}/HR_{max} and power output approach. It was proposed that heart rate is more pertinent to ultraendurance cross-country racing in order to avoid catastrophic fatigue. It was also recommended that these methods should be calculated and implemented on an individual basis.

10.5.2 Nutritional contributions

For the first time absolute and temporal energy consumption and fluid intake values for a full-duration 24XCT race were determined. Due to the wealth of variables measured during the race, the influence of nutrition on other performance parameters were able to be compared. It was established that energy consumption during a 24XCT race is considerably less than energy expenditure, and that the over-reliance on recovery periods for energy intake (which is a typical practice during such competitions) is not the best strategy to optimally reduce the energy deficit. It was also suggested that current sport-specific nutritional guidelines may not be realistic when applied to ultraendurance racing and that new real-world guidelines need to be established.

10.5.3 Technical and tactical contributions

The in-race monitoring of external work and the real-time estimation of metabolic work-rate enabled gross-efficiency to be determined during the work-shifts. This enabled the novel observation that gross-efficiency improved towards the end of the race. It was reported that familiarisation with the course at analogous speeds to racing was a potential contributor to the improvement of gross-efficiency. Crucially, this improvement was associated with an increase in race speed. This technical improvement can inform the coaching process such that the tactical preparation of competitors should include pre-riding the course at race speeds.

10.5.4 Environmental and circadian contributions

Circadian variations of physiological and hormonal responses to 24XCT were reported. In particular, it was found in Chapter Eight that salivary cortisol levels are attenuated following serial acute bouts of exercise during a 24 h period. Furthermore circadian variations in race performance were observed. This is the first time this has been reported during a full-duration 24XCT race. However, a causal relationship was not established, and as such it provides a platform for future research.

10.5.5 Research contributions

The 24XCT race required a vanguard method in order to test within the race. A minimally invasive protocol for field-testing during 24XCT racing was designed and successfully implemented. This will hopefully provide a blueprint for future sports science research.

It was established that the Ergomo®Pro, a bottom bracket based ambulatory power meter, has good agreement with criterion methods of measuring power output during off-road field-testing. This additional, unobtrusive method of monitoring power output is of great relevance to riders, coaches and sports scientists.

For the first time an integrative model of the factors that influence ultraendurance mountain biking was proposed. In addition to being of practical use to coaches and athletes, it is hoped that this model will prompt future research.

10.6 Directions for future research

During the field testing, ensuring maximum ecological validity negated controlling all extraneous variables in order to determine a causal nexus. As such patterns were observed that require further investigation in order to elucidate the exact cause(s). The main directions for future research are outlined below.

10.6.1 Physiological directions

In line with the recommendation of Laursen and Rhodes (2001) for ascertaining an ultraendurance threshold for road cycling, a protocol needs to be established for determining the optimal pacing strategy for ultraendurance mountain bike racing. Based on the studies in this thesis, it would be doubtful whether this could be achieved in a laboratory. As such the protocol needs to be developed for a race setting. This is a challenging and exciting direction for future research.

10.6.2 Nutritional directions

It was clear from Study Six that the energy consumption of the participants was considerably less than their energy expenditure. It was also evident that their strategies to refuel were below those recommended for endurance sports. Future research should focus on optimal glycogen resynthesis strategies during such races. Furthermore, considering the wealth of other studies in the literature reporting that ultraendurance athletes cannot match intake with expenditure, more realistic guidelines need to be developed.

10.6.3 Technical and tactical directions

It was proposed in Study Five that the participants became increasingly familiar with the course as the race progressed resulting in an improvement in gross efficiency. In this particular race the increase in gross efficiency was observed after six antecedent laps. Whether this was the optimal number of laps is unclear. The participants' familiarisation may have improved further with an increased number of laps. Considering the potential effect this may have on gross efficiency, future work should investigate the optimal number of laps that need to be performed in order to become fully familiarised with a course. This will need to be established in conjunction with the potential detrimental effects of serial fatigue. Furthermore, with current advancements in GPS accuracy it may be possible to determine, when racing, the locations on the course where efficiency increases.

Following on from the above point, there is considerable scope for research into the optimal lap strategy during 24XCT racing. There is currently no empirical evidence whether a one-lap, two-lap, or three-lap work-shift strategy (or indeed any combination of laps) yields optimal results.

10.6.4 Environmental and circadian directions

During the 24XCT race, the participants demonstrated troughs in performance and in several other variables, most notably during the night-time. It was not clear whether this was due to circadian rhythms or environmental factors. Future research should attempt to elucidate the exact cause(s).

10.6.5 Psychological directions

It was established from the participants' PANAS responses that their mood fluctuated throughout the race. Whether or not this influenced performance was inconclusive. Future researches may wish to investigate whether a link between mood states and performance during ultraendurance mountain bike racing exists.

10.6.6 Replication studies

Due to the sample sizes in the studies, the conclusions are limited to the cohorts that were studied and the findings cannot be extrapolated to the wider ultraendurance mountain bike population. As such replication studies are required in order to evaluate the efficacy of the proposed model.

10.7 Overall conclusion

This thesis has enhanced the understanding of the physiology and bioenergetics of ultraendurance mountain bike racing. The anthropometric and physiological characteristics of well-trained ultraendurance cross-country mountain bike competitors were established, and the energy dynamics of racing were analysed. The successful testing methods developed for the field-based data collection now provides a template for future research. The field-based 24XCT study showed that physiological variables fluctuate throughout the race, and that gross efficiency and speed increased during the final work-shifts. This knowledge can inform the coaching process and have an impact on how competitors should optimally prepare for such races in the future. The energy expended by the participants was shown to be far greater than their energy intake, and that carbohydrate feeding both during the race and the recovery periods was not optimised. This finding has important ramifications for how competitors maximise their nutritional strategies. The interrelationships between the factors that affect ultraendurance mountain bike performance have been integrated into a conceptual model. It is hoped that this model is of practical importance to coaches and athletes, and that it provides a stimulus for future research. Field-based studies on ultraendurance mountain bike racing remain rare and continue to require research attention.

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Appendix A: UCI mountain bike discipline events

The different mountain bike disciplines as recognised by the Union Cycliste Internationale.

Category	Discipline
A.	Cross-country: XC Olympic Cross-country: XCO Marathon Cross-country: XCM Cross-country point-to-point: XCP (point to point) Short circuit Cross-country: XCC (Criterium) Cross-country time trial: XCT (Time Trial) Cross-country team relay: XCR (Team Relay)
B.	Downhill: DH (downhill) Individual downhill: DHI Massed-start downhill: DHM 4X (Four Cross) Parallel slalom: DS (Dual Slalom)
C.	Stage races

(Union Cycliste Internationale, 2006)

Figure A.1: The different mountain bike disciplines as recognised by the Union Cycliste Internationale

Appendix B: Positive and negative affect scale (PANAS) questionnaire.

Rider ________________ Pre / Post Shift: 1 2 3 4 5

This scale consists of a number of words that describe different feelings and emotions. Read each item and then mark the appropriate answer in the space next to that word.

	Not at all	A little	Moderately	Quite a bit	Extremely
Interested	1	2	3	4	5
Distressed	1	2	3	4	5
Excited	1	2	3	4	5
Upset	1	2	3	4	5
Strong	1	2	3	4	5
Guilty	1	2	3	4	5
Scared	1	2	3	4	5
Hostile	1	2	3	4	5
Enthusiastic	1	2	3	4	5
Proud	1	2	3	4	5
Irritable	1	2	3	4	5
Alert	1	2	3	4	5
Ashamed	1	2	3	4	5
Inspired	1	2	3	4	5
Nervous	1	2	3	4	5
Determined	1	2	3	4	5
Attentive	1	2	3	4	5
Jittery	1	2	3	4	5
Active	1	2	3	4	5
Afraid	1	2	3	4	5

(Watson *et al.*, 1988)

Appendix C: University of Central Lancashire Health Questionnaire and Physical Activity Readiness Questionnaire

UCLan Sports Science Labs: Health Screen Questionnaire

Name_________________________ Age________ Gender M F

Address____

____________________________________ Phone________________

Height_____________ Weight______________ Date of test _________

Profession____

Stage 1 - Known Diseases (Medical Conditions)

1. List the medications you take on a regular basis.
2. Do you have diabetes? No Yes
   a) if yes, please indicate if it is insulin-dependent diabetes mellitus (IDDM) or non-insulin-dependent diabetes mellitus (NIDDM). IDDM NIDDM
   b) if IDDM, for how many years have you had IDDM? ________ years
3. Have you had a stroke? No Yes
4. Has your doctor ever said you have heart trouble? No Yes
5. Do you take asthma medication? No Yes
6. Are you or do you have reason to believe you may be pregnant? No Yes
7. Is there any other physical reason that prevents you from participating in an exercise program (e.g. cancer; osteoporosis; severe arthritis; mental illness; thyroid, kidney or liver disease)? No Yes

Stage 2 - Signs and Symptoms

8. Do you often have pains in your heart, chest, or surrounding areas, especially during exercise? No Yes
9. Do you often feel faint or have spells of severe dizziness during exercise? No Yes
10. Do you experience unusual fatigue or shortness of breath at rest or with mild exertion? No Yes
11. Have you had an attack of shortness of breath that came on after you stopped exercising? No Yes
12. Have you been awakened at night by an attack of shortness of breath? No Yes
13. Do you experience swelling or accumulation of fluid in or around your ankles? No Yes
14. Do you often get the feeling that your heart is beating faster, racing, or skipping beats, either at rest or during exercise? No Yes

15. Do you regularly get pains in your calves and lower legs during exercise which are not due to soreness or stiffness? No Yes

16. Has your doctor ever told you that you have a heart murmur? No Yes

Stage 3 - Cardiac Risk Factors

17. Do you smoke cigarettes daily, or have you quit smoking within the past two years? No Yes

    If yes, how many cigarettes per day do you smoke (or did you smoke in the past two years)? ________ per day

18. Has your doctor ever told you that you have high blood pressure? No Yes

19. Has your father, mother, brother, or sister had a heart attack or suffered from cardiovascular disease before the age of 65? No Yes
    If yes,
    a) Was the relative male or female? ______________
    b) At what age did he or she have the stroke or heart attack? ______________
    c) Did this person die suddenly as a result of the stroke or heart attack? No Yes

20. Have you experienced menopause before the age of 45? No Yes
    If yes, do you take hormone replacement medication? No Yes

If known, enter blood pressure and blood lipid values:

21. What is your systolic blood pressure? _________mmHg

22. What is your diastolic blood pressure? _________mmHg

23. What is your serum cholesterol level? ______mmol/L or mg/dL

24. What is your serum HDL level? ______mmol/L or mg/dL

25. What is your serum triglyceride level? ______mmol/L or mg/dL

Stage 4 - Exercise Intentions

26. Does your job involve sitting for a large part of the day? No Yes

27. What are your current activity patterns?
    a) Frequency: ______exercise sessions per week
    b) Intensity: Sedentary Moderate Vigorous
    c) History: <3 months 3-12 months >12 months
    d) Duration: ______minutes per session

28. What types of exercises do you do?

29. Do you want to exercise at a moderate intensity (e.g. brisk walking) or at a vigorous intensity (e.g. jogging)? Moderate Vigorous

I acknowledge that the above information is correct to the best of my knowledge.

Sign: ______________________________ Date: __________________

PAR-Q & YOU

(A Questionnaire for People Aged 15 to 69)

Regular physical activity is fun and healthy, and increasingly more people are starting to become more active every day. Being more active is very safe for most people. However, some people should check with their doctor before they start becoming much more physically active.

If you are planning to become much more physically active than you are now, start by answering the seven questions in the box below. If you are between the ages of 15 and 69, the PAR-Q will tell you if you should check with your doctor before you start. If you are over 69 years of age, and you are not used to being very active, check with your doctor.

Common sense is your best guide when you answer these questions. Please read the questions carefully and answer each one honestly: check YES or NO.

YES	NO		
☐	☐	**1.**	**Has your doctor ever said that you have a heart condition <u>and</u> that you should only do physical activity recommended by a doctor?**
☐	☐	**2.**	**Do you feel pain in your chest when you do physical activity?**
☐	☐	**3.**	**In the past month, have you had chest pain when you were not doing physical activity?**
☐	☐	**4.**	**Do you lose your balance because of dizziness or do you ever lose consciousness?**
☐	☐	**5.**	**Do you have a bone or joint problem (for example, back, knee or hip) that could be made worse by a change in your physical activity?**
☐	☐	**6.**	**Is your doctor currently prescribing drugs (for example, water pills) for your blood pressure or heart condition?**
☐	☐	**7.**	**Do you know of <u>anyotherreason</u> why you should not do physical activity?**

If you answered Yes to one or more questions

Talk with your doctor by phone or in person BEFORE you start becoming much more physically active or BEFORE you have a fitness appraisal. Tell your doctor about the PAR-Q and which questions you answered YES.

- You may be able to do any activity you want — as long as you start slowly and build up gradually. Or, you may need to restrict your activities to those which are safe for you. Talk with your doctor about the kinds of activities you wish to participate in and follow his/her advice.
- Find out which community programmes are safe and helpful for you.

If you answered No to all questions

- start becoming much more physically active – begin slowly and build up gradually. This is the safest and easiest way to go.
- take part in a fitness appraisal – this is an excellent way to determine your basic fitness so that you can plan the best way for you to live actively. It is also highly recommended that you have your blood pressure evaluated. If your reading is over 144/94, talk with your doctor before you start becoming much more physically active.

"I have read, understood and completed this questionnaire. Any questions I had were answered to my full satisfaction."

Name ____ Signature _____________________________________

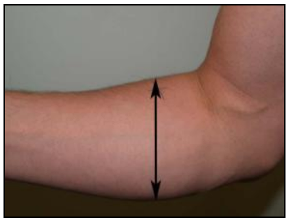
Date ____ Witness ______________________________________

Appendix D: Sites for Skinfold Measurement (Jackson & Pollock, 1978)

All measurements were taken from the right hand side of the subject.

Table D.1: Sites for Skinfold Measurement

Site	Direction of fold	Anatomical reference	Measurement	Illustration
Pectoral	Oblique	Axilla and nipple	Fold is taken ½ distance between axilla and nipple as high as possible on anterior axillary fold. Measurement taken 1 cm below fingers.	
Axilla	Horizontal	Xiphisternal junction (point where costal cartilage of ribs 5-6 articulate with sternum, slightly above inferior tip of xiphoid process)	Fold is taken on midaxillary line at level of Xiphisternal junction.	
Abdominal	Vertical	Umbilicus	Fold is taken 3 cm lateral and 1 cm inferior to centre of the umbilicus.	
Suprailium	Oblique	Iliac crest	Fold is grasped posteriorly to midaxillary line and superiorly to iliac crest along natural cleavage of skin. Calipers applied 1 cm below fingers.	
Subscapular	Oblique	Inferior angle of scapula	Fold is along natural cleavage line of skin just inferior to inferior angle of scapula. Calipers applied 1 cm below fingers.	

Site	Direction of fold	Anatomical reference	Measurement	Illustration
Triceps	Vertical (midline)	Acromial process of scapula and olecranon process of ulna	Distance between lateral projection of Acromial process and inferior margin of olecranon process is measured on lateral aspect of arm with elbow flexed 90° using a tape measure. Midpoint is marked on lateral side of arm. Fold is lifted 1 cm above marked line on posterior aspect of arm. Calliper is applied at marked level.	
Thigh	Vertical (midline)	Inguinal crease and patella	Fold is lifted on anterior aspect of thigh midway between inguinal crease and proximal border of patella. Body weight should be shifted onto left foot. Calipers applied 1 cm below fingers.	
Calf	Vertical (medial aspect)	Maximal calf circumference	Fold is lifted at level of maximal calf circumference on medial aspect of calf with knee and hip flexed to 90°.	
Forearm		Maximal forearm circumference		

Adapted from Heyward, (1991, pp.161-162)

Appendix E: Salivary cortisol analysis procedure

Detailed procedure for Salimetrics High Sensitivity Salivary Cortisol Enzyme Immunoassy kit as used in study 3. The information is adapted from Salimetrics (2010).

High Sensitivity Salivary Cortisol Enzyme Immunoassay kit

Materials supplied with the kit:

	Item	Quantity/Size
1	**Microtitre Plate** Coated with monoclonal anti-cortisol antibodies.	1/96-well
2	**Cortisol Standards** Ready to use, traceable to NIST standard: 3.0, 1.0, 0.333, 0.111, 0.037, 0.012 µg/dL (82.77, 27.59, 9.19, 3.06, 1.02, 0.33 nmol/L). Contain: cortisol, buffer, preservative.	6 vials/500 µL each
3	**Cortisol Controls** High, Low. Ready to use, see vials for target values. Contain: cortisol, buffer, preservative.	2 vials/500 µL each
4	**Wash Buffer Concentrate (10x)** Dilute before use according to Reagent Preparation. Contains: phosphate buffer, detergent, preservative.	1 bottle/100 mL
5	**Assay Diluent** Contains: phosphate buffer, pH indicator, preservative.	1 bottle/60 mL
6	**Cortisol Enzyme Conjugate** Concentrate. Dilute before use with assay diluent. (See step 5 of Procedure.) Contains: cortisol conjugated to HRP, preservative.	1 vial/50 µL
7	**TMB Substrate Solution** Non-toxic, ready to use.	1 bottle/25 mL
8	**3 M Stop Solution*** Contains: sulfuric acid.	1 bottle/12.5 mL
9	**Non-Specific Binding (NSB) Wells** Do not contain anti-cortisol antibody.	1 strip

Additional materials used:

- Precision pipette to deliver 15 and 25 µL
- Precision multichannel pipette to deliver 50 µL and 200 µL Vortex
- Plate rotator
- Spectramax plus plate reader (Molecular Devices, California, U.S.A.) with a 450 nm filter
- Computer software for data reduction
- Deionized water
- Reagent reservoirs
- One disposable tube capable of holding 24 mL Pipette tips
- Serological pipette to deliver up to 24 mL

Reagent preparation

- All reagents were brought to room temperature and mixed before use (minimum of 1.5 hours).
- Microtitre plate was also at room temperature before use.
- 1X wash buffer was prepared by diluting wash buffer concentrate 10-fold with room- temperature deionised water (100 mL of 10X wash buffer to 900 mL of deionised H_2O).

Procedure

Step 1: Plate layout was determined.

	1	2	3	4	5	6	7	8	9	10	11	12
A	3.000	3.000	Ctrl-H	Ctrl-H								
B	1.000	1.000	Ctrl-L	Ctrl-L								
C	0.333	0.333	Unk-1	Unk-1								
D	0.111	0.111	Unk-2	Unk-2								
E	0.037	0.037	Unk-3	Unk-3								
F	0.012	0.012	Unk-4	Unk-4								
G	Zero	Zero	Unk-5	Unk-5								
H	NSB	NSB	Unk-6	Unk-6								

Step 2: The desired number of strips was kept the strip holder and remaining strips were removed.

Step 3: 24 mL of assay diluent was pipetted into a disposable tube and set aside for Step 5.

Step 4:

- 25 µL of standards, controls, and unknowns were pipetted into appropriate wells. Standards, controls, and unknowns were assayed in duplicate.
- 25 µL of assay diluent were pipetted into 2 wells to serve as the zero value.
- 25 µL of assay diluent were pipette into each NSB well.

Step 5: A 1:1600 dilution of the conjugate was made by adding 15 µL of the conjugate to the 24 mL of assay diluent prepared in Step 3. The diluted conjugate solution was immediately mixed and 200 µL was pipetted into each well using a multichannel pipette.

Step 6: The plate was mixed on a rotator for 5 minutes at 500 rpm and incubated at room temperature for an additional 55 minutes.

Step 7: The plate was washed four times with 1X wash buffer by pipetting 300 µL of wash buffer into each well, and then discarding the liquid by inverting the plate over a sink. After each wash, the plate should be thoroughly blotted on paper towels before being turned upright.

Step 8: 200 µL of TMB solution was added to each well with a multichannel pipette.

Step 9: It was then mixed on a plate rotator for 5 minutes at 500 rpm and incubated in the dark at room temperature for an additional 25 minutes.

Step 10: 50 µL of stop solution was added with a multichannel pipette.

Step 11: It was then mixed on a plate rotator for 3 minutes at 500 rpm. The bottom of plate was wiped with a water-moistened, lint-free cloth and wiped dry. The plate was read in a Spectramax plus plate reader (Molecular Devices, California, U.S.A.) at 450 nm within 10 minutes of adding the stop solution.

Assay Procedure Summary

1. **Bring all reagents to room temperature and mix before use.**
2. **Prepare 1X wash buffer (and reconstitute stop solution, if appropriate).**
3. **Bring plate to room temperature and prepare for use with NSB wells.**
4. **Prepare tube with 24 mL of assay diluent for conjugate dilution, which will be made later.**
5. **Pipette 25 µL of standards, controls, and unknowns into appropriate wells.**
6. **Pipette 25 µL of assay diluent into zero and NSB wells.**
7. **Make final 1:1600 dilution of conjugate (15 µL into 24 mL assay diluent), mix, and immediately pipette 200 µL into each well.**
8. **Mix plate for 5 minutes at 500 rpm. Incubate for an additional 55 minutes at room temperature.**
9. **Wash plate 4 times with 1X wash buffer. Blot.**
10. **Add 200 µL TMB solution to each well.**
11. **Mix plate for 5 minutes at 500 rpm. Incubate in dark at room temperature for 25 additional minutes.**
12. **Add 50 µL stop solution to each well. Mix for 3 minutes at 500 rpm.**
13. **Wipe plate bottom clean and read within 10 minutes of adding stop solution.**

Calculations

1. The average optical density (OD) was computed for all duplicate wells.
2. The average OD for the NSB wells was subtracted from the average OD of the zero, standards, controls, and unknowns.
3. The percent bound (B/Bo) was calculated for each standard, control, and unknown by dividing the average OD (B) by the average OD for the zero (Bo).
4. The concentrations of the controls and unknowns were determined by interpolation using software capable of logistics. We recommend using a 4-parameter sigmoid minus curve fit.

Typical Results

Well	Sample	Average OD	B	B/Bo	Cortisol (µg/dL)
A1,A2	S1	0.094	0.071	0.048	3.000
B1,B2	S2	0.236	0.213	0.145	1.000
C1,C2	S3	0.524	0.501	0.340	0.333
D1,D2	S4	0.897	0.874	0.593	0.111
E1,E2	S5	1.219	1.196	0.812	0.037
F1,F2	S6	1.379	1.356	0.921	0.012
G1,G2	Bo	1.496	1.473	NA	NA
H1,H2	NSB	0.023	NA	NA	NA

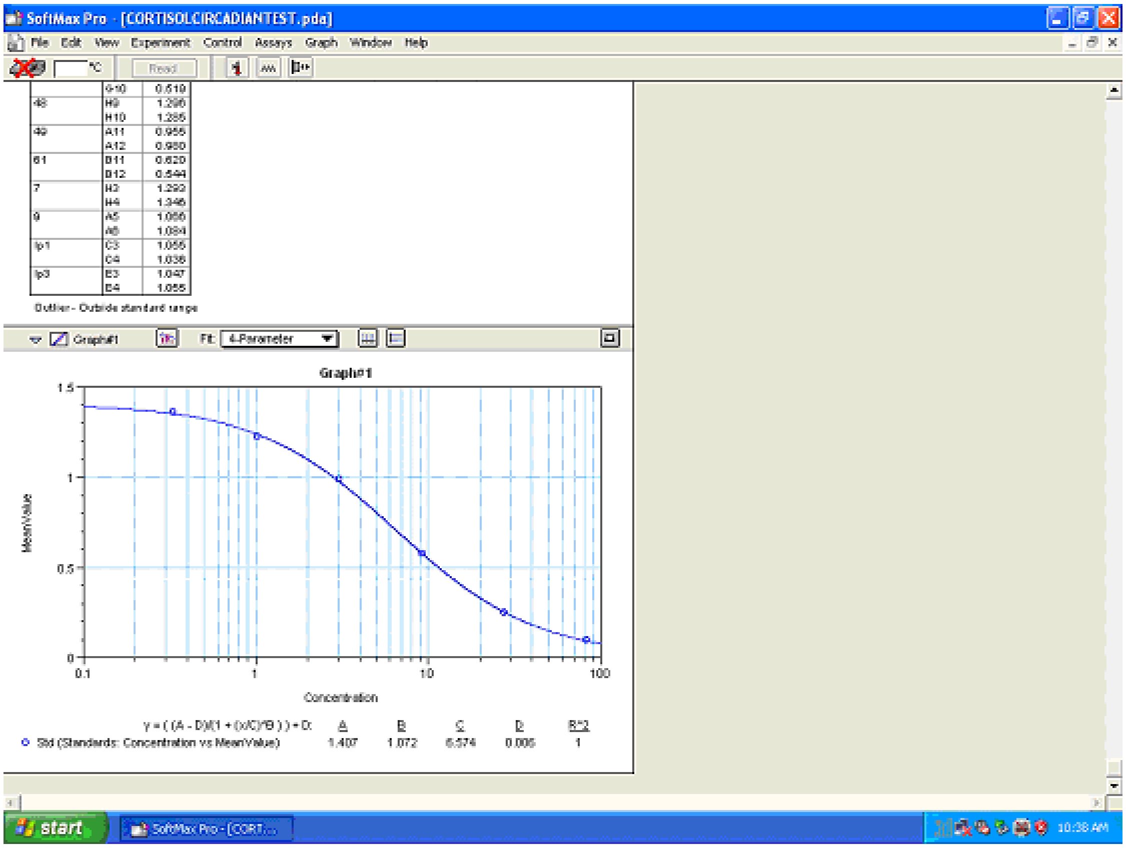


Figure E.1 Screen print of calibration curve using Softmax Pro. (Version 4.7.1, Molecular Devices, California, US).

Table E.1: Mean, S.D. and coefficient of variance (C.o.V) for pipette technique for experimenter (sample data from a single test trial).

	1	2	3	4	5	6	7	8	9	10
1	101	102	101	99	99	101	101	97	100	100
2	102	100	101	99	100	102	99	101	100	101
3	100	99	102	98	102	100	101	99	101	100
4	99	101	98	100	99	100	100	100	99	100
5	97	100	100	100	100	99	100	101	100	100
6	101	99	100	101	102	99	101	100	101	99
7	100	101	98	99	99	101	99	98	98	98
8	101	101	99	101	99	100	100	98	98	101
9	102	100	100	99	99	102	101	100	101	101
10	100	102	101	98	101	101	101	100	100	101
Mean	**100.3**	**100.5**	**100.0**	**99.4**	**100.0**	**100.5**	**100.3**	**99.4**	**99.8**	**100.1**
S.D.	**1.49**	**1.08**	**1.33**	**1.07**	**1.25**	**1.08**	**0.82**	**1.35**	**1.14**	**0.99**
C.o.V.	**1.49**	**1.07**	**1.33**	**1.08**	**1.25**	**1.07**	**0.82**	**1.36**	**1.14**	**0.99**

Appendix F: Representative sample data for calibration and HR response during XCM race

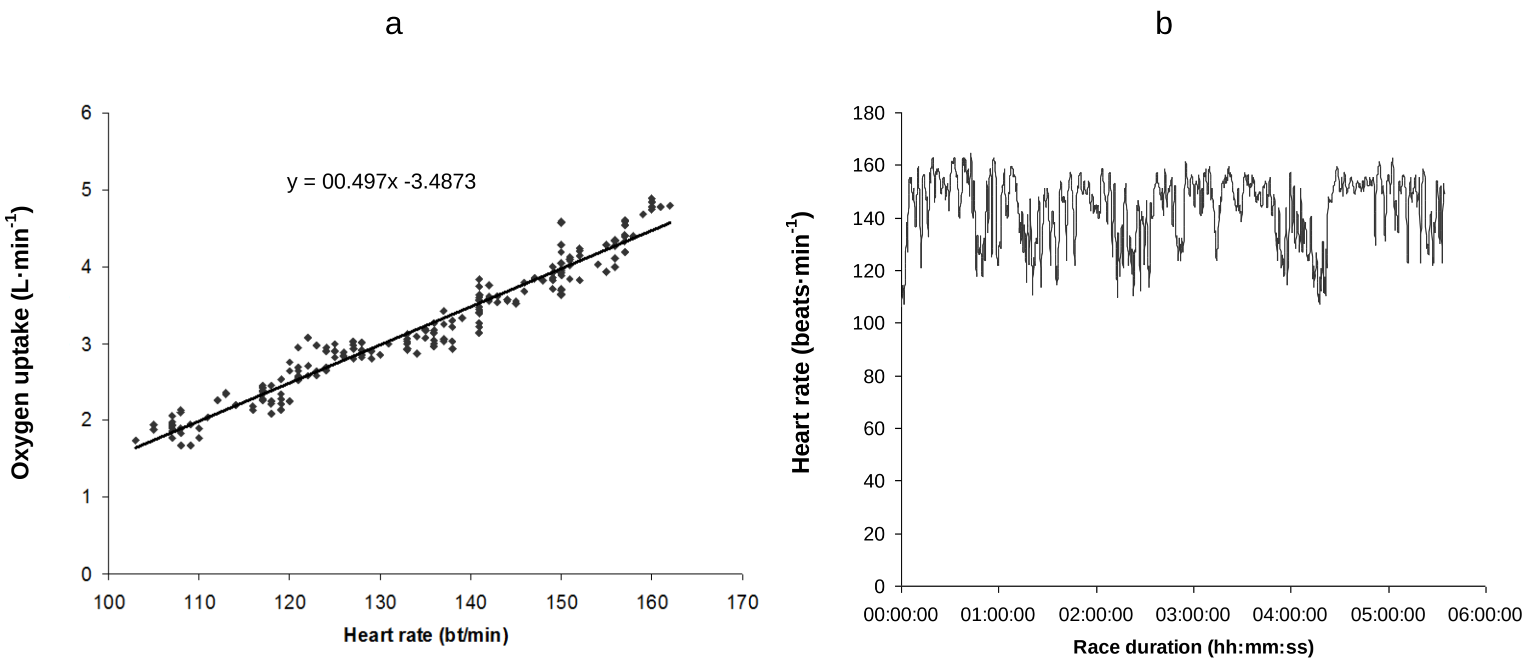


Figure F.1: Representative sample data for EE calibration curve (HR_{100} – 85% HRmax) taken from a $\dot{V}O_2$peak test (a) and respective race HR response (b) for a single subject

Appendix G: Calculation of course profile.

Global positioning system (GPS) data were collected from a single participant using a FRWD F500 receiver (FRWD Technologies, Oulu, Finland) and downloaded using FRWD PRO Replayer software (Build 70, Version 1.3.5, FRWD Technologies, Oulu, Finland). As GPS data only give a location to within a few metres, the data were manually overlaid onto a digital Ordinance Survey (OS) map (Memory-Map OS Edition Version 5.2.7) in order to improve accuracy. Figure H.1 shows a screen print of the GPS data for the XCM race course.

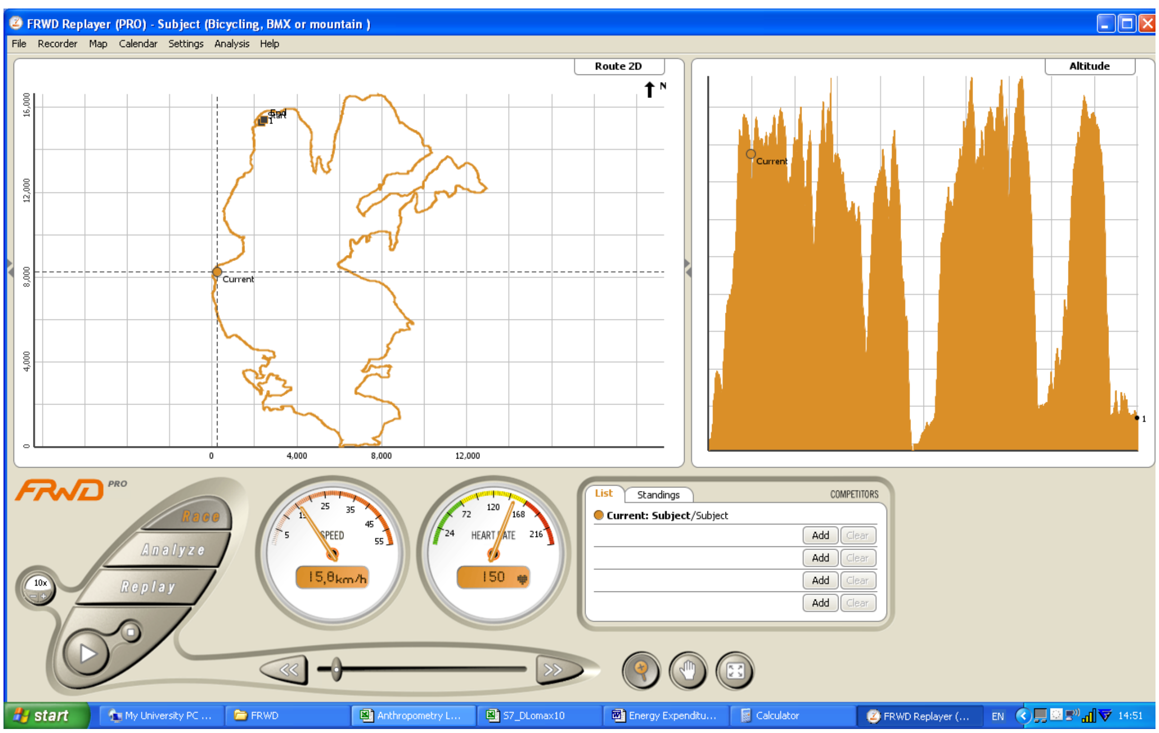


Figure G.1: Screen print of GPS data in FRWD PRO Replayer software (Build 70, Version 1.3.5, FRWD Technologies, Oulu, Finland).

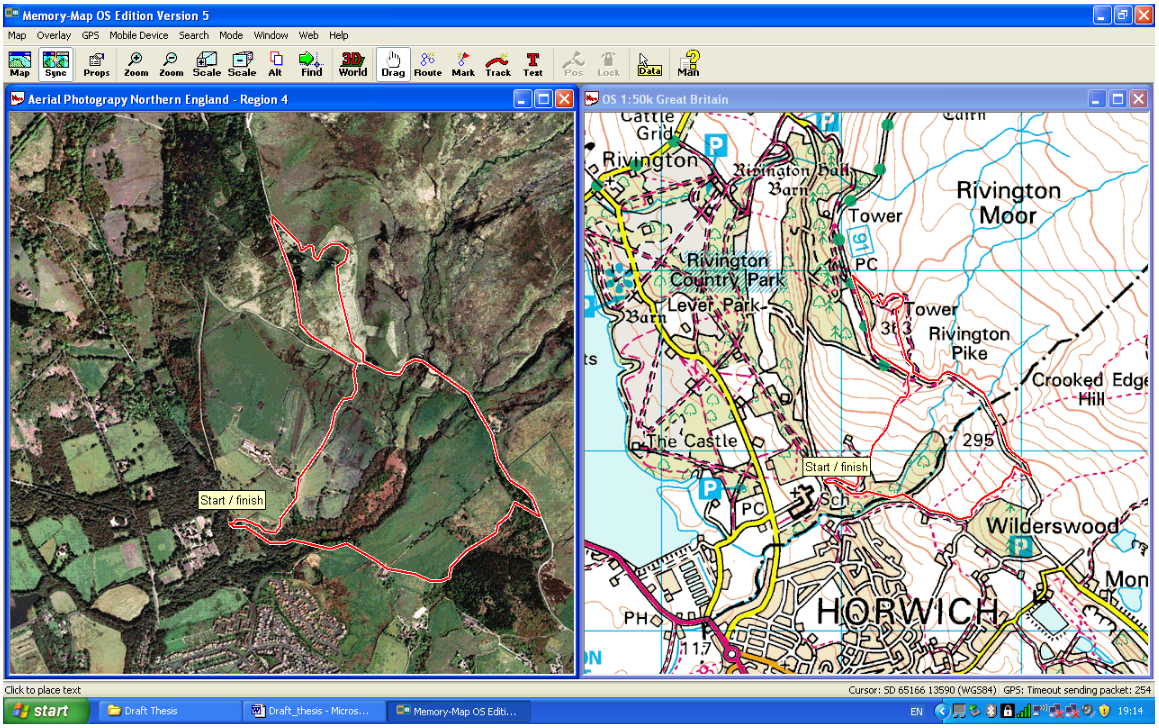


Figure G.2: Screen print of aerial photograph and Ordinance Survey map of the cross-country course used in the power meter agreement study. Viewed in Memory Map software (Memory-Map OS Edition Version 5.2.7, Aldermaston, UK)

Appendix H: Correlation matrix for XCM race

		Fat %	Stature	VO_2	PPO	$PPO·kg^{-1}$	PO_{LT}	$PO_{LT}·kg^{-1}$	PO_{OBLA}	$PO_{OBLA}·kg^{-1}$	Body mass	Speed
Fat %	Pearson	1	-.448	-.512	-.350	.092	-.232	.066	-.087	.288	-.333	.236
	Sig. (2-tailed)		.265	.194	.395	.829	.580	.877	.837	.489	.421	.574
	N	8	8	8	8	8	8	8	8	8	8	8
Stature	Pearson	-.448	1	.775*	.732*	-.615	-.078	-.719*	.521	-.586	.935**	.069
	Sig. (2-tailed)	.265		.024	.039	.105	.855	.044	.186	.127	.001	.870
	N	8	8	8	8	8	8	8	8	8	8	8
VO_2	Pearson	-.512	.775*	1	.716*	-.488	-.178	-.710*	.248	-.728*	.843**	.074
	Sig. (2-tailed)	.194	.024		.046	.220	.674	.048	.554	.041	.009	.862
	N	8	8	8	8	8	8	8	8	8	8	8
PPO	Pearson	-.350	.732*	.716*	1	-.058	.250	-.398	.640	-.298	.737*	.120
	Sig. (2-tailed)	.395	.039	.046		.891	.550	.328	.088	.473	.037	.777
	N	8	8	8	8	8	8	8	8	8	8	8
$PPO·kg^{-1}$	Pearson	.092	-.615	-.488	-.058	1	.357	.717*	-.151	.644	-.716*	.196
	Sig. (2-tailed)	.829	.105	.220	.891		.385	.045	.720	.085	.046	.641
	N	8	8	8	8	8	8	8	8	8	8	8
PO_{LT}	Pearson	-.232	-.078	-.178	.250	.357	1	.693	.691	.689	-.086	-.411
	Sig. (2-tailed)	.580	.855	.674	.550	.385		.057	.058	.059	.840	.312
	N	8	8	8	8	8	8	8	8	8	8	8
$PO_{LT}·kg^{-}$	Pearson	.066	-.719*	-.710*	-.398	.717*	.693	1	.046	.907**	-.774*	-.253
	Sig. (2-tailed)	.877	.044	.048	.328	.045	.057		.913	.002	.024	.545
	N	8	8	8	8	8	8	8	8	8	8	8
PO_{OBLA}	Pearson	-.087	.521	.248	.640	-.151	.691	.046	1	.283	.526	-.082
	Sig. (2-tailed)	.837	.186	.554	.088	.720	.058	.913		.497	.180	.847
	N	8	8	8	8	8	8	8	8	8	8	8
$PO_{OBLA}·kg^{-1}$	Pearson	.288	-.586	-.728*	-.298	.644	.689	.907**	.283	1	-.664	.000
	Sig. (2-tailed)	.489	.127	.041	.473	.085	.059	.002	.497		.073	1.000
	N	8	8	8	8	8	8	8	8	8	8	8
Body mass	Pearson	-.333	.935**	.843**	.737*	-.716*	-.086	-.774*	.526	-.664	1	-.043
	Sig. (2-tailed)	.421	.001	.009	.037	.046	.840	.024	.180	.073		.920
	N	8	8	8	8	8	8	8	8	8	8	8
Speed	Pearson	.236	.069	.074	.120	.196	-.411	-.253	-.082	.000	-.043	1
	Sig. (2-tailed)	.574	.870	.862	.777	.641	.312	.545	.847	1.000	.920	
	N	8	8	8	8	8	8	8	8	8	8	8

*. Correlation is significant at the 0.05 level (2-tailed). **. Correlation is significant at the 0.01 level (2-tailed).
PPO = Peak power output; PO = Power output; LT = Lactate threshold; OBLA = Onset of blood lactate accumulation

DEUTSCHER KALIBRIERDIENST **DKD**

Kalibrierlaboratorium für die Messgröße Drehmoment
Calibration laboratory for the measuring value torque
Akkreditiert durch die / accredited by the
Akkreditierungsstelle des DKD bei der
PHYSIKALISCH-TECHNISCHEN BUNDESANSTALT (PTB)

Lorenz ® *messtechnik gmbh*

DKD-K-37801

Kalibrierschein
Calibration certificate

Kalibrierzeichen
Calibration mark
0029
DKD-K-37801
05-11

Gegenstand: *Object*	**Drehmomentaufnehmer 100 N·m**	
Hersteller: *Manufacturer*	**Lorenz Messtechnik GmbH D-73553 Alfdorf**	
Typ: *Type*	Aufnehmer:	**DR-2212**
	Ausgeber:	**Keithley 2000**
Fabrikate/Serien-Nr.: *Serial number*	Aufnehmer:	**68180**
	Ausgeber:	**0921942 E 0717**
Auftraggeber: *Customer*	**SG Sensortechnik GmbH & Co. KG Am Berg 32 D-64546 Mörfelden - Walldorf**	
Auftragsnummer: *Order No.*	**1070**	
Anzahl der Seiten des Kalibrierscheines: *Number of pages of the certificate*	**6**	

Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Der DKD ist Unterzeichner des multilateralen Übereinkommens der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

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The user is obliged to have the object recalibrated at appropriate intervals.

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Stempel *Seal*	Leiter des Kalibrierlaboratoriums *Head of the calibration laboratory*	Bearbeiter *Person responsible*
Deutscher Kalibrierdienst DKD-K-37801	Dr. W. Krimmel	A. Botscher
Postanschrift/Mail address	Telefon/Telephon extension	e-Mail
Lorenz Messtechnik GmbH Obere Schlosstraße 131 D-73553 Alfdorf	07172 / 93730-0	info@lorenz-messtechnik.de

Prüfzertifikat
Document of calibration

Kalibriersystem / *Testequipment*

Kalibriereinrichtung / *Calibration rig:*	Typ : 0430 Nr. 11634	
Kalibrierzeichen / *Calibration sign*:	0029_DKD-K-37801_05-11	
Messunsicherheit im verwendeten Messbereich / *Measuring incertainity of measuring range used:*		< 0,25 %
Kalibriertemperatur / *Calibration temperature*:		22 °C
Kalibrierverfahren / *Calibration process:*	mit Referenzaufnehmer / with reference transducer	

Kalibrierung ergomo Sensor / *calibration ergomo sensor*

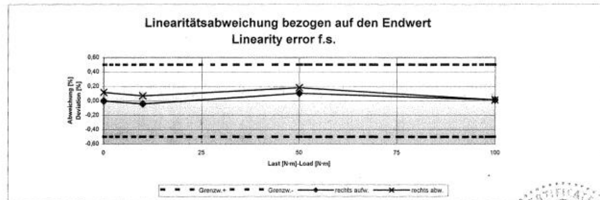
Messbereich / *Range* :	100 N·m
Genauigkeitsklasse / *Accuracy class:*	< 0,5 %

Ser. Nr. / *Ser. No* : S-3448
Lastrichtung / *Torque direction* : links(-) *counter clockwise(-)*

Beta Last Signal / *Nominal signal*	216,36 Digits
Beta Null Signal / *Beta zero signal* :	1172,44 Digits
Kalibrier Faktor / Calibration factor :	196

Vergleichsmessung / *comparison measurement*

Kalibriersystem / *Testequipment*	ergomo Sensor / *ergomo sensor*	Fehler v.E./ *error f.s.*
104,78 [Watt]	104,11 [Watt]	-0,06 [%]
523,37 [Watt]	524,63 [Watt]	0,12 [%]
1047,06 [Watt]	1046,62 [Watt]	-0,04 [%]
523,53 [Watt]	525,41 [Watt]	0,18 [%]
104,60 [Watt]	104,70 [Watt]	0,01 [%]



Prüfer / *Inspector* : Rene Ewald 5
14.06.2006 10:51:12

SG Sensortechnik GmbH & co. KG - Am Berg 32 - Germany - 64546 Mörfelden-Walldorf - Fon: +49 (0) 6105-27310 - www.ergomo.net

Figure I.1: Calibration certificates for the Ergmo®Pro power meter.

Calibration Sheet

BRITISH CYCLING

Calibration History	630	PM Serial Number	3548
Calibration Sheet #	620	Date	22-Apr-05

SRM Reported Slope	14.47	Temperature (C)	22
# of strain gauges	8	Weight Applied (kg)	43.8
Location	Velodrome	Weight ID	wt10-21
CalibratedBy	Tony Robinson	Radius (mm)	108.43
		Torque (Nm)	46.59

Raw Data

0° unloaded	0° loaded	90° unloaded	90° unloaded
317	995	317	1002
317	995	317	1002
317	995	317	1002
0° Slope	14.55	90° Slope	14.70

180° unloaded	180° loaded	270° unloaded	270° loaded
316	988	316	983
316	988	316	983
316	988	316	983
180° Slope	14.42	270° Slope	14.32

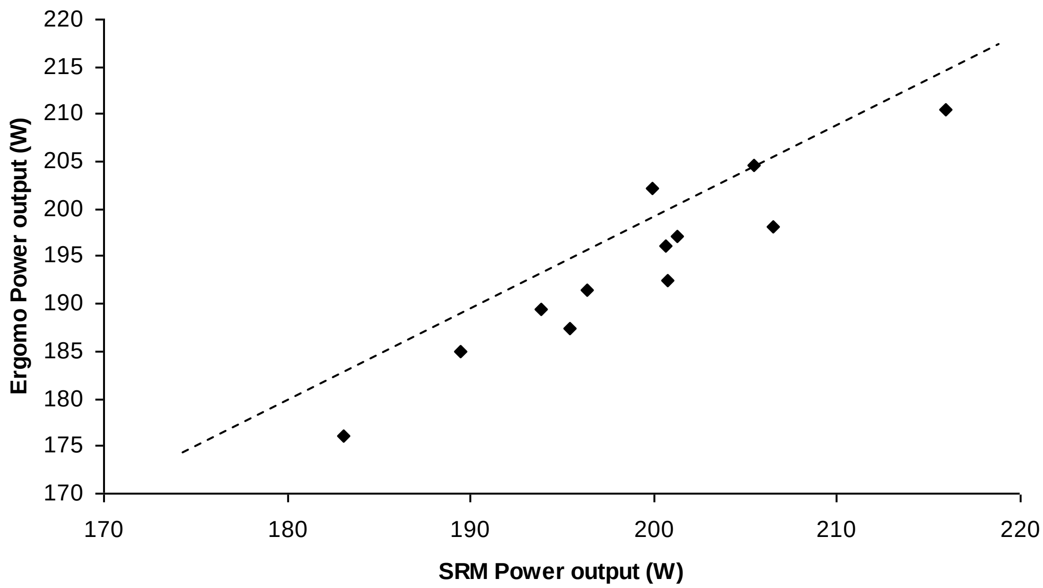
SlopeAverage	14.50	PercentChange	0.01

Calibration Engineer Signature:

Figure I.2: Calibration certificate for the SRM power meter.

Appendix J: Agreement study between power meters

A



B

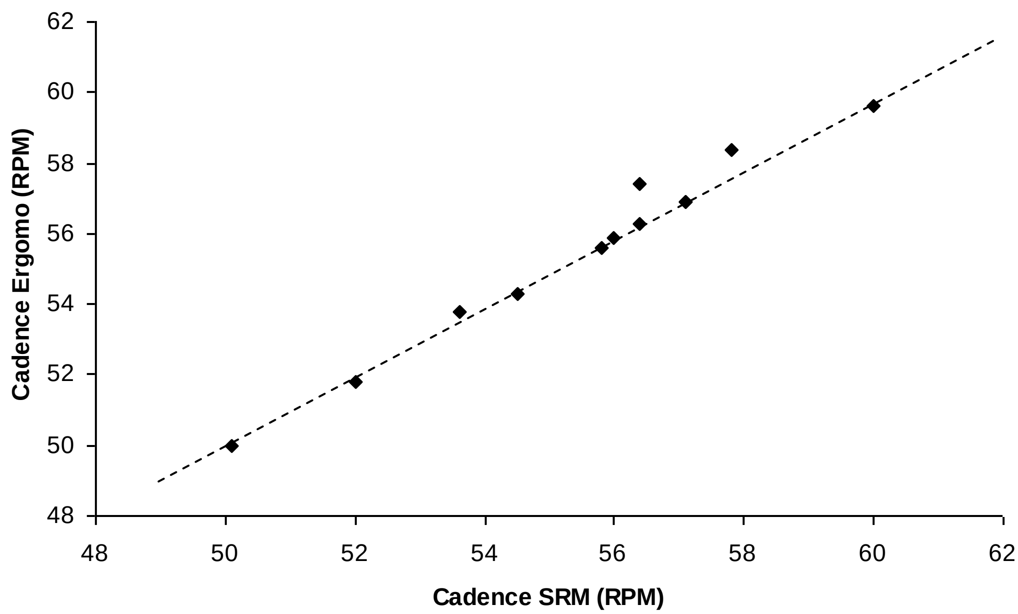


Figure J.1: Lines of equality for power output (A) and cadence (B) between the Ergomo®Pro and SRM power meters.

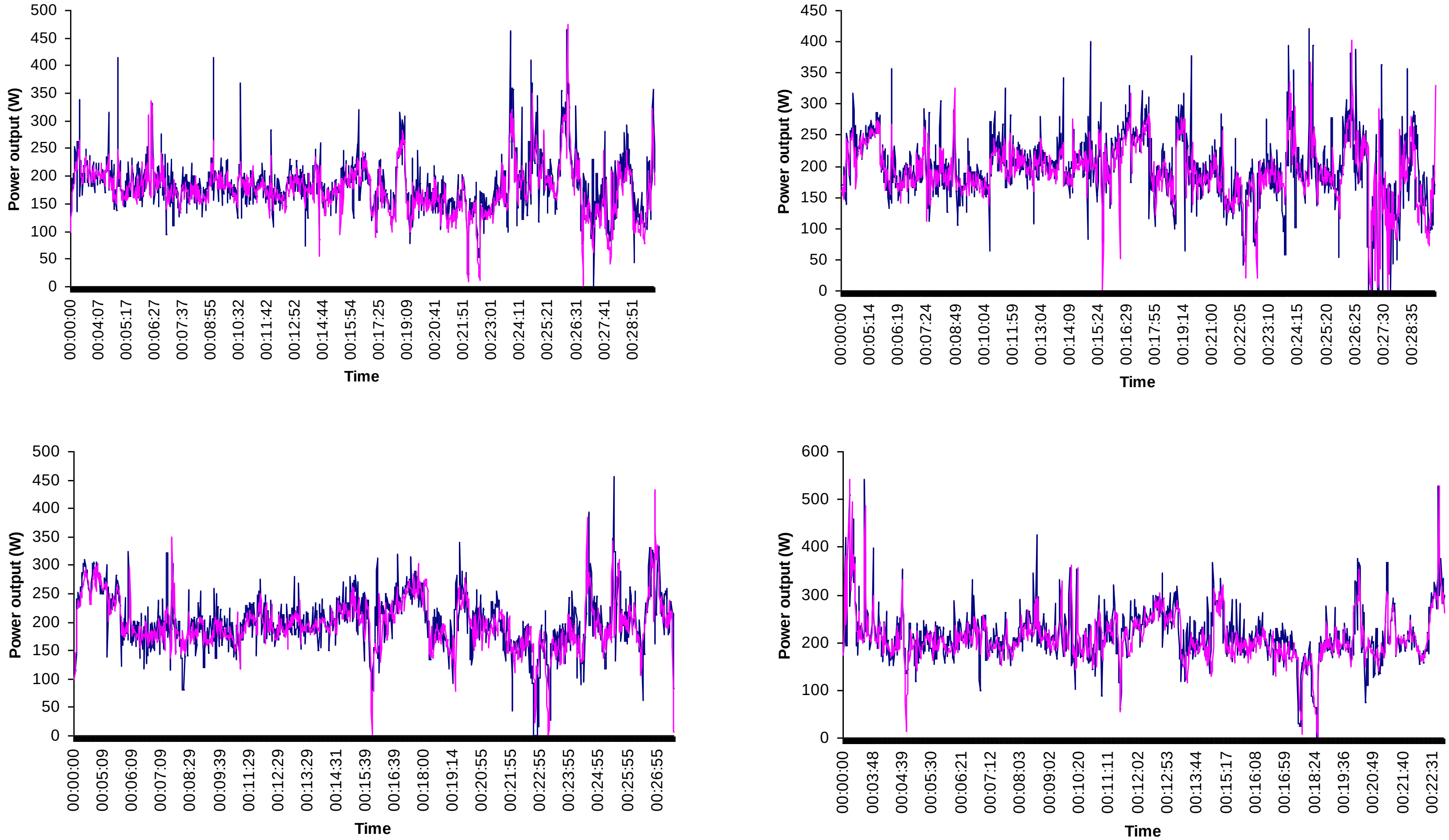


Figure J.2: Sample SRM (–) and Ergomo®Pro (–) power output data from four of the trials from Study Four.

Table K.1: General classification results for the 24XCT race (first 20 placed finishers).

24 h Open Male

Place	No.	laps	Team name	Lap 1	Lap 2	Lap 3	Lap 4	Lap 5	Lap 6	Lap 7	Lap 8	Lap 9	Lap 10
1	620	39	[redacted]	00:32:04	00:33:53	00:37:35	00:36:19	00:35:47	00:32:25	00:33:26	00:37:59	00:36:10	00:35:35
2	643	39	[redacted]	00:39:04	00:34:51	00:33:55	00:38:43	00:35:34	00:36:44	00:34:33	00:34:26	00:37:36	00:37:37
3	648	37	[redacted]	00:39:18	00:37:02	00:38:24	00:37:22	00:37:52	00:37:27	00:37:13	00:36:43	00:37:07	00:38:58
4	612	35	[redacted]	00:44:00	00:41:08	00:32:03	00:33:12	00:48:49	00:42:44	00:38:10	00:37:42	00:53:26	00:47:39
5	631	35	[redacted]	00:47:06	00:38:29	00:43:16	00:37:46	00:40:04	00:42:26	00:40:00	00:38:55	00:36:35	00:37:45
6	637	35	[redacted]	00:39:52	00:35:27	00:46:24	00:38:33	00:40:24	00:36:41	00:43:42	00:38:40	00:41:53	00:36:59
7	628	34	[redacted]	00:37:46	00:40:46	00:41:43	00:37:41	00:36:37	00:41:49	00:43:00	00:39:13	00:35:29	00:42:18
8	649	34	[redacted]	00:47:38	00:42:00	00:42:08	00:39:16	00:38:24	00:43:08	00:43:03	00:40:19	00:39:15	00:38:24
9	644	33	[redacted]	00:46:22	00:41:26	00:37:56	00:42:57	00:38:08	00:42:21	00:44:12	00:39:59	00:40:21	00:38:14
10	639	33	[redacted]	00:46:20	00:38:20	00:42:13	00:43:13	00:40:38	00:38:52	00:46:30	00:42:28	00:41:13	00:38:41
11	641	33	[redacted]	00:43:00	00:39:36	00:42:09	00:39:22	00:41:15	00:39:44	00:44:30	00:41:01	00:42:29	00:39:39
12	638	33	[redacted]	00:48:47	00:43:25	00:40:57	00:42:15	00:39:19	00:41:40	00:41:12	00:41:09	00:40:40	00:42:23
13	613	32	[redacted]	00:44:04	00:41:31	00:38:01	00:37:40	00:40:55	00:41:46	00:43:04	00:38:05	00:37:58	00:41:03
14	621	32	[redacted]	00:43:06	00:37:06	00:42:32	00:43:24	00:40:38	00:37:05	00:42:52	00:48:10	00:41:03	00:37:24
15	622	31	[redacted]	00:43:20	00:37:56	00:41:22	00:43:19	00:42:11	00:38:26	00:43:18	00:43:34	00:44:49	00:39:45
16	611	31	[redacted]	00:49:03	00:48:07	00:44:20	00:43:06	00:38:02	00:49:17	00:44:00	00:44:56	00:37:27	00:50:43
17	603	31	[redacted]	00:41:29	00:44:44	00:44:59	00:48:15	00:43:51	00:38:52	00:45:45	00:43:42	00:48:54	00:44:03
18	647	31	[redacted]	00:51:32	00:45:23	00:45:17	00:39:23	00:45:00	00:45:39	00:44:48	00:39:05	00:45:35	00:49:24
19	617	30	[redacted]	00:40:01	00:39:06	00:42:53	00:43:30	00:45:24	00:45:26	00:38:29	00:41:10	00:42:09	00:43:50
20	606	30	[redacted]	00:54:28	00:51:07	00:42:28	00:40:20	00:40:06	00:45:33	00:50:49	00:43:26	00:40:44	00:39:38

Table K.1 continued

Place	No.	laps	Team name	Lap 11	Lap 12	Lap 13	Lap 14	Lap 15	Lap 16	Lap 17	Lap 18	Lap 19	Lap 20
1	620	39	[redacted]	00:31:46	00:33:09	00:37:30	00:35:49	00:35:54	00:35:13	00:48:05	00:33:22	00:32:19	00:40:05
2	643	39	[redacted]	00:34:05	00:35:57	00:38:09	00:33:58	00:33:41	00:38:42	00:40:17	00:38:24	00:40:10	00:36:07
3	648	37	[redacted]	00:37:53	00:38:15	00:34:41	00:37:48	00:37:56	00:45:06	00:40:37	00:37:57	00:41:43	00:41:37
4	612	35	[redacted]	00:31:50	00:32:22	00:43:17	00:43:59	00:40:34	00:40:24	00:44:37	00:47:32	00:37:51	00:44:47
5	631	35	[redacted]	00:43:00	00:40:05	00:40:12	00:37:31	00:40:17	00:48:10	00:49:48	00:45:13	00:49:26	00:50:23
6	637	35	[redacted]	00:38:35	00:44:30	00:40:09	00:40:46	00:39:03	00:48:21	00:42:52	00:38:28	00:49:02	00:54:49
7	628	34	[redacted]	00:42:16	00:40:35	00:36:41	00:43:23	00:43:40	00:41:19	00:57:30	00:48:28	00:45:18	00:43:44
8	649	34	[redacted]	00:41:48	00:43:16	00:50:22	00:41:34	00:40:17	00:52:31	00:43:55	00:45:19	00:53:25	00:31:05
9	644	33	[redacted]	00:40:26	00:44:29	00:45:49	00:39:16	00:40:19	00:47:38	00:47:36	00:43:26	01:04:06	00:24:46
10	639	33	[redacted]	00:45:59	00:43:35	00:43:20	00:41:47	00:51:08	00:48:24	00:49:22	00:50:44	00:44:52	00:48:32
11	641	33	[redacted]	00:43:25	00:40:28	00:43:18	00:51:49	00:43:45	00:52:48	00:51:05	00:49:15	00:48:07	00:45:23
12	638	33	[redacted]	00:39:13	00:41:47	00:43:06	00:47:52	00:42:44	00:50:42	00:51:16	00:49:07	00:51:01	00:47:59
13	613	32	[redacted]	01:24:47	00:38:41	00:39:39	00:41:54	00:44:06	00:55:43	00:50:14	01:05:47	00:28:55	00:48:24
14	621	32	[redacted]	00:42:53	00:59:16	00:45:39	00:40:09	00:48:44	00:48:36	00:48:34	01:17:07	00:27:45	00:51:02
15	622	31	[redacted]	00:43:05	00:43:34	00:42:56	01:00:45	00:42:38	00:45:01	00:49:15	00:49:58	00:51:10	00:46:59
16	611	31	[redacted]	00:44:49	00:43:51	00:41:34	00:52:46	00:46:28	00:47:07	00:42:51	00:58:22	00:44:45	00:47:44
17	603	31	[redacted]	00:39:48	00:47:30	00:46:16	00:54:00	00:47:36	00:44:37	00:56:46	00:49:39	00:55:39	00:54:35
18	647	31	[redacted]	00:45:19	00:40:37	00:46:55	00:48:14	00:52:01	01:03:08	00:50:36	00:50:43	00:53:15	00:48:11
19	617	30	[redacted]	00:48:01	00:53:11	00:40:17	00:42:42	00:45:15	00:48:49	00:56:11	01:09:26	00:29:01	00:44:35
20	606	30	[redacted]	01:28:59	00:54:16	00:58:13	00:49:42	00:47:14	00:51:58	00:48:38	00:42:50	00:44:20	00:53:28

Table K.1 continued

Place	No.	laps	Team name	Lap 21	Lap 22	Lap 23	Lap 24	Lap 25	Lap 26	Lap 27	Lap 28	Lap 29	Lap 30
1	620	39	[redacted]	00:43:13	00:39:00	00:43:56	00:38:33	00:41:41	00:39:43	00:40:50	00:36:50	00:36:10	00:39:25
2	643	39	[redacted]	00:36:34	00:56:39	00:30:07	00:40:38	00:43:35	00:36:58	00:37:37	00:41:55	00:42:26	00:40:53
3	648	37	[redacted]	00:54:38	00:26:51	00:49:56	00:41:56	00:42:34	00:43:17	00:41:22	00:39:37	00:40:06	00:40:24
4	612	35	[redacted]	00:43:20	00:50:46	00:49:09	00:47:06	00:43:19	00:47:50	00:33:39	00:34:12	00:51:25	00:50:48
5	631	35	[redacted]	00:42:42	00:39:46	00:40:05	00:44:38	00:42:23	00:46:24	00:48:41	00:41:07	00:37:20	00:40:16
6	637	35	[redacted]	00:43:44	00:43:17	00:42:21	00:41:36	00:49:42	00:39:16	00:48:42	00:43:21	00:45:37	00:39:17
7	628	34	[redacted]	00:39:19	00:47:53	00:44:47	00:38:53	00:47:22	00:47:06	00:37:13	00:43:03	00:53:31	00:41:30
8	649	34	[redacted]	00:55:06	00:44:57	00:46:16	00:43:09	00:40:02	00:49:00	00:43:53	00:44:18	00:40:14	00:39:45
9	644	33	[redacted]	00:46:32	00:58:40	01:07:11	00:39:39	00:40:03	00:45:40	00:44:43	00:43:35	00:43:21	00:48:17
10	639	33	[redacted]	00:48:18	00:45:07	00:48:28	00:46:48	00:45:28	00:40:42	00:49:16	00:46:16	00:41:51	00:40:04
11	641	33	[redacted]	00:47:07	00:52:11	00:46:49	00:46:55	00:45:50	00:48:23	00:43:16	00:43:57	00:41:42	00:41:18
12	638	33	[redacted]	00:43:12	00:43:30	00:50:12	00:45:54	00:45:59	00:47:20	00:49:00	00:46:23	00:47:45	00:40:46
13	613	32	[redacted]	00:44:42	00:45:40	00:43:23	00:44:38	01:07:51	00:41:09	00:42:01	00:42:24	00:43:48	00:43:37
14	621	32	[redacted]	00:52:13	00:52:27	00:53:42	00:55:06	00:42:42	00:38:06	00:47:37	00:47:28	00:43:24	00:38:55
15	622	31	[redacted]	01:06:49	00:54:55	00:43:46	00:43:22	00:47:40	00:47:26	00:48:57	00:49:57	00:41:15	00:47:09
16	611	31	[redacted]	00:42:26	00:52:04	00:54:34	00:49:04	00:50:49	00:41:37	00:44:39	00:47:58	00:48:22	00:43:29
17	603	31	[redacted]	00:47:55	00:50:18	00:51:52	00:54:46	00:48:31	00:40:36	00:44:49	00:48:05	00:51:22	00:46:18
18	647	31	[redacted]	00:47:05	00:44:03	00:53:42	00:57:21	00:48:59	00:45:41	00:49:58	00:42:15	00:51:29	00:44:49
19	617	30	[redacted]	00:51:39	00:53:34	00:59:46	01:06:53	00:44:06	00:46:02	00:55:04	00:55:43	00:45:33	00:44:26
20	606	30	[redacted]	00:54:39	00:43:56	00:50:23	00:45:17	00:44:47	00:51:14	00:47:32	00:43:36	00:42:00	00:47:46

Table K.1 continued

Place	No.	laps	Team name	Lap 31	Lap 32	Lap 33	Lap 34	Lap 35	Lap 36	Lap 37	Lap 38	Lap 39
1	620	39	[redacted]	00:38:08	00:48:48	00:33:42	00:42:27	00:36:56	00:35:41	00:33:30	00:34:01	00:35:50
2	643	39	[redacted]	00:41:33	00:36:11	00:36:59	00:36:34	00:35:36	00:35:40	00:40:49	00:34:14	00:55:07
3	648	37	[redacted]	00:42:35	00:38:33	00:39:35	00:38:18	00:41:41	00:36:34	00:40:46		
4	612	35	[redacted]	00:37:45	00:38:32	00:41:00	00:32:05	00:33:51				
5	631	35	[redacted]	00:43:01	00:42:25	00:37:04	00:36:03	00:38:05				
6	637	35	[redacted]	00:40:32	00:45:38	00:36:25	00:43:32	00:55:06				
7	628	34	[redacted]	00:44:16	00:47:47	00:36:58	00:39:24					
8	649	34	[redacted]	00:42:31	00:44:24	00:40:16	00:38:40					
9	644	33	[redacted]	00:50:01	00:38:47	00:39:04						
10	639	33	[redacted]	00:46:41	00:44:15	01:02:54						
11	641	33	[redacted]	00:43:44	00:41:33	01:07:29						
12	638	33	[redacted]	00:41:14	00:42:24	01:02:48						
13	613	32	[redacted]	00:42:52	00:43:02							
14	621	32	[redacted]	00:40:42	00:38:39							
15	622	31	[redacted]	00:42:43								
16	611	31	[redacted]	00:48:35								
17	603	31	[redacted]	01:07:16								
18	647	31	[redacted]	00:57:55								
19	617	30	[redacted]									
20	606	30	[redacted]									

= team recruited for studies five and six.

Appendix L: Data for fifth work-shifts

Table L.1: Fifth work-shift* data for participant 1.

Speed (km·h^{-1})	18.4
Power (W)	274
HR (beats·min^{-1})	170
Cadence (RPM)	74
Efficiency (%)	15.8

*this work-shift comprised only one lap (duration = 41 min)

Table L.2: Fifth work-shift data for participant 2.**

Speed (km·h^{-1})	22.9
Power (W)	210
HR (beats·min^{-1})	150
Cadence (RPM)	71
Efficiency (%)	21.3

**this work-shift comprised two laps (duration = 66 min 06 sec)

Appendix M: Correlation matrix for measured variables during the 24XCT race

Table M.1: Correlation matrix for measured variables during the 24XCT race

		Speed	HR	rpm	Power	Fluid	CHO	EC	TEE	Urine	Sweat rate	RPE pre	RPE post	Osmo pre	Osmo post	Glu pre	Glu post	Lac pre	Lac post	BM pre	BM post	Light	Temp	Core pre	Core post	Cort. pre	Cort. post	Eff.
Speed	Pearson	1	.448	.818**	.656*	.366	.351	.411	-.713	.398	-.148	-.539	-.320	-.163	-.137	-.075	.284	-.526	-.027	-.616*	-.642*	-.076	.272	.287	-.042	.330	-.288	.642**
	Sig.		.082	.000	.006	.163	.182	.114	.002	.127	.584	.031	.907	.545	.613	.784	.286	.036	.921	.011	.007	.780	.309	.281	.943	.211	.335	.007
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
HR	Pearson	.448	1	.479	.406	.494	.099	.171	.103	.287	.296	-.180	-.422	-.045	-.091	.544*	.330	-.069	.229	.163	.017	.377	.820**	.719**	.422	-.278	.529*	-.004
	Sig.	.082		.060	.119	.052	.715	.527	.704	.282	.265	.506	.104	.869	.739	.029	.212	.800	.394	.545	.950	.151	.000	.002	.103	.296	.035	.989
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
rpm	Pearson	.818**	.479	1	.486	.367	.302	.206	-.352	.141	-.313	-.130	.000	-.259	-.179	-.051	.138	-.312	-.003	-.343	-.255	-.038	.273	.458	.193	.132	.258	.376
	Sig.	.000	.060		.056	.162	.255	.445	.182	.603	.238	.633	1.000	.332	.508	.851	.610	.240	.992	.194	.341	.890	.307	.074	.473	.626	.334	.151
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Power	Pearson	.656*	.406	.486	1	.237	-.003	-.022	-.579*	.448	.257	-.628**	-.411	-.200	-.312	.202	.385	-.298	.001	-.636**	-.660**	.206	.259	.368	.117	.192	.033	.832**
	Sig.	.006	.119	.056		.377	.992	.936	.019	.082	.337	.009	.114	.457	.239	.453	.141	.262	.997	.008	.005	.443	.333	.160	.667	.475	.905	.000
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Fluid	Pearson	.366	.494	.367	.237	1	.594*	.656**	-.128	-.240	.407	-.214	-.339	.146	.344	.017	.045	-.079	-.017	-.082	-.105	.462	.662**	.435	.188	-.060	.376	.082
	Sig.	.163	.052	.162	.377		.015	.006	.638	.370	.117	.427	.200	.590	.192	.949	.869	.772	.950	.762	.699	.071	.005	.092	.486	.826	.151	.763
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
CHO	Pearson	.351	.099	.302	-.003	.594*	1	.698**	-.282	-.229	-.040	-.315	.084	-.013	.069	-.243	.193	-.260	-.365	-.379	-.319	.049	.259	.062	-.284	-.232	.416	.147
	Sig.	.182	.715	.255	.992	.015		.003	.289	.393	.883	.234	.756	.961	.800	.364	.474	.330	.165	.148	.229	.856	.333	.820	.287	.388	.109	.587
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
EC	Pearson	.411	.171	.206	-.022	.656**	.698**	1	-.404	-.081	.161	-.415	-.084	.236	.335	-.177	-.086	-.448	-.262	-.225	-.267	.151	.394	-.021	-.409	-.053	.279	.138
	Sig.	.114	.527	.445	.936	.006	.003		.120	.764	.551	.110	.758	.379	.205	.512	.751	.082	.328	.401	.318	.577	.131	.938	.116	.847	.295	.611
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
TEE	Pearson	-.713	.103	-.352	-.579*	-.128	-.282	-.404	1	-.272	.059	.755**	-.133	-.043	-.080	.376	-.333	.612*	.330	.888**	.916**	.109	.118	-.002	.405	-.238	.041	-.892**
	Sig.	.002	.704	.182	.019	.638	.289	.120		.307	.829	.001	.623	.875	.769	.152	.208	.012	.212	.000	.000	.688	.663	.995	.119	.376	.880	.000
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Urine	Pearson	.398	.287	.141	.448	-.240	-.229	-.081	-.272	1	-.231	-.327	-.117	-.213	-.602*	.218	.255	-.172	.366	-.247	-.340	-.087	.065	-.044	-.134	-.007	.234	.338
	Sig.	.127	.282	.603	.082	.370	.393	.764	.307		.390	.217	.666	.428	.014	.418	.340	.525	.163	.357	.197	.750	.812	.872	.622	.981	.382	.201
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Sweat rate	Pearson	-.148	.296	-.313	.257	.407	-.040	.161	.059	-.231	1	-.395	-.402	.126	.265	.561*	.097	-.075	-.224	.103	-.043	.415	.553*	.205	.165	-.103	-.140	.072
	Sig.	.584	.265	.238	.337	.117	.883	.551	.829	.390		.130	.123	.643	.321	.024	.721	.784	.405	.704	.876	.110	.026	.446	.542	.705	.604	.791
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
RPE pre	Spearman	-.539	-.180	-.130	-.628**	-.214	-.315	-.415	.755**	-.327	-.395	1	.070	-.082	.070	-.019	-.441	.655**	.311	.711**	.816**	-.210	-.282	-.151	.333	-.068	-.014	-.785**
	Sig.	.031	.506	.633	.009	.427	.234	.110	.001	.217	.130		.795	.763	.797	.945	.087	.006	.241	.002	.000	.435	.290	.577	.208	.802	.958	.000
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16

Table M.1 continued

		Speed	HR	rpm	Power	Fluid	CHO	EC	TEE	Urine	Sweat rate	RPE pre	RPE post	Osmo pre	Osmo post	Glu pre	Glu post	Lac pre	Lac post	BM pre	BM post	Light	Temp	Core pre	Core post	Cort. pre	Cort. post	Eff.
RPE post	Spearman	-.320	-.422	.000	-.411	-.339	.084	-.084	-.133	-.117	-.402	.070	1	-.266	-.072	-.285	-.099	.042	-.141	-.116	-.056	-.122	-.373	-.370	-.280	.171	-.014	-.059
	Sig.	.907	.104	1.000	.114	.200	.756	.758	.623	.666	.123	.795		.319	.792	.285	.714	.878	.602	.670	.836	.651	.155	.158	.294	.527	.958	.829
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Osmo pre	Pearson	-.163	-.045	-.259	-.200	.146	-.013	.236	-.043	-.213	.126	-.082	-.266	1	.502*	-.424	.025	-.250	.279	.135	.072	.129	.060	.128	.092	-.075	.027	-.133
	Sig.	.545	.869	.332	.457	.590	.961	.379	.875	.428	.643	.763	.319		.047	.102	.926	.351	.295	.619	.790	.635	.825	.637	.734	.783	.921	.624
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Osmo post	Pearson	-.137	-.091	-.179	-.312	.344	.069	.335	-.080	-.602*	.265	.070	-.072	.502*	1	-.318	.045	-.135	-.295	.111	-.005	-.202	-.039	.198	-.018	-.092	-.239	-.131
	Sig.	.613	.739	.508	.239	.192	.800	.205	.769	.014	.321	.797	.792	.047		.230	.870	.617	.267	.682	.986	.453	.885	.462	.948	.735	.373	.628
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Glu. pre	Pearson	-.075	.544*	-.051	.202	.017	-.243	-.177	.376	.218	.561*	-.019	-.285	-.424	-.318	1	.122	.126	-.096	.354	.229	.173	.538*	.156	.248	-.353	.102	-.192
	Sig.	.784	.029	.851	.453	.949	.364	.512	.152	.418	.024	.945	.285	.102	.230		.652	.643	.723	.179	.393	.521	.032	.564	.354	.180	.706	.476
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Glu. post	Pearson	.284	.330	.138	.385	.045	.193	-.086	-.333	.255	.097	-.441	-.099	.025	.045	.122	1	-.218	-.283	-.475	-.586*	-.242	.148	.403	.030	-.623*	.056	.384
	Sig.	.286	.212	.610	.141	.869	.474	.751	.208	.340	.721	.087	.714	.926	.870	.652		.418	.288	.063	.017	.367	.584	.122	.913	.010	.835	.142
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Lac. pre	Pearson	-.526	-.069	-.312	-.298	-.079	-.260	-.448	.612*	-.172	-.075	.655**	.042	-.250	-.135	.126	-.218	1	.391	.414	.524*	.112	-.071	-.183	.272	-.075	.028	-.495
	Sig.	.036	.800	.240	.262	.772	.330	.082	.012	.525	.784	.006	.878	.351	.617	.643	.418		.134	.111	.037	.681	.794	.497	.308	.783	.919	.051
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Lac. post	Pearson	-.027	.229	-.003	.001	-.017	-.365	-.262	.330	.366	-.224	.311	-.141	.279	-.295	-.096	-.283	.391	1	.356	.376	.530	.107	.011	.420	.303	.271	-.258
	Sig.	.921	.394	.992	.997	.950	.165	.328	.212	.163	.405	.241	.602	.295	.267	.723	.288	.134		.176	.152	.035	.693	.967	.105	.254	.311	.334
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
BM pre	Pearson	-.616*	.163	-.343	-.636**	-.082	-.379	-.225	.888**	-.247	.103	.711**	-.116	.135	.111	.354	-.475	.414	.356	1	.941**	.182	.210	.062	.432	-.108	.143	-.915**
	Sig.	.011	.545	.194	.008	.762	.148	.401	.000	.357	.704	.002	.670	.619	.682	.179	.063	.111	.176		.000	.561	.434	.821	.095	.689	.597	.000
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
BM post	Pearson	-.642*	.017	-.255	-.660**	-.105	-.319	-.267	.916**	-.340	-.043	.816**	-.056	.072	-.005	.229	-.586*	.524*	.376	.941**	1	.161	.108	-.054	.419	-.036	.064	-.918**
	Sig.	.007	.950	.341	.005	.699	.229	.318	.000	.197	.876	.000	.836	.790	.986	.393	.017	.037	.152	.000		.551	.689	.843	.106	.893	.814	.000
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Amb. Light	Pearson	-.076	.377	-.038	.206	.462	.049	.151	.109	-.087	.415	-.210	-.122	.129	-.202	.173	-.242	.112	.530	.182	.161	1	.658*	.190	.512*	.410	.302	-.024
	Sig.	.780	.151	.890	.443	.071	.856	.577	.688	.750	.110	.435	.651	.635	.435	.521	.367	.681	.035	.561	.551		.006	.678	.043	.114	.256	.929
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Amb. Temp	Pearson	.272	.820**	.273	.259	.662**	.259	.394	.118	.065	.553*	-.282	-.373	.060	-.039	.538*	.148	-.071	.107	.210	.108	.658*	1	.563*	.434	-.210	.482	-.086
	Sig.	.309	.000	.307	.333	.005	.333	.131	.663	.812	.026	.290	.155	.825	.885	.032	.584	.794	.693	.434	.689	.006		.023	.093	.435	.059	.751
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Core. pre	Pearson	.287	.719**	.458	.368	.435	.062	-.021	-.002	-.044	.205	-.151	-.370	.128	.198	.156	.403	-.183	.011	.062	-.054	.190	.563*	1	.535*	-.164	.387	.106
	Sig.	.281	.002	.074	.160	.092	.820	.938	.995	.872	.446	.577	.158	.637	.462	.564	.122	.497	.967	.821	.843	.481	.023		.033	.545	.139	.697
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16

Table M.1 continued

		Speed	HR	rpm	Power	Fluid	CHO	EC	TEE	Urine	Sweat rate	RPE pre	RPE post	Osmo pre	Osmo post	Glu pre	Glu post	Lac pre	Lac post	BM pre	BM post	Light	Temp	Core pre	Core post	Cort. pre	Cort. post	Eff.
Core post	Pearson	-.042	.422	.193	.117	.188	-.284	-.409	.405	-.134	.165	.333	-.280	.092	-.018	.248	.030	.272	.420	.432	.419	.510*	.434	.535*	1	.106	.157	-.262
	Sig.	.877	.103	.473	.667	.486	.287	.116	.119	.622	.542	.208	.294	.734	.948	.354	.913	.308	.105	.095	.106	.043	.093	.033		.697	.561	.326
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Cort. pre	Pearson	.330	-.278	.132	.192	-.060	-.232	-.053	-.238	-.007	-.103	-.068	.171	-.075	-.092	-.353	-.623*	-.075	.303	-.108	-.036	.410	-.210	-.164	.106	1	-.203	.304
	Sig.	.211	.296	.626	.475	.826	.388	.847	.376	.981	.705	.802	.527	.783	.735	.180	.010	.783	.254	.689	.893	.114	.435	.545	.697		.451	.253
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Cort. post	Pearson	-.288	.529*	.258	.033	.376	.416	.279	.041	.234	-.140	-.014	-.014	.027	-.239	.102	.056	.028	.271	.143	.064	.302	.482	.387	.157	-.203	1	-.151
	Sig.	.335	.035	.334	.905	.151	.109	.295	.880	.382	.604	.958	.958	.921	.373	.706	.835	.919	.311	.597	.814	.256	.059	.139	.561	.451		.576
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Eff.	Pearson	.642*	-.004	.376	.832**	.082	.147	.138	-.892**	.338	.072	-.785**	-.059	-.133	-.131	-.192	.384	-.495	-.258	-.915**	-.918**	-.024	-.086	.106	-.262	.304	-.151	1
	Sig.	.007	.989	.151	.000	.763	.587	.611	.000	.201	.791	.000	.829	.624	.628	.476	.142	.051	.334	.000	.000	.929	.751	.697	.326	.253	.576	
	N	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16

EC = energy consumed; TEE = Total energy expended; Osmo = osmolarity; Gluc. = glucose Lact = lactate Amb = ambient; Core = core temperature; Cort = cortisol; Eff = efficiency

Table N.1: Performance, physiological data and summary statistics for 4 competitors in a 24 h team race.

	Work-shift 1	Work-shift 2	Work-shift 3	Work-shift 4	Main effect for work-shift
Speed ($km \cdot h^{-1}$)	19.4 ± 2.9	18.7 ± 3.6	16.7 ± 1.2	18.4 ± 3.3	$F_{(3,9)} = 2.34$; $p = 0.14$; $\eta^2 = 0.44$
Power output (W)	242.0 ± 58.5	226.5 ± 55.7	192.5 ± 32.6	216.8 ± 57.0	$F_{(3,9)} = 3.34$; $p = 0.07$; $\eta^2 = 0.53$
Power ($W \cdot kg^{-1}$)	3.0 ± 0.8	2.9 ± 0.8	2.4 ± 0.5	2.7 ± 0.8	$F_{(3,9)} = 3.29$; $p = 0.07$; $\eta^2 = 0.52$
Cadence (rpm)	68.0 ± 8.5	63.0 ± 10.4	61.0 ± 8.7	64.5 ± 10.0	$F_{(3,9)} = 1.21$; $p = 0.39$; $\eta^2 = 0.27$
Heart rate ($Beats \cdot min^{-1}$)	167 ± 4	164 ± 5	150 ± 7	149 ± 10	$F_{(3,9)} = 6.83$; $p = 0.01$; $\eta^2 = 0.70$
Percent HR_{max} (%)	90 ± 6	89 ± 3	81 ± 1	80 ± 6	$F_{(3,9)} = 5.96$; $p = 0.02$; $\eta^2 = 0.67$
Gross efficiency (%)	17.6 ± 4.9	17.1 ± 5.4	16.8 ± 5.1	18.6 ± 5.2	$F_{(3,9)} = 3.51$; $p = 0.06$; $\eta^2 = 0.54$

A one-way ANOVA was used to assess: race speed; power output; cadence; exercise intensity and gross efficiency. **Heart rate:** Least Significant Difference (LSD) post-hoc test reported significant differences for mean heart rate between work-shifts one and three ($p = 0.05$), one and four ($p = 0.05$), and two and three ($p = 0.03$). **Exercise intensity:** Least Significant Difference (LSD) post-hoc test reported significant differences for mean heart rate between work-shifts one and three ($p = 0.05$), one and four ($p = 0.05$), and two and three ($p = 0.03$).

Table N.2: Pre and post-shift mean data and summary statistics for 4 competitors in a 24 h team race.

	Work-shift 1 Pre	Work-shift 1 Post	Work-shift 2 Pre	Work-shift 2 Post	Work-shift 3 Pre	Work-shift 3 Post	Work-shift 4 Pre	Work-shift 4 Post	Main effect Pre and Post	Main effect for work-shift	Interaction effect
Blood lactate ($mmol·L^{-1}$)	1.67 ± 0.4	3.35 ± 0.7	1.7 ± 0.5	3.0 ± 1.0	1.75 ± 0.8	2.02 ± 0.6	1.8 ± 0.7	3.78 ± 0.9	$F_{(1,3)}$ = 146.7; p = 0.00; η^2 = 0.98	$F_{(3,9)}$ = 1.80; p = 0.22; η^2 = 0.37	$F_{(3,9)}$ = 3.94; p = 0.05; η^2 = 0.57
Cortisol ($nmol·L-^{1}$)	4.9 ± 1.1	13.2 ± 2.0	2.0 ± 0.3	16.5 ± 3.8	1.9 ± 0.8	9.3 ± 4.9	9.3 ± 3.4	10.0 ± 1.1	$F_{(1,3)}$ = 61.64; p = 0.00; η^2 = 0.95	$F_{(3,9)}$ =2.97; p = 0.09; η^2 = 0.50	$F_{(3,9)}$ =10.22; p = 0.00; η^2 = 0.77
Intra- aural temperature (°C)	36.4 ± 0.28	36.3 ± 0.26	36.1 ± 0.42	35.8 ± 0.58	36 ± 0.29	35.9 ± 0.46	35.8 ± 0.59	36 ± 0.69	$F_{(1,3)}$ = 0.09; p = 0.78; η^2 = 0.03	$F_{(3,9)}$ = 1.73; p = 0.23; η^2 = 0.37	$F_{(3,9)}$ = 1.047; p = 0.42; η^2 = 0.26

Two-way repeated measures ANOVA were used to assess: blood lactate; and salivary cortisol. Paired t-tests were used for post-hoc analysis of blood lactate and cortisol. **Blood lactate:** The Bonferroni adjusted ($p \leq 0.013$) post-hoc analysis reported differences between pre and post blood lactate concentrations for shifts one ($t_{(3)}$ = -6.16, p = 0.01, d = -1.58) and four ($t_{(3)}$ = -10.55, p = 0.00, d = -1.52). **Cortisol:** Significant differences were observed for work-shift 1 ($t_{(3)}$ = -12.31, p = 0.00, d = -5.19), work-shift 2 ($t_{(3)}$ = -7.83, p = 0.00, d = -5.4), and work-shift 3 ($t_{(3)}$ = -3.23, p = 0.05, d = -2.09). However, following a Bonferroni adjustment in order to avoid a family-wise error ($p \leq 0.013$), there was only significant differences for work-shifts 1 and 2.

Table O.1: Summary statistics for measured variables by bucket* for 4 participants in a 24XCT race

	Bucket 1 EC	**Bucket 1 TEE**	**Bucket 2 EC**	**Bucket 2 TEE**	**Bucket 3 EC**	**Bucket 3 TEE**	**Bucket 4 EC**	**Bucket 4 TEE**	**Main effect EC and TEE**	**Main effect for work-shift**	**Interaction effect**
Energy dynamics (kJ) (includes recovery period)	5036.2 ± 1200	7557.7 ± 1167	4390.1 ± 310	7846.5 ± 1664	3986.4 ± 477	7566.7 ± 1174	3921.9 ± 1065	7398.4 ± 1459	$F_{(1,3)}$ = 11.79; *p* = 0.04; η^2 = 0.80	$F_{(3,9)}$ = 3.427; *p* = 0.07; η^2 = 0.53	$F_{(3,9)}$ = 0.73, *p* = 0.56, η^2 = 0.20
	Pre	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Main effect pre & post**	**Main effect for work-shift**	**Interaction effect**
Blood glucose (mmol·L^{-1})	6.2 ± 0.9	6.5 ± 1.0	6.6 ± 1.0	7.2 ± 1.0	5.7 ± 1.2	7.4 ± 0.8	4.5 ± 1.4	5.5 ± 0.4	$F_{(1,3)}$ = 2.09; *p* = 0.24; η^2 = 0.41	$F_{(3,9)}$ = 5.87; *p* = 0.02; η^2 = 0.67	$F_{(3,9)}$ = 0.68, *p* = 0.59, η^2 = 0.18
Urine osmolality (mOsmol·kg^{-1}$H_2$0)	675 ± 161	675 ± 257	525 ± 274	407.5 ± 293	537.5 ± 285	677.5 ± 80	595 ± 360	556.7 ± 280	$F_{(1,3)}$ = 0.03; *p* = 0.88; η^2 = 0.01	$F_{(3,9)}$ = 0.91; *p* = 0.47; η^2 = 0.23	$F_{(3,9)}$ = 0.56; *p* = 0.65; η^2 = 0.16
Body mass (kg)	81.6 ± 4.7	80.2 ± 4.9	80.9 ± 4.8	79.1 ± 3.8	80.1 ± 4.9	79.5 ± 4.1	80.2 ± 3.5	80 ± 4	$F_{(1,3)}$ = 4.80; *p* = 0.12; η^2 = 0.62	$F_{(3,9)}$ = 1.66; *p* = 0.24; η^2= 0.36	$F_{(3,9)}$ = 1.41; *p* = 0.30; η^2 = 0.32
Intra- aural temperature (°C)	36.4 ± 0.28	36.3 ± 0.26	36.1 ± 0.42	35.8 ± 0.58	36 ± 0.29	35.9 ± 0.46	35.8 ± 0.59	36 ± 0.69	$F_{(1,3)}$ = 0.092; *p* = 0.78; η^2 = 0.30	$F_{(3,9)}$ = 1.734; *p* = 0.23; η^2 = 0.36	$F_{(3,9)}$ = 1.05; *p* = 0.42; η^2 = 0.26

***Bucket** = workshift and recovery period; **EC** = Energy consumption; **TEE** = Total energy expended.
Energy dynamics: Post hoc analysis reported significant differences for each shift ($t_{(3)}$ = -2.339, *p* = 0.05, *d* = 1.98; $t_{(3)}$ = -3.222, *p* = 0.02, *d* = 2.5; $t_{(3)}$ = -3.559, *p* = 0.01, *d* = -3.64; and $t_{(3)}$ = -2.801 *p* = 0.03, *d* = 2.5 for buckets 1 to 4 respectively). However, following a Bonferroni adjustment in order to avoid a family-wise error ($p \leq 0.012$), there was only a significant difference for shift 3.

Table O.2: Summary statistics for carbohydrate intake, fluid intake and sweat rate by bucket for 4 participants in a 24XCT race

	Bucket 1	Bucket 2	Bucket 3	Bucket 4	Main effect for bucket
CHO intake (g)	191 ± 93	207.2 ± 53	172.4 ± 64	148.7 ± 47	$F_{(3,9)} = 0.87$; $p = 0.49$; $\eta^2 = 0.23$
Fluid intake (L)	2.42 ± 0.64	1.51 ± 0.16	1.11 ± 0.37	1.23 ± 0.29	$F_{(3,9)} = 6.44$; $p = 0.01$; $\eta^2 = 0.68$
Sweat rate ($mL \cdot min^{-1}$)	11.27 ± 1.63	8.38 ± 4.92	7.31 ± 2.76	5.43 ± 3.62	$F_{(3,9)} = 2.557$; $p = 0.120$; $\eta^2 = 0.46$

“Bucket” includes workshift and recovery period.

Fluid intake: Least Significant Difference (LSD) post-hoc test reported significant differences between buckets one and three ($p = 0.03$, $d = 2.5$), and buckets one and four ($p = 0.04$, $d = 2.4$).

RISK ASSESSMENT: 24 h Mountain bike racing

Managing risk: Participants will be present at the race briefing and will adhere to the race rules. Participants will obey race organisers (and official race-marshals' instructions). All participants have completed previous races of this distance and are familiar with race requirements.

Who is at risk: All participants.

Location of Activity and terrain: Twentyfour12 race course, Newnham Park, Plympton, Plymouth, Devon. Course contains: ascents and descents, single track, and fireroads.

Hazard	Likelihood & seriousness of injury	Control measures in place	Remaining risk
Equipment failure	Possible. Serious.	• Participants will use own bike following inspection. • All bikes receive pre-ride checks. • Lights will be fully charged and checked.	Low
Fall from moving bike	Possible. Serious	• Participants will pre-ride the course the day before at a slow pace. • Safety equipment worn and correctly fitted (helmet/gloves/eyewear). • Hazardous sections of trail highlighted in advance and managed effectively. • Participants will adhere to race-marshals' instructions at all times. • Participants' clothing and straps secured to avoid entrapment in moving parts of cycle. • Lights will be fully charged and checked.	Low-Medium
Adverse weather conditions	Unlikely. Minor	• Weather forecasts interpreted, and likely conditions assessed. • Appropriate clothing will be used. • Continual dynamic risk assessment carried out by researcher/ participants	**Low**

Hazard	Likelihood & seriousness of injury	Control measures in place	Remaining risk
Collision with other road/trail user	Unlikely. Serious/fatal	• Marshalled, waymarked, oneway course. • Managed in accordance with race organiser's rules. • Ride appropriate to terrain and vision. • Participants will pre-ride the course the day before at a slow pace.	**Low**
Trees – low branches, stumps etc.	Likely. Serious	• Participants will pre-ride the course the day before at a slow pace. • Safety equipment worn and correctly fitted (helmet/gloves/eyewear).	**Low**
Poor light conditions/ darkness	Likely. Serious	• Fully-charged race-standard lights fitted to the participants' bikes.	**Low**
Physiological testing issues	Unlikely	• Standard protocols and safety measure will be employed in accordance with University protocols and policy. • Researcher proficient in the administration of the tests.	

Researcher signature: …………………………..……………………………………..….

Date ……………………

Appendix Q: Photographs of the 24XCT race

Figure Q.1: The start of the 24XCT race (above), and a participant during a work-shift (right).

Figure Q.2: Participants' mountain bikes during a recovery period (left) and the Ergomo®Pro in situ (right).

Figure Q.3: A participant during a work-shift (left) and the finish of the race (right).

Appendix R: Published work

Metcalfe, J., Atkins, S., Kelly, J. (2010) Energy balance during a 24 hour team mountain bike race. Journal of Sports Sciences, 28(S1), S136-137

Cross-country relay (XCR) mountain bike racing, over a twenty four hour period, has developed a high profile in recent years. No studies to date have investigated the energy balance during such a race. The purpose of this study was to estimate energy intake (EI) and energy expenditure (EE) during a 24 h XCR mountain bike race.

Following approval by the University of Central Lancashire Ethics Committee, one team, comprising four elite male mountain bikers (mean age 36 years, *s* = 8.5; stature 1.77 m, *s* = 0.05; body mass 80.2 kg, *s* = 3.1; VO_{2max} 66.1 $ml \cdot kg^{-1} \cdot min^{-1}$, *s* = 9.6), volunteered to participate in the study. Prior to the race, individual relationships between heart rate (HR) and oxygen uptake ($\dot{V}O_2$) were established during an incremental laboratory test. HR data were recorded throughout the race-shifts and the corresponding $\dot{V}O_2$ per minute was calculated. EE for each race shift for each participant was estimated by assigning 20.2 kJ to every litre of oxygen consumed (Weir, 1949). EE during the recovery periods were calculated using the Harris-Benedict (1919) formula. Participants brought pre-planned food caches to the event. They were instructed to record the type, amount and time of food consumed. Energy intake (EI) was calculated from analysing nutritional information on the food packaging in conjunction with WinDiets software (WinDiets Research, Scotland). Data were separated into four buckets relating to time of day (Bucket 1: 12:00:00 – 17:17:48; Bucket 2: 17:17:49 – 22:57:06; Bucket 3: 22:57:07 – 05:02:14; Bucket 4: 05:02:15 – 12:25:00). Each bucket contained the collective mean data for the riders' EI and total EE (race plus recovery) for the riders' first, second, third and fourth race-shifts respectively.

A one-way ANOVA returned a significant difference between EI and EE for buckets ($F_{(1,3)} = 11.79$; $p = 0.04$; $\eta^2 = 0.79$). Post hoc analysis revealed a difference between EI and EE for each bucket. The mean EI was 17 335 kJ (s = 2244 which accounted for only 57% of the mean total energy expended during the race (30 369 kJ, s = 6061).

These results show that total EE progressively outstripped EI during the 24 h XCR mountain bike race, and that an endogenous energy supply was therefore required. The riders' energy consumption during the race-shifts was compromised due to the technical nature and the intensity of the sport. The results suggest that optimal refuelling during the recovery periods should play an important role when preparing nutritional strategies for such events.

Harris, J. A., Benedict, F. G. (1919) *A biometric study of basal metabolism in man.* Carnegie Institution of Washington, Washington.

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